Handbook of Vegetables & Vegetable Processing

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WILEY-BLACKWELL

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Preface

Fresh and processed vegetables are a fast-growing segment of the food industry and occupy an important place in the global commerce and economy of many countries. Various studies have demonstrated the importance of vegetables to human health, contributing fibe , vitamins, minerals, bioactive phytochemicals, and other nutrients in our diet. Botanically and organoleptically diverse vegetables are primarily grown on regional and seasonal basis. Because of their highly perishable nature, search for efficien and better methods of preservation has been continuing along side the developments in production, postharvest handling, processing, and quality improvements. This handbook with 37 chapters contributed by more than 50 authors from North America, Europe, Australia, Asia, and Middle East is organized in fi e parts, which review and discuss important developments in vegetables and vegetable processing.

Part I of the handbook has 7 chapters on physiology, biochemistry, sensory and fl vor properties, nutrition, phytochemical properties, genetic engineering, and microbiology.

Part II has 2 chapters on postharvest physiology and technology.

Part III has 12 chapters covering various aspects of vegetable processing including fresh-cut vegetables, vegetable parts, herbs and essential oils, vegetable juices, minimal processing and new technologies, refrigeration and freezing, drying, computer applications, packaging, and waste management.

Part IV includes 3 chapters on product and plant safety, including microbial safety, GAP and GMP, and HACCP.

Part V covers processing of important vegetables including green, leafy, tuber and root, and other vegetables. It also includes chapters on dry beans, olives, and avocadoes which are used as vegetables.

This handbook is intended as a contemporary source book on vegetable and vegetable processing for the industry, students, academia, libraries, research institutes, laboratories, and other interested professionals. To our knowledge, there are few books on vegetables and vegetable processing with associated coverage of scientifi aspects and industrial practices. Although the readers are the fina judge, we hope this handbook would meet the growing need for a quality book in this field The editorial team acknowledges many individuals for their supports during the conception and development of this book. Our sincere thanks and gratitude to all authors for their contributions and for bearing with us during the review process. We would like to thank the publishing and copy editing departments, especially, Mark Barrett, Susan Engelken and Ronald D'souza for their supports to this project. We are grateful to the institutions we are associated with and to our families for their supports.

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Part I

Biology, Biochemistry, Nutrition, Microbiology, and Genetics

Chapter 1

Biology and Classification of Vegetables

Theodore J. K. Radovich

Introduction

Vegetables enrich and diversify the human diet. They are the primary source of mineral nutrients, vitamins, secondary plant metabolites, and other compounds that support human health and nutrition. Vegetables, especially roots and tubers, can also possess signifi can caloric value, serving as staple crops in many parts of the world, particularly in the tropics. Although vegetables account for less than 1% of the world's plants, the genetic, anatomical, and morphological diversity of vegetables as a group is astounding (Graham et al. 2006; Maynard and Hochmuth 2007). Hundreds of vegetable taxa are grown for food in subsistence and commercial agricultural systems worldwide. This chapter reviews and explains the biology and classifica tion of vegetables.

Biology and Classification of Vegetables

A primary reason for the diversity among vegetable crops is the broad definitio of the word "vegetable" itself. Any plant part consumed for food that is not a mature fruit or seed is by definitio a vegetable. These include petioles (e.g., celery, *Apium graveolens* Dulce group), entire leaves (e.g., lettuce, *Lactuca sativa*), immature fruits (e.g., cucumber, *Cucumis sativus*), roots (e.g., carrot, *Dacus carota*), and specialized structures such as bulbs (e.g., onion, *Allium cepa* Cepa group) and tubers (e.g., white potato, *Solanum tuberosum*).

Further expanding this already generous definitio is the inclusion of mature fruits that are consumed as part of a main meal rather than dessert (e.g., tomato, *Solanum lycopersicum*). This culinary exception to the anatomical rule was given legal precedence in the US Supreme Court decision Nix v. Hedden (1893) that confirme common usage of "vegetable" in reference to tomato. This has since been extended to beans and other fruits. Even dessert melons (e.g., cantaloupe, *Cucumis melo* Cantalupensis group), which are fruits by every botanical, legal, and culinary definition are frequently "lumped" in with vegetables because of similarities in biology and culture that they share with their more vegetal cousins in the *Cucurbitaceae* (Iltis and Doebley 1980) (Table 1.1).

The biological diversity among vegetables necessitates a systematic method for grouping vegetables in order to efficientl access information and make management decisions. Understanding the biology of vegetable crops will aid decision making associated with production, postharvest handling, and marketing. Ultimately, vegetable classificatio is inextricably linked with crop biology. Three

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Table 1.1 Botanical names, common names, and edible parts of select vegetables by family. Families in the Monocotyledons are listed first (shaded) followed by families in Dicotyledons

Family	Botanical name	Common name	Edible plant part
***Alliaceae* (Onion family)**			
	Allium ampeloprasum L. Ampeloprasum group	Great-headed garlic	Bulb and leaf
	Allium ampeloprasum L. Kurrat group	Kurrat	Pseudostem
	Allium ampeloprasum L. Porrum group	Leek	Pseudostem and leaf
	Allium cepa L. Aggregatum group	Shallot	Pseudostem and leaf
	Allium cepa L. Cepa group	Onion	Bulb
	Allium cepa L. Proliferum group	Tree onion, Egyptian onion	Aerial bulb
	Allium chinense G. Don.	Rakkyo	Bulb
	Allium fistulosu L.	Welsh onion, Japanese bunching onion	Pseudostem and leaf
	Allium grayi Regel	Japanese garlic	Leaf
	Allium sativum L.	Garlic	Bulb and leaf
	Allium schoenoprasum L.	Chive	Leaf
	Allium scorodoprasum L.	Sand leek, giant garlic	Leaf and bulb
	Allium tuberosum Rottler ex Sprengel	Chinese chive	Leaf, immature fl wer
	Allium victorialis L. Platyphyllum group, Hult.	Longroot onion	Bulb, leaf
***Araceae* (Arum family)**			
	Alocasia macrorrhiza (L.) Schott	Giant taro, alocasia	Corm, immature leaf, petiole
	Amorphophallus paeoniifolius (Dennst.) Nicolson	Elephant yam	Corm
	Colocasia esculenta (L.) Schott	Taro, dasheen, cocoyam	Corm, immature leaf
	Cyrtosperma chamissonis (Schott) Merr.	Giant swamp taro	Corm
	Cyrtosperma merkusii (Hassk.) Schott.	Gallan	Corm
	Xanthosoma brasiliense (Desf.) Engler	Tannier spinach, catalou	Immature leaf
	Xanthasomas agittifolium (L.) Schott	Tannia, yellow yautia	Corm and young leaf
***Cyperaceae* (Sedge family)**			
	Cyperus esculentus L.	Rushnut, chufa	Tuber
	Eleocharis dulcis (Burm.f.) Trin. Ex Henschel	Water chestnut, Chinese water chestnut	Corm
	Eleocharis kuroguwai Ohwi	Wild water chestnut	Corm
***Dioscoreaceae* (Yam family)**			
	Dioscorea alata L.	White yam, water yam	Tuber
	Dioscorea batatas Decue.	Chinese yam	Tuber
	Dioscorea bulbifera L.	Potato yam, aerial yam	Tuber
	Dioscorea cayenensis Lam.	Yellow yam	Tuber

Dioscorea dumetorum (Kunth) Pax.	Bitter yam	Tuber
Dioscorea esculenta (Lour.) Burk.	Lesser yam	Tuber
Dioscorea rotundata Poir.	White Guinea yam	Tuber
Dioscorea trifid L. f.	Indian yam	Tuber
***Liliaceae* (Lily family)**		
Asparagus officinali L.	Asparagus	Shoot
Hemerocallis spp.	Daylily	Flower
***Musaceae* (Banana family)**		
Musa x paradisiaca L. Paradisiaca group	Plantain	Fruit, fl wer bud
***Poaceae* (Grass family)**		
Bambusa spp.	Bamboo shoots	Young shoot
Dendrocalamus latifloru Munro	Bamboo shoots	Young shoot
Phyllostachys spp.	Bamboo shoots	Young shoot
Zea mays L. subsp. *mays*	Sweet corn	Immature kernels and immature cob with kernel
***Zingiberaceae* (Ginger family)**		
Alpinia galanga (L.) Sw.	Greater galangal	Floral sprout and fl wer, tender shoot, rhizome
Curcuma longa L.	Tumeric	Rhizome
Zingiber officinal Roscoe	Ginger	Rhizome and tender shoot
***Amaranthaceae* (Amaranth family)**		
Amaranthus spp.	Amaranthus, tampala	Tender shoot, leaf, sprouted seed
***Apiaceae* (Carrot family)**		
Angelica spp.	Angelica	Tender shoot and leaf
Anthriscus cerefolium (L.) Hoffm.	Chervil	Leaf
Apium graveolens L. Dulce group (Mill.) Pers.	Celery	Petiole, leaf
Apium graveolens L. Rapaceum group (Mill.) Gaud.	Celeriac, turnip-rooted celery	Root, leaf
Coriandrum sativum L.	Coriander	Leaf and seed
Daucus carota L. subsp. *sativus* (Hoffm.) Arcang.	Carrot	Root and leaf
Foeniculum vulgare	Fennel	Leaf, Petiole
Pastinaca sativa L.	Parsnip	Root and leaf
Petroselinum crispum (Mill.) Nym. Crispum group	Parsley	Leaf
Petroselinum crispum (Mill.) Nym. Tuberosum group	Turnip-rooted parsley	Root and leaf
Petroselinum crispum (Mill.) Nym. Neapolitanum group	Italian parsley	Leaf

(*Continued*)

Table 1.1 (*Continued*)

Family	Botanical name	Common name	Edible plant part
***Asteraceae* (Sunfl wer family)**			
	Arctium lappa L.	Edible burdock	Root, petiole
	Artemisia dracunculus L. subsp. *sativa* L.	French tarragon	Leaf
	Chrysanthemum spp.	Edible chrysanthemum	Leaf and tender shoot
	Cichorium endivia L.	Endive, escarole	Leaf
	Cichorium intybus L.	Chicory, witloof chicory	Leaf
	Cynara cardunculus L.	Cardoon	Petiole
	Cynara scolymus L.	Globe artichoke	Immature fl wer bud
	Helianthus tuberose L.	Jerusalem artichoke	Tuber
	Lactuca sativa L. Asparagina group Bailey	Asparagus lettuce, celtuce	Stem
	Lactuca sativa L. Capitata group L.	Head lettuce, butterhead lettuce	Leaf
	Lactuca sativa L. Longifolia group Lam.	Romaine lettuce, leaf lettuce	Leaf
	Taraxacum officinal Wiggers	Dandelion	Leaf, root
	Tragopogon spp.	Salsify	Root and young leaf
***Basellaceae* (Basella family)**			
	Basella alba L.	Indian spinach, Malabar spinach	Leaf and young shoot
***Boraginaceae* (Borage family)**			
	Borago officinali L.	Borage	Petiole
	Symphytum spp.	Comfrey	Leaf and tender shoot
***Brassicaceae* (Mustard family)**			
	Armoracia rusticana Gaertn., Mey., Scherb.	Horseradish	Root, leaf, sprouted seed
	Brassica carinata A. Braun	Abyssinian mustard	Leaf
	Brassica juncea (L.) Czernj. & Coss.	Mustard	Leaf
	Brassica napus L. Napobrassica group (L.) Reichb.	Rutabaga	Root and leaf
	Brassica napus L. Napus group	Vegetable rape	Leaf and young fl wer stalk
	Brassica napus L. Pabularia group (DC.) Reichb.	Siberian kale, Hanover salad	Leaf
	Brassica nigra L. Koch.	Black mustard	Leaf
	Brassica oleracea L. Acephala group DC.	Kale, collards	Leaf
	Brassica oleracea L. Alboglabra group Bailey	Chinese kale	Young fl wer stalk and leaf
	Brassica oleracea L. Botrytis group L.	Caulifl wer	Immature flora stalk
	Brassica oleracea L. Capitata group L.	Cabbage	Leaf
	Brassica oleracea L. Costata group DC.	Portuguese cabbage, tronchuda cabbage	Leaf and inflorescenc
	Brassica oleracea L. Gemmifera group Zenk.	Brussels sprouts	Axillary bud
	Brassica oleracea L. Gongylodes group L.	Kohlrabi	Enlarged stem
	Brassica oleracea L. Italica group Plenck.	Broccoli	Immature fl wer stalk

Brassica oleracea L. Sabauda group L.	Savoy cabbage	Leaf
Brassica perviridis Bailey	Spinach mustard, tendergreen mustard	Leaf
Brassica rapa L. Chinensis group (Rupr.) Olsson	Pak choi, Chinese mustard	Leaf
Brassica rapa L. Narinosa group (Bailey) Olsson	Broad-beaked mustard	Leaf
Brassica rapa L. Parachinensis group (Bailey) Tsen & Lee	Mock pak choi, choy sum	Leaf
Brassica rapa L. Pekinensis group (Lour.) Olsson	Chinese cabbage, pe-tsai	Leaf
Brassica rapa L. Rapa group (DC.) Metzg.	Turnip	Enlarged root
Brassica rapa L. Utilis group (DC.) Metzg.	Turnip green	Leaf
Brassica rapa L. Septiceps group (DC.) Metzg.	Turnip broccoli, broccoli raab	Inflorescenc
Eruca sativa Miller	Rocket salad, arugula	Leaf
Lepidium sativum L.	Garden cress	Leaf
Nasturtium officinal R. Br.	Watercress	Leaf
Raphanus sativus L. Caudatus group	Rat-tail radish	Immature seed pod
Raphanus sativus L. Radicula group	Radish	Root
Raphanus sativus L. Daikon group	Daikon	Root
Sinapis alba L.	White mustard	Leaf and young fl wer stalk
Wasabia japonica (Miq.) Matsum.	Wasabi, Japanese horseradish	Rhizome, young shoot
***Chenopodiaceae* (Goosefoot family)**		
Atriplex hortensis L.	Orach	Leaf
Beta vulgaris L. Cicla group	Chard, Swiss chard	Leaf
Beta vulgaris L. Crassa group	Garden Beet	Root and leaf
Chenopodium quinoa Willd.	Quinoa	Leaf
Spinacia oleracea L.	Spinach	Leaf
***Convolvulaceae* (Bindweed family)**		
Ipomoea aquatica Forssk.	Water spinach, kangkong	Tender shoot and leaf
Ipomea batatas (L.) Lam.	Sweet potato	Root and leaf
***Cucurbitaceae* (Gourd family)**		
Benincasa hispida (Thunb.) Cogn.	Wax gourd	Immature/mature fruit
Citrullus lanatus Lantanus group (Thunb.) Matsum & Nakai	Watermelon	Ripe fruit and seed
Citrullus lanatus Citroides group (Bailey) Mansf.	Citron, preserving melon	Fruit
Cucumis anguria L.	West Indian gherkin	Immature fruit
Cucumis melo L. Cantaloupensis group	Cantaloupe	Fruit
Cucumis melo L. Flexuosus group	Japanese cucumber, snake melon	Immature fruit
Cucumis melo L. Inodorus group	Honeydew melon, casaba melon	Fruit
Cucumis melo L. Reticulatus group	Muskmelon (cantaloupe), Persian melon	Ripe fruit

(*Continued*)

Table 1.1 (*Continued*)

Family	Botanical name	Common name	Edible plant part
	Cucumis metuliferus E. Meyer ex Naudin	African horned cucumber	Fruit
	Cucumis sativus L.	Cucumber	Immature fruit
	Cucurbita argyrosperma Huber	Pumpkin	Young/mature fruit and seed
	Cucurbita maxima Duchesne	Giant pumpkin, winter squash	Mature fruit and seed
	Cucurbita moschata Duchesne	Butternut squash, tropical pumpkin	Young and mature fruit
	Cucurbita pepo L.	Summer squash, zucchini	Young fruit
	Cucurbita pepo L.	Common fiel pumpkin	Mature fruit and seed
	Lagenaria siceraria (Mol.) Standl.	Bottle gourd, calabash gourd	Immature fruit, tender shoot, and leaf
	Luffa spp.	Loofah	Immature fruit
	Momordica charantia L.	Bitter gourd, balsam pear	Immature fruit and young leaf
	Sechium edule (Jacq.) Swartz.	Chayote, vegetable pear	Fruit, tender shoot, leaf
***Euphorbiaceae* (Spurge family)**			
	Manihot esculenta Crantz	Yucca, cassava, manioc	Root and leaf
	Sauropus androgynus (L.) Merr.	Common sauropus	Leaf
***Fabaceae* (Pea family)**			
	Arachis hypogaea L.	Peanut, groundnut	Immature/mature seed
	Bauhinia esculenta Burchell	Marama bean	Immature pod and root
	Cajanus cajan (L.) Huth.	Cajan pea, pigeon pea	Immature pod/leaf
	Canavalia ensiformis (L.) DC.	Jack bean, horse bean	Immature seed
	Canavalia gladiata (Jacq.) DC.	Sword bean, horse bean	Immature seed
	Cicer arietinum L.	Garbanzo, chickpea	Seed
	Glycine max (L.) Merr.	Soybean	Immature and sprouted seed
	Lablab purpurus (L.) Sweet.	Hyacinth bean	Immature seed
	Lens culinaris Medikus	Lentil	Immature pod, sprouted seed
	Lupinus spp.	Lupin	Seed
	Neptunia oleracea Lour.	Water mimosa	Leaf and tender shoot
	Pachyrhizus erosus (L.) Urban	Jicama, Mexican yam bean	Root, immature pod, seed
	Phaseolus acutifolius A. Gray	Tepary bean	Seed, immature pod
	Phaseolus coccineus L.	Scarlet runner bean	Immature pod and seed
	Phaseolus lunatus L.	Lima bean	Immature seed, mature seed
	Phaseolus vulgaris L.	Garden bean, snap bean	Immature pod and seed
	Pisum sativum L. Sativum group	Pea, garden pea	Immature seed, tender shoot
	Pisum sativum L. Macrocarpon group	Edible-podded pea	Immature pod
	Pisum sativum L. Saccharatum group	Snow pea, China pea	Immature seed, tender shoot
	Psophocarpus tetragonolobus (L.) DC.	Goa bean, winged bean	Immature pod, seed, leaf, root

Pueraria lobata (Willd.) Ohwi	Kudzu	Root, leaf, tender shoot
Tetragonolobus purpureus Moench	Asparagus pea, winged pea	Immature pod
Trigonella foenum-graecum L.	Fenugreek	Leaf, tender shoot, immature pod
Vicia faba L.	Fava bean, broad bean, horse bean	Immature seed
Vigna aconitifolia (Jacq.) Marechal	Moth bean	Immature pod and seed
Vigna angularis (Willd.) Ohwi & Ohashi	Adzuki bean	Seed
Vigna mungo (L.) Hepper	Black gram, urd	Immature pod and seed
Vigna radiata (L.) Wilcz.	Mung bean	Immature pod, sprouted seed, seed
Vigna subterranean (L.) Verdn.	Madagascar groundnut	Immature/mature seed
Vigna umbellata (Thunb.) Ohwi & Ohashi	Rice bean	Seed
Vigna unguiculata (L.) Walp. Sesquipedalis group (L.)	Asparagus bean, yard-long bean	Immature pod and seed
Vigna unguiculata (L.) Walp. Unguiculata group (L.)	Southern pea, cowpea	Immature pod and seed
***Lamiaceae* (Mint family)**		
Mentha spicata L. em. Harley	Spearmint	Leaf and inflorescenc
Ocimum basilicum L.	Common basil, sweet basil	Leaf
Ocimum canum Sims.	Hoary basil	Young leaves
Origanum vulgare L.	Marjoram	Flowering plant and inflorescenc
Perilla frutescens (L.) Britt. Crispa group (Thunb.) Deane	Perilla	Leaf and seed
***Malvaceae* (Mallow family)**		
Abelmoschus esculentus (L.) Moench	Okra, gumbo	Immature fruit
Hibiscus sabdariffa L.	Jamaican sorrel	Calyx and leaf
***Moringacea* (Moringa family)**		
Moringa oleifera L.	Horseradish tree	Leaf, pods, fl wers
***Nelumbonaceae* (Lotus root)**		
Nelumbo nucifera Gaertn.	Lotus root	Rhizome, leaf, seed
***Polygonaceae* (Buckwheat family)**		
Rheum rhabarbarum L.	Rhubarb, pieplant	Petiole
Rumex spp.	Sorrel	Leaf
***Portulacaceae* (Purslane family)**		
Portulaca oleracea L.	Purslane	Leaf and young shoot

(*Continued*)

Table 1.1 (*Continued*)

Family	Botanical name	Common name	Edible plant part
***Solanaceae* (Nightshade family)**			
	Capsicum annuum L. Grossum group	Bell pepper	Fruit
	Capsicum annuum L. Longum group	Cayenne pepper, chile pepper	Mature fruit
	Capsicum chinense Jacq.	Scotch bonnet, datil, habanero pepper	Fruit
	Capsicum frutescens L.	Tabasco pepper	Fruit
	Physalis ixocarpa Brot. ex Hornem.	Tomatillo	Unripe fruit
	Physalis peruviana L.	Cape gooseberry	Ripe fruit
	Solanum lycopersicum Mill.	Tomato	Ripe fruit
	Solanum pimpinellifolium (L.) Mill.	Currant tomato	Ripe fruit
	Solanum melongena L.	Eggplant, aubergine	Immature fruit
	Solanum muricatum Ait.	Pepino, sweet pepino	Ripe fruit
	Solanum tuberosum L.	Potato	Tuber
***Tropacolaceae* (Nasturtium family)**			
	Tropaeolum majus L.	Nasturtium	Leaf, fl wer

Source: Abridged and modifie from Maynard and Hochmuth (2007).

Table 1.2 Definitions of selected terms relating to vegetable anatomy, biology, and classification

Term	Definitio
Andromonoecious	Staminate and hermaphrodite fl wers on same plant
Annual	Plant that completes life cycle (sets seed) and dies in one year
Axillary bud	Bud occurring in the leaf axil, as in Brussels' sprouts
Berry	Fruit flesh throughout
Biennial	Plant that completes life cycle (sets seed) and dies in two years
Bolt	Develop inflorescenc prematurely, as in lettuce and spinach
Bract	Modifie leaf or scale at base of fl wer
Bulb	Bud surrounded by flesh and papery scales attached to stem plate
Calyx	Sepals or outer whorl of perianth
Carpel	Individual unit of compound pistil
Caryopsis	Fruit (grain) of grass, as in sweet corn
Corm	Vertically oriented flesh , solid stem at or below soil surface, e.g., taro
Cortex	Storage tissues of root or stem, between epidermis and vascular tissue
Cultivar	Group of cultivated plants with distinguishing characteristics that are retained when plants are reproduced
Curd	Fleshy inflorescenc with fl wer buds undifferentiated, e.g., caulifl wer
Determinant	Branch stops growing at fl wering
Dioecious	Staminate (male) and pistillate (female) fl wers on separate plants
Endocarp	Inner layer of flesh fruit wall
Endodermis	Inner layer of cortex, adjacent to vascular tissue
Epidermis	Thin outer layer of leaf, stem, or root
Exocarp	Outermost layer (e.g., rind or skin) of fruit wall
Floret	Small fl wer on inflorescence e.g., artichoke
Fruit	Mature ovary.
Gynoecious	Producing predominantly, or only, female fl wers
Indeterminant	Branch continues to grow after fl wering starts
Legume	Single carpel fruit with two sutures, seed attached along one suture
Lenticel	Raised, unsuberized dot or pore for gas exchange
Mesocarp	Middle layer of pericarp or fruit wall
Locule	Seed cavity of fruit. Also compartment of ovary or anther
Midrib	Pronounced central vein of leaf
Monoecious	Male and female fl wers on same plant
Node	Enlarged area on stem where buds emerge
Pedicel	Stalk or stem of individual fl wer or flore
Peduncle	Primary fl wer stalk of inflorescenc
Pepo	Cucurbit fruit, leathery or woody exocarp inseparable from endocarp
Perfect fl wer	Flower with both male and female parts
Pericarp	Fruit wall
Perennial	Plants persisting for three years or more
Petiole	Leaf stalk
Rhizome	Horizontally oriented underground stem modifie for storage, with nodes capable of forming new roots and shoots
Scales	Fleshy or dry modifie leaves of a bulb
Silique	Specialized fruit of Brassicaceae, with two fused carpels
Stele	Central core of vascular strengthening tissue in roots and stems
Tuber	Fleshy, enlarged stems occurring at end of rhizomes

basic approaches toward classificatio of vegetables that are based on commonalities among groups are as follows:

1. Tissues and organs consumed
2. Ecological adaptation
3. Taxonomy

All three of the above approaches toward classificatio are based on some level of commonality in crop biology, with the precision of classificatio varying from relatively low (plant part consumed) to very high (taxonomic). Table 1.2 gives definition of selected terms related to vegetable anatomy, biology and classification

Vegetable Tissues and Organs

The phenotypic diversity among vegetables is actually based on relatively few types of specialized cells and tissues. Dermal, ground, and vascular tissue make up the three basic tissue systems. Ultimately, the structure of these cells and tissues determine their function.

Dermal Tissues

Epidermal cells, together with cutin and cuticular waxes, make up the outer layers of leaves, fruit, and other above-ground structures and protect against water loss and other adverse abiotic and biotic factors. The periderm (cork) layer of mature roots and stems is analogous to the epidermis, but consists of nonliving cells supplemented with suberin. Stomatal guard cells are epidermal cells specialized in regulating gas exchange, and are especially dense on the abaxial surface of leaves. Lenticels are specialized, unsuberized dermal structures (appearing as raised dots or bumps) that regulate gas exchange on roots, stems, and fruits. Trichomes and root hairs are dermal cells with excretory, absorptive, and other functions critical to the ecology of vegetables.

Ground Tissues

Ground tissues are comprised of the parenchyma, collenchyma, and sclerenchyma. Parenchyma cells are thin-walled cells that make up much of the ground tissues of vegetables. Parenchyma cells often serve to store starch and other compounds. The cortex and pith of white potato are examples of ground tissues dominated by parenchyma. Collenchyma cells have alternating thin and thick cell walls that provide fl xible support for stems, as in the strings of celery (*Apium graveolens*). Sclerenchyma tissues include sclerids and fiber with tough cell walls. Sclerenchyma cells are typically scarce in edible vegetable organs, but are important components of seed coats, nut shells, and the stony endocarps of peaches (*Prunus persica*) and related fruits.

Conducting Tissues

Vascular tissues conduct water, minerals, photosynthates, and other compounds throughout the plant. The xylem is part of the apoplast and consists primarily of nonliving tracheids and vessel elements. The xylem transports water, mineral nutrients, and some organic compounds, generally from the roots to leaves. The phloem is part of the symplast, consists primarily of sieve cells and companion cells, and is important in conducting sugars, amino acids, and other compounds from source (usually leaves) to sink (actively growing meristems, roots, developing fruits, and seeds). Both xylem and phloem are supported by parenchyma cells and fibe . Some xylem cells (i.e., tracheids) have thickened cell walls that contribute significantl to the structural support of tissues.

The differentiation and variable structure of plant tissues result in diverse functions among the plant organs (stems, roots, and leaves) and organ systems (e.g., fruits, fl wers, buds, and bulbs) consumed as vegetables. The classificatio of vegetables by edible parts has been termed "Supermarket Botany" (Graham et al. 2006). Although broad and not always anatomically correct, the grouping of commodities as leafy, fruit, and root vegetables has value to growers, distributors, and others in the market chain because of similarities in cultural and postharvest requirements within groups. In addition to being practical, the division of vegetables by anatomical structure highlights the impressive crop improvement accomplishments of the early agriculturalists, which both exploited and expanded the structural diversity inherent in the plant kingdom.

Leafy Vegetables

Leaves are the primary site of photosynthesis in plants and are generally the most nutrient

dense and most perishable of the vegetables. Leaves, particularly dark green leaves, contain relatively high levels of minerals (e.g., Fe, Mg, Ca), enzymes (protein), and secondary metabolites (e.g., carotenes and xanthophylls). These compounds, important to human nutrition, are required by the plant for light collection, electron transport, photoprotection, carbon fixation and many other biochemical processes abundant in leaves. Stomata are especially dense on the abaxial surface of leaves and are the terminal point of transpiration, which is the primary mechanism for dissipating heat accumulated from intercepting solar radiation. High stomatal density combined with the high surface area make leafy vegetables more susceptible to postharvest water loss than other vegetables. Subsequently, rapid cooling after harvest and storage under high humidity are particularly important postharvest procedures for leafy vegetables (Kader 2002).

Leafy vegetables are concentrated in the *Asteraceae* (*Compositae*), *Brassicaceae* (*Cruciferae*), and *Chenopodiaceae*. Culinary herbs, dominated by the *Lamiaceae* (*Labiatae*), are also categorized as leafy vegetables. Other vegetables consumed primarily for leaf structures include *Impomea aquatica* (*Convolvulaceae*), celery (*Apiaceae*), and *Amaranthus* spp. (*Amaranthaceae*). The leaves of many plants grown primarily for other organs (fruits, roots, specialized structures) are often utilized to supplement the diet. The leaves of taro (*Colocasia esculenta*) and cassava (*Manihot esculenta*), as well as the young leaves and shoots of sweet potato (*Ipomea batatas*) and many cucurbits (*Cucurbitaceae*) are typical examples of vegetables in this category.

Leafy vegetables that are generally cooked before consumption to soften texture and improve fl vor (e.g., mature leaves of many *Brassica* spp. and *Chenopodiaceae*) are sometimes classifie as "greens" to differentiate them from leafy vegetables that that are consumed raw, often as salad (e.g., most *Compositae* and the very young leaves of many *Brassica*). "Potherb" is used to describe greens used in small quantity for fl voring in cooking.

While generally softer and lighter in fla vor than cooking greens, salad crops vary in their texture and fl vor, and these differences are important in differentiating among leafy vegetables consumed raw. Examples include textural differences among lettuce (crisphead vs butterhead types) and variable levels of texture and pungency in species used in mesclun mixes. Textural and fl vor differences are caused by variability in leaf structure (cuticle thickness), cell type, succulence, as well as type and quantity of phyochemicals (e.g., glucosinolates) present (Figure 1.1).

Root Vegetables

Root vegetables include true roots (carrot, sweet potato and cassava) as well as specialized structures such as tubers, bulbs, corms (e.g., taro), and hypocotyls (e.g., radish, *Raphanus sativus*). These specialized structures are classifie as root vegetables because of their full or partial subterranean habit, their physical proximity to true roots, and their function as storage organs for starch and other compounds. Most of these specialized structures consist primarily of stem tissue, with bulbs being a notable exception. Although significan variability in caloric value and shelf life exists within the roots crops, they are typically higher in calories and less perishable than other vegetables due to their storage function, suberized periderm or protective skin, and high dry matter content (Figure 1.2).

True Roots

The biology and anatomy of true root vegetables are exemplifie by a comparison of three important crops: carrot, sweet potato, and cassava. All true roots consist of secondary vascular tissue arising from a cambial

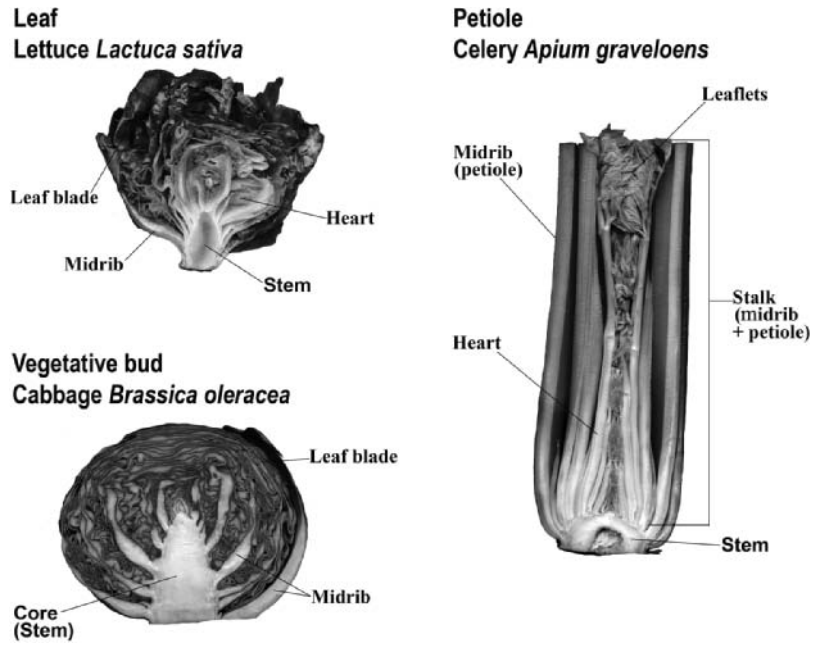

Figure 1.1 Anatomy of select leafy vegetables.

layer, with phloem (cortical) tissue extending outward and xylem tissue inward. Secondary plant products are found throughout root tissues, but many are particularly abundant in the pericycle, which is closely associated with the periderm and is removed upon peeling.

In carrot (a primary tap root), the majority of the edible portion is comprised of sugar-storing parenchyma associated with secondary phloem tissue. Sucrose is the dominant sugar in mature roots, and roots contain little starch. The tissue associated with the secondary xylem in the center of roots (pith) is of coarser texture and small pith is desirable in commercial carrots (Rubatzky and Yamaguchi 1997). In contrast, the majority of the edible portions of sweet potato and cassava are internal to the vascular ring of enlarged secondary roots and consist of starch-containing storage parenchyma, which surround a matrix of xylem vessels. In cassava, all cortical tissue is removed along with the periderm (collectively, the peel) prior to cooking, and a dense bundle of fibrou vascular tissue in the center of roots is also removed before consumption. Although the majority of sweet potato and cassava starch is amylopectin, variation in the minority quantity of amylose affects texture of the cooked product. Glutinous texture, stickiness, or waxiness of the product increases with a decreasing ratio of amylose to amylopectin.

Modified Stems

Tubers are enlarged, fles y underground stems that share some of the characteristics of true roots, including development underground, a suberized periderm, and starch-storing parenchyma. The best-known vegetable examples of tubers are the white potato and the yams (*Dioscorea* spp.).

Potato tubers form at the end of rhizomes originating from the main stem. Recessed buds (eyes) and leaf scars (eyebrows) on the skin surface are conspicuous indicators that the potato is derived from stem rather than

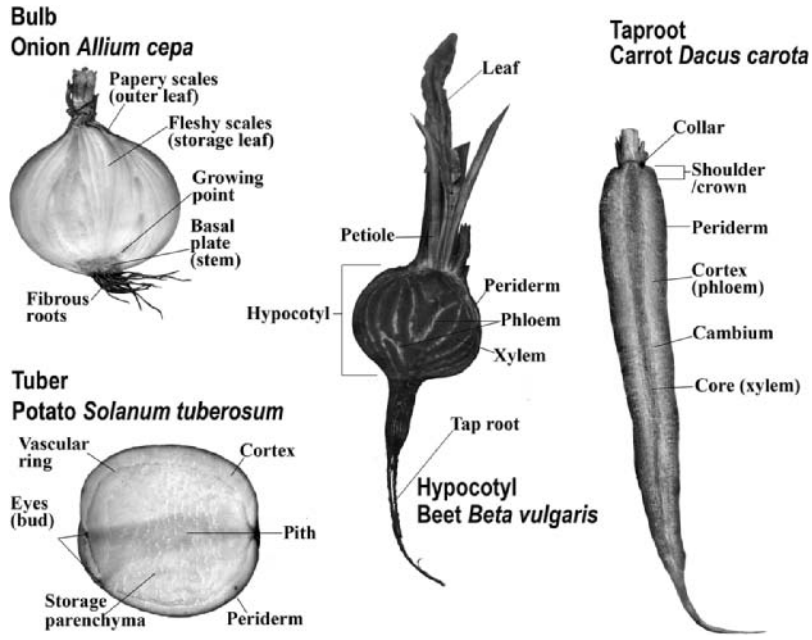

Figure 1.2 Anatomy of select vegetables classified as "root crops."

root tissue (Figure 1.2). In the absence of dormancy or chemical inhibition, these buds will sprout and allow for the vegetative reproduction of potato from "seed" pieces or small whole potatoes. In contrast to potato, yam tubers lack conspicuous buds, leaf scars, and other outward signs of being derived from stem tissue. Sprouts will form from yam tubers and tuber pieces, but generate most readily from the proximal end of tubers. As with true roots, cooking quality of tubers is influ enced by starch type, dry matter content, and cell size.

The swollen hypocotyl tissues of table beet (*Beta vulgaris* group Crassa) and radish (*Rhaphanus sativus*) are closely associated with the taproot, and the edible portion is described as the hypocotyl-root axis. The multiple cambia and differentially pigmented vascular tissues in beet result in the characteristic banding observed in cross sections of the vegetable (Figure 1.2).

Corms are a third type of modifie stem grouped with the root vegetables and are exemplifie by taro (*Colocasia esculenta*) and other members of the *Araceae*. Corms are vertically oriented, apically dominant, compressed starchy stem bases that initiate underground, but continue to grow partially above ground. Adventitious shoots eventually arise from the parent corm to form secondary corms or cormels.

Bulb vegetables, mainly in the *Alliaceae*, are comprised primarily of swollen, fles y leaves (scales) specialized for storage of carbohydrates and other compounds (Figure 1.2). These leaves arise in a whorl from a compressed conical stem called a basal plate. Dry, papery scales of the bulb exterior protect the bulb.

Fruit Vegetables

Fruit vegetables are concentrated in the *Solanaceae*, *Cucurbitaceae*, and *Fabaceae*, but occur in other families as well. Large fruited annual vegetables of the *Cucurbitaceae* and *Solanaceae* are generally warm- and

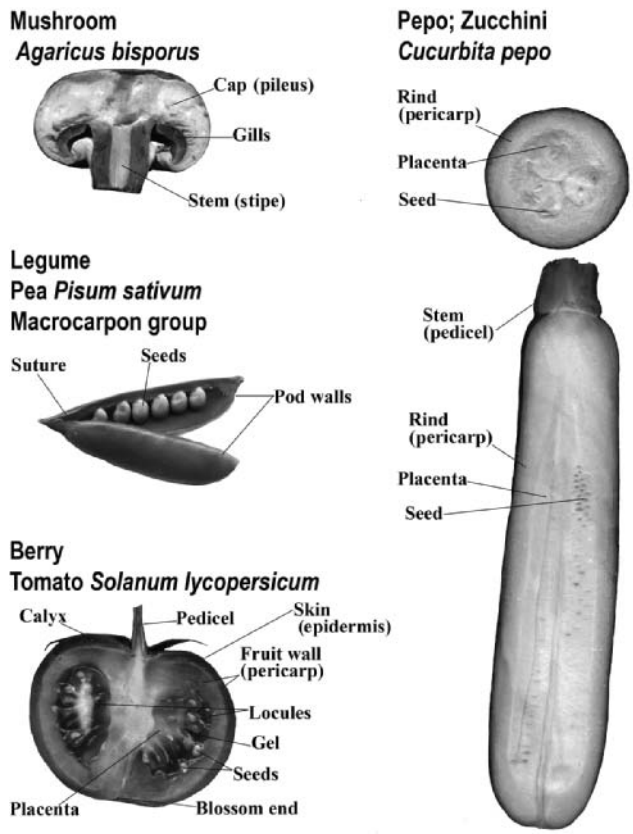

Figure 1.3 Anatomy of select vegetables composed of fruits and fruiting bodies (mushroom).

hot-season crops because their wild progenitors evolved in tropical and subtropical latitudes where growing seasons are long enough to produce enough vegetative growth to support large fruits in a single year (see ecological adaptation below). Other vegetables in this group are okra (*Abelmochus esculentus*) and *Phaseolus* spp. Intensive selection has since resulted in early cultivars of most fruiting vegetables that will produce fruit in the short growing periods of northern latitudes.

Among the commercial vegetables, simple fruits dominate. Berry, pepo, and legume are the characteristic fruit types of the *Solanaceae*, *Cucurbitaceae*, and *Fabaceae*, respectively. Specialized pods produced by okra (capsule) and the *Brassicaceae* and *Morigaceae* (silique) are dry and at least partially dehiscent at maturity but are consumed immature green, while still succulent. Each kernel on an ear of corn is a simple indehiscent fruit (caryopsis) (Figure 1.3).

In many fruit vegetables, the whole fruit is edible although not necessarily consumed. In tomato, eggplant (*Solanum melogena*), cucumber, and other vegetables, the entire pericarp along with placenta and other tissue is consumed. These vegetables may be peeled to soften texture and lighten fl vor by removing toughened dermal cells as well as cutin, waxes, and other secondary metabolites that are associated with organ protection, and which are concentrated in the epidermis and outer pericarp (exocarp). Immature fruit of

bittermelon (*Momordica charantia*) may also be peeled to reduce bitterness caused by momordicosides and other compounds concentrated in the outer pericarp, while the tough endocarp and spongy placenta of bittermelon are discarded along with the seeds. The edible portion of mature *Cucurbita* fruit is pericarp tissue. In *Cucumis melo* (e.g., cantaloupe and muskmelon) the most internal portions of the pericarp (endocarp and mesocarp) are eaten, with the leathery rind (exocarp and some mesocarp) discarded. In watermelon (*Citrullus lanatnus*) the rind includes much of the pericarp, with placental tissue making up a substantial portion of what is consumed, although succulent parts of the rind can be pickled and otherwise prepared.

Other Vegetables

Other vegetables that are comprised primarily of stem material include stem lettuce (*Lactuca sativa*), kohlrabi (*Brassica oleracea* Gongyloides group), asparagus (*Asparagus officinali*), bamboo shoot (*Poaceae*), and heart-of-palm (*Araceae*). Also, flowers of many plant taxa are consumed either raw or cooked. Important vegetables comprised of flora structures include broccoli and globe artichoke (*Cynara scolymus*) (Figure 1.4).

Ecological Adaptation of Vegetables

The environmental optima (e.g., temperature, light, and soil moisture) of vegetable crops will depend greatly on the center of origin of their wild progenitors. For example, vegetables whose center of origin lies in the tropics are often generally classifie as warm-season, short-day plants. In contrast, crops with temperate origins are often considered cool-season, long-day plants. Our need for food and fibe has resulted in strong, artifi cial selection pressure for broad adaptability in many vegetables crops (Wien 1997; Sung et al. 2008). Nevertheless, many vegetables can be grouped with regard to their environmental requirements, and knowledge of these requirements is critical for crop managers to make effective decisions (Table 1.3).

Temperature

Classificatio of vegetable crops by temperature is based on three sets of values, or cardinal temperatures, that describe the minimum, maximum, and optimum temperature ranges for crop growth. Minimum and maximum temperatures represent the limits at which growth and development are thought to stop or at least slow to a negligible rate, while plant growth and normal development are most rapid within the optimum temperature range. Krug (1997) stratifie the simple classificatio of "warm" and "cool" season crops to account for subtle but significan differences in cardinal temperatures. For example, the effective growth range for hot-season crops does not include temperatures as low as the minima for warm-season crops, while heat-tolerant cool crops have temperature maxima that exceed those of other cool-season crops (Figure 1.4).

A practical application resulting from the dominant influenc of temperature on vegetable crop biology is the use of a heat unit system (or temperature sum concept) to predict plant growth. The most simple and oft-cited example is that used to predict harvest dates for corn. Daily heat units (HU) accumulated are often calculated using the equation $\mathrm{HU} = \Sigma\ (T_{\mathrm{avg}} - T_{\mathrm{base}})$, where T_{avg} is the average daily temperature and T_{base} is the minimum temperature for the crop, below which no growth is expected. Cool-season crops grown during the summer in temperate zones will frequently be exposed to supraoptimal temperatures, and HU calculations must account for the negative effect of high temperatures on crop growth. In head cabbage, HU calculations using upper and lower threshold

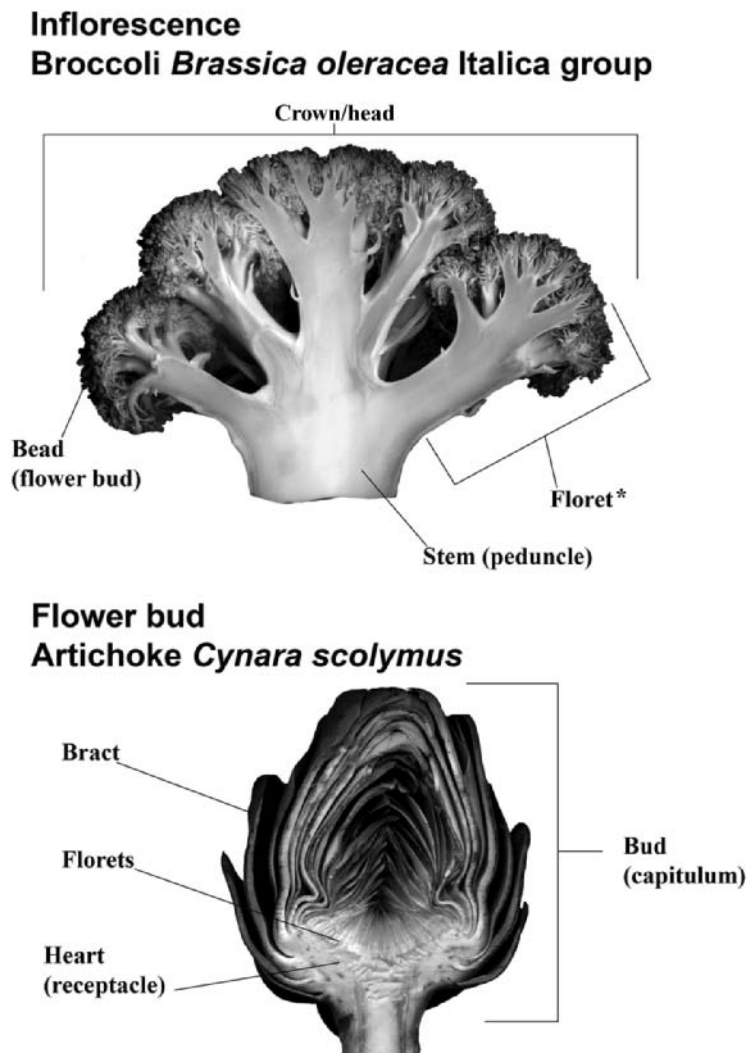

Figure 1.4 Anatomy of select vegetables composed of flowers and associated structures. Asterisk (*) indicates "floret" used as an industry designation for individual branches of inflorescence in broccoli.

temperatures of 21 and 0°C have been used effectively to explain seasonal variability in head size and weight (Radovich et al. 2004; Figure 1.5). If the daily maximum temperature (T_{max}) falls below the upper threshold, then HU are calculated as described above for corn. If T_{max} exceeds 21°C, then an intermediate cutoff method is employed, where $HU = [(T_{min} + 21)/2)] - [(T_{max} - 21) * 2]$. Using this cutoff method, $HU = 0$ when $T_{max} \geq 30°C$.

Unfortunately, single factor models such as HU are not adequate to predict all developmental events. In the cabbage example above, variation in HU fails to explain year-to-year variability in head density. Similarly, while estimation of head density changes in lettuce is improved by the inclusion of light intensity into the HU equation (i.e., photothermal units), the inclusion of an additional factor is not adequate to satisfactorily predict density changes (Jenni and Bourgeois 2008). This

Table 1.3 Classification of vegetables based on lifecycle, temperature growth requirements, and photoperiodicity

Classificatio	Examples
Life cycle	
Perennial	*Asparagus officinal , Capsicum* spp., *Ipomea batatas*, *Solanum* sp.
Biennial	*Beta vulgaris*, *Brassica oleracea* Capitata group, *Dacus carota*
Annual	*Spinacia oleracea*, *Cucurbita* spp., *Brassica oleracea* Italica group
Temperature demand* (temperature range for effective growth)	
Hot (18–35°C)	*Abelmochus esculentus*, *Citrullus lanatus*, *Capsicum chinense*
Warm (12–35°C)	*Cucumis sativus*, *Cucurbita* spp., *Zea mays*, *Capsicum annuum*
Cool (heat tolerant) (7–30°C)	*Colocasia escultenta*, *Allium* spp., *Cynara scolymus, Brassica rapa L.* Chinensis group
Cool (7–25°C)	*Brassica oleracea*, *Raphanus sativus*, *Latuca sativa*, *Solanum tuberosm*
Photoperiod	
Short day	*Amaranthus* spp., *Pachyrhizus erosus*, *Solanum tuberosum*
Day neutral	*Solanum lycopersicum*, *Phaseolus* spp., *Cucurbita* spp.
Long day	*Allium cepa* Cepa group, *Spinacia oleracea*

Source: After Pierce (1987).
*After Krug (1997).

highlights the potentially complex relationship between ontogeny and environmental factors.

While heat drives vegetative growth in most vegetables, a certain number of cold units (time of exposure to temperatures below some critical minimum) are required to initiate fl wering in many temperate biennial vegetables. This phenomenon, termed vernalization, is exhibited by *Brassica*, beets, and other vegetables. In crops that are insensitive to photoperiod, cold units may be calculated similarly as described above, while photothermal units are employed for photoperiodic crops.

Light

All plants require light for photosynthesis. While a degree of shading will improve the growth of some vegetables, this is often a temperature response to cooling resulting from reduced solar radiation. Similarly, while the quality (i.e., wavelength) of light significantl affects crop phenology, light quantity (intensity and daylength) generally impacts vegetable crops in a similar manner. However, crops often differ substantially in their response to photoperiod.

As a rule, plants exhibit some sensitivity to photoperiod in their development, particularly with regard to fl wering and storage organ development (Waycott 1995; Martinez-Garcia et al. 2002). As mentioned previously, tropical and temperate crops are frequently considered short- and long-day plants respectively, although the actual stimulus is the duration of the dark period and day neutral cultivars have been developed for many crops. Short-day crops include yam bean, cowpea, sweet potato, and potato. Onion, lettuce, and spinach are examples of long-day vegetables (Mettananda and Fordham 1997).

Taxonomy of Vegetables

Botanical classificatio is the most precise and ultimately most useful method of organizing plants by biological commonality. The vast majority of vegetables are Angiosperms (subclass Monocotyledons and Dicotyledons) in the division Spermophyta. The Tallophyta (algae and fungi) are also important.

The broadest taxonomic grouping relevant to vegetable production and management is the Family. Similarities in structure and

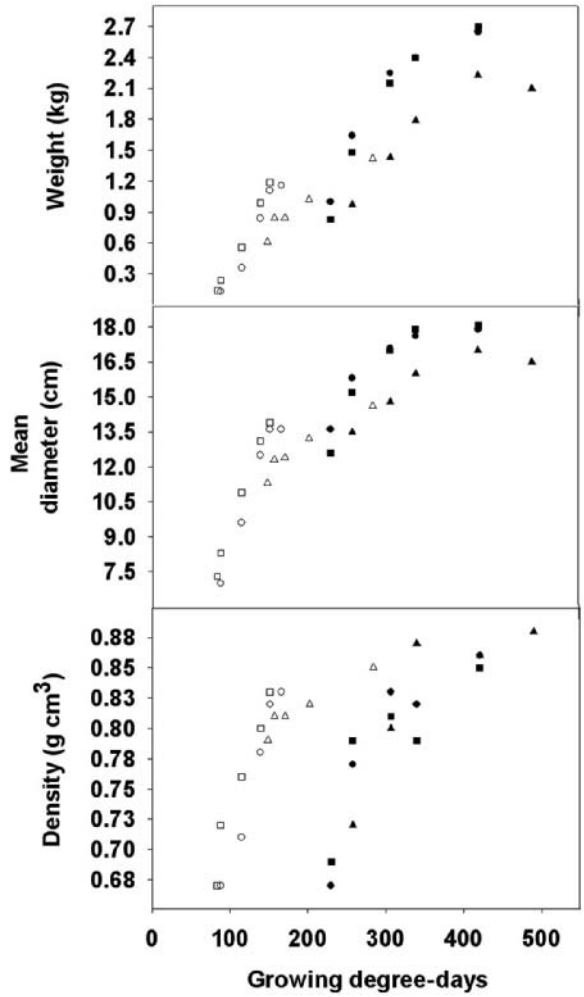

Figure 1.5 Relationship between growing degree-days and head traits of cabbage (*Brassica oleracea* Capitata group) grown in 2001 (full symbols) and 2002 (open symbols) at the Ohio Agricultural Research and Development Center. Treatment means of cultivars "Bravo," "Bronco," and "Transam," are represented by circles, squares, and triangles, respectively (from Radovich et al. 2004).

adaptation among plants within Families are generally conspicuous enough to be useful in olericulture. For example, ecological and physiological differences among Families are often adequate enough to be resistant to many of each other's specifi pathogens. A practical application of this by crop managers is to avoid successive planting of crops from the same Family when designing vegetable rotations in production.

Subordinate to the Family is Genus, followed by the species designation. Members of a species are usually genetically isolated from those of other species, and can freely interbreed with individuals from the same species. Biological differences tend to be minor below the species level, but infraspecifi variability in vegetable morphology and ecological adaptation is relevant enough to warrant further classification

Significan confusion and a lack of consistency in vegetable nomenclature at the subspecifi level centers around three terms: subspecies, *varietas*, and group. All are categories of vegetables sharing distinct features of functional relevance and have been used interchangeably. Subspecies and *varietas* are botanical terms, while group is used exclusively by horticulturalists. The differences between subspecies (ssp.) and *varietas* (also variety, var.) have been recognized as subtle but distinct, with the latter subordinate to the former (Kapadia 1963). However, by current convention, the terms are used interchangeably, with ssp. more frequently used in Europe and var. more common in the United States (Hamilton and Reichard 1992). Characteristics that distinguish ssp. and var. are expected to go beyond the morphological and have geographic, ecologic, or evolutionary integrity (Hamilton and Reichard 1992; Peralta and Spooner 2001). In contrast, horticultural groups may be define exclusively by functional similarities in morphology, as governed by the International Code of Nomenclature for Cultivated Plants (ICNCP or Cultivated Plant Code) (Brickell et al. 2004).

Botanical precedence has been cited for preferential use of "variety" over "group" in infraspecifi classificatio (Kays and Silva Dias 1996). However, botanical classifica tion is dynamic and botanical variety status may change. Also, while botanical varieties of cultivated plants by definitio qualify for status as horticultural groups, the reverse is not true. Consequently, variety is used for one species and group for another in some texts, and important authors differ in their use of variety and group for the same vegetables (Rubatzky and Yamaguchi 1997; Maynard and Hochmuth 2007). This inconsistent usage can easily lead to confusion. Therefore, this author proposes that "group" be used in lieu of "variety" (if not "subspecies") as a consistent, inclusive, and uniquely horticultural term to describe subspecifi categories of vegetables sharing distinct features of functional relevance. The vegetables of *Brassica oleracea*, including broccoli (Italica group), kohlrabi (Gongylodes group), Brussels sprouts (Gemmifera group), head cabbage (Capitata group), and collards (Acephala group) are well-known examples.

The cultivated variety (cultivar, cv.) is subordinate to the group classification and is used to distinguish plants with one or more definin characteristics. Although the term variety is sometimes used in lieu of cultivar, cultivar should not be confused with the botanical variety (*varietas*, var.) as described above. To qualify for cultivar status, distinguishing characteristics must be preserved when plants are reproduced.

Although not preferred, the term "strain" is sometimes used for vegetables derived from a well-known cultivar, but with minor differences in form. "Clone" is used to describe genetically uniform plants vegetatively propagated from a single individual. The term "line" generally refers to inbred, sexually propagated individuals.

Writing Nomenclature

As with other organisms, the Latin binomial of vegetables is written in italics, with the firs letter of the generic name capitalized and the specifi name in lowercase letters. Current convention is to use single quotation marks to indicate cultivar status, e.g., *Phaseolus vulgaris* 'Manoa Wonder', while use of *cv.* preceding the cultivar name is considered obsolete (Brickell et al. 2004). As a designation, the word "group" may either precede or follow the group name, and is listed in parentheses prior to the cultivar name, e.g., *Brassica oleracea* (Capitata group) "Bravo." The name of the person (authority) who firs described the taxon may also be included in the complete name. For example, *Cucurbita moschata* Duchesne indicates that the species was named by Duchesne, while *Cucurbita moschata* (Duchesne) Poir indicates

that credit for the naming is given to Duchesne in Poir (Paris 2000).

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Chapter 2

Biochemistry of Vegetables: Major Classes of Primary (Carbohydrates, Amino Acids, Fatty Acids, Vitamins, and Organic Acids) and Secondary Metabolites (Terpenoids, Phenolics, Alkaloids, and Sulfur-Containing Compounds) in Vegetables

N. Hounsome and B. Hounsome

Introduction

Historically, major plant constituents were divided as primary and secondary metabolites. Kössel (1891) define primary metabolites as present in every plant cell that is capable of reproduction, while secondary metabolites are present only "accidentally." Plant metabolites determine the food's nutritional quality, color, taste, and smell, and its antioxidative, anticarcinogenic, antihypertension, anti-inflammator , antimicrobial, immunostimulating, and cholesterol-lowering properties. Primary metabolites are found across all species within broad phylogenetic groups, and are produced using the same (or nearly the same) biochemical pathways. Primary metabolites, such as carbohydrates, amino acids, fatty acids, and organic acids, are involved in growth and development, respiration and photosynthesis, and the synthesis of hormones and proteins. A general scheme of major primary metabolic pathways in plants is shown in Figure 2.1.

Secondary metabolites include terpenoids, phenolics, alkaloids, and sulfur-containing compounds such as glucosinolates. They determine the color of vegetables, protect plants against herbivores and microorganisms, attract pollinators and seed-dispersing animals, and act as signal molecules under stress conditions (Seiger 1998; Crozier et al. 2006). Secondary metabolism is characterized by the high "degree of chemical freedom," which is thought to evolve under the selection pressure of a competitive environment (Hartmann 1996).

Primary and secondary metabolites cannot readily be distinguished on the basis of precursor molecules, chemical structures, or biosynthetic origins. For example, terpenoids include primary as well as secondary metabolites (e.g., phytol and gibberellins are primary metabolites, while limonene and menthol are secondary metabolites). A compound such as phylloquinone (vitamin K_1) is usually classifie as terpenoid quinone, rather than

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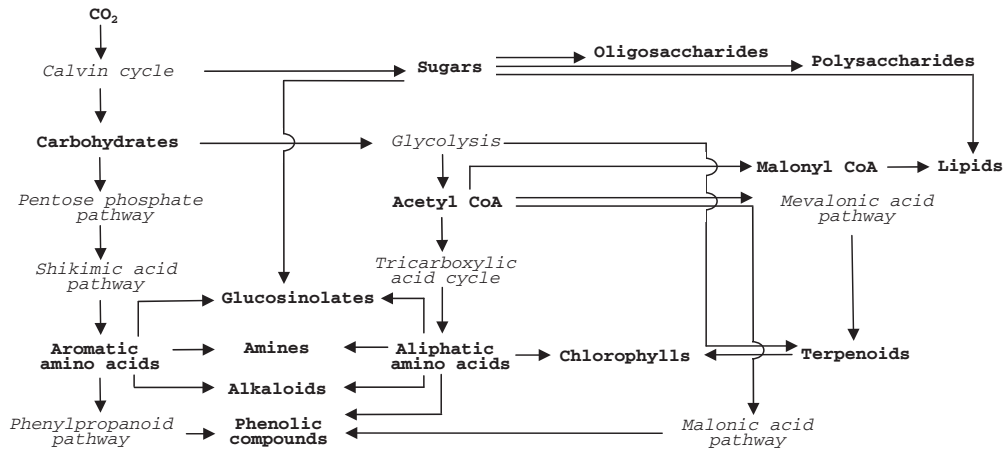

Figure 2.1 General scheme of primary metabolic pathways in plants.

phenolic, while other quinones, such as benzoquinones and anthraquinones, are regarded as phenolic compounds. Nonprotein amino acids (e.g., canavanine and citrulline) are sometimes discussed as primary metabolites since they act as intermediates in the synthesis of the protein amino acids (Morot-Gaudry et al. 2001). At the same time, they can be regarded as secondary metabolites due to their involvement in plant defense mechanisms (Rosenthal 2001; Besson-Bard et al. 2008).

In this chapter, we provide an overview of the major classes of plant metabolites found in vegetables, emphasizing their roles in human health and nutrition. The chapter also contains information about plant metabolites with reported antioxidant properties. The content of selected primary and secondary metabolites in vegetables is presented in Tables 2.1 and 2.2.

Primary Metabolites

Carbohydrates

Carbohydrates are a class of organic compounds originating from the Calvin Cycle and consisting of carbon, hydrogen, and oxygen $(CH_2O)_n$. In plants, carbohydrates occur as monosaccharides (e.g., arabinose, glucose, fructose, galactose, and rhamnose), disaccharides (e.g., sucrose, maltose, and trehalose), sugar alcohols (e.g., sorbitol, mannitol, and xylitol), oligosaccharides (e.g., raffinose stachyose, and fructooligosaccharides), and polysaccharides (e.g., starch, cellulose, hemicellulose, and pectins). The chemical structure of selected carbohydrates is shown in Figure 2.2.

Monosaccharides, sucrose, and polysaccharides are present in all vegetables. Raffinos and stachyose have been found in beetroot, broccoli, lentil, pea, onion, and soybean (Obendorf et al. 1998; Frias et al. 1999; Peterbauer et al. 2001; Muir et al. 2009). Fructooligosaccharides (e.g., kestose and nystose) are accumulated in artichoke, broccoli, garlic, leek, and onion (Shiomi 1992; Benkeblia and Shiomi 2006; Muir et al. 2007; Muir et al. 2009). Sorbitol was found in broccoli, cabbage, caulifl wer, kale, maize corn, and tomato; mannitol in broccoli, caulifl wer, celery, and fennel (Cataldi et al. 1998; Nilsson et al. 2006; Muir et al. 2009).

In terms of their physiological or nutritional role, carbohydrates are often classifie as available and unavailable. Available carbohydrates are those that are hydrolyzed by enzymes of the human gastrointestinal system to monosaccharides, such as sucrose and

Table 2.1 Content of selected primary metabolites in vegetables.

Compounds	Vegetables	Concentrations	References
Carbohydrates			
Glucose	Cabbage	1.4–2.06 g/100 g FW	Lee et al. (1970)
	Onion	1.76–2.34	
	Pumpkin	1.54–1.84	
	Tomato	0.88–1.25	
Fructose	Asparagus	1.2–1.4 g/100 g FW	Lee et al. (1970)
	Broccoli	0.52–0.87	
	Cabbage	1.14–1.74	
	Cucumber	0.82–0.97	
	Brussels sprout	0.6–0.9	
Sucrose	Red beet	5.58–6.64 g/100 g FW	Lee et al. (1970)
	Cabbage	0.02–0.5	
	Broccoli	0.36–0.5	
	Carrot	3.68–4.54	
	Sweet corn	2.62–4.0	
Raffinos	Broccoli	0.1–0.16 g/100 g FW	Lee et al. (1970)
	Cabbage	0.06–0.1	
	Caulifl wer	0.02–0.06	
Stachyose	Red beet	0.04 g/100 g FW	Lee et al. (1970)
	Broccoli	0.18–0.22	
	Cabbage	0.06	
	Leek	0.56	
	Onion	0.24–1.16	
Mannitol	Artichoke	184 mg/100 g DW (2)	Wang and van Eys (1981)
	Asparagus	170	
	Endive	334	
	Onion	47.5	
	Pumpkin	200	
Xylitol	Carrot	86.5 mg/100 g DW	Wang and van Eys (1981)
	Caulifl wer	300	
	Lettuce	131	
	Spinach	107	
Sorbitol	Red beet	77 mg/100 g DW	Wang and van Eys (1981)
Total dietary fibe	Cabbage	23.24 g/100 g DW	Anderson and Bridges (1988)
	Carrot	23.76	
	Lettuce	21.02	
	Potato	9.48	
	Tomato	13.13	
Nonstarch polysaccharides	Cabbage	22.41 g/100 g DW	Anderson and Bridges (1988)
	Carrot	22.75	
	Lettuce	19.0	
	Potato	8.58	
	Tomato	11.44	
Lignin	Cabbage	0.83 g/100 g DW	Anderson and Bridges (1988)
	Carrot	1.01	
	Lettuce	2.02	
	Potato	0.9	
	Tomato	1.69	
Amino acids and amines			
Arginine	Broccoli	242 mg/100 g FW	FAO (1981)
	Cbbage	135	
	Carrot	50	
	Cucumber	61	
	Pea	575	
	Spinach	139	

(*Continued*)

Table 2.1 (*Continued*)

Compounds	Vegetables	Concentrations	References
Histidine	Brussels sprout	108 mg/100 g FW	FAO (1981)
	Caulifl wer	54	
	Endive	31	
	Lettuce	21	
	Onion	14	
	Pea	140	
Isoleucine	Brussels sprout	230 mg/100 g FW	FAO (1981)
	Carrot	33	
	Lettuce	50	
	Pea	273	
	Spinach	106	
	Tomato	20	
Leucine	Broccoli	201 mg/100 g FW	FAO (1981)
	Cabbage	86	
	Onion	37	
	Pea	457	
	Spinach	208	
	Tomato	30	
Lysine	Brussels sprout	252 mg/100 g FW	FAO (1981)
	Caulifl wer	160	
	Cucumber	35	
	Carrot	44	
	Pea	479	
	Endive	50	
Methionine	Broccoli	44 mg/100 g FW	FAO (1981)
	Cucumber	8	
	Endive	22	
	Pea	61	
	Onion	16	
	Tomato	7	
Phenylalanine	Brussels sprout	172 mg/100 g FW	FAO (1981)
	Cabbage	49	
	Carrot	31	
	Cucumber	19	
	Endive	78	
	Pea	289	
Tryptophan	Brussels sprout	58 mg/100 g FW	FAO (1981)
	Caulifl wer	39	
	Cucumber	6	
	Onion	20	
Valine	Caulifl wer	156 mg/100 g FW	FAO (1981)
	Cabbage	68	
	Onion	30	
	Pea	311	
	Spinach	133	
	Tomato	24	
Tyramine	Spinach	0.8 mg/100 g FW	Moret et al. (2005)
	Potato	0.7	
	Savoy cabbage	0.3	
	Tomato	0.2	
Histamine	Spinach	2.0 mg/100 g FW	Moret et al. (2005)
	Broad bean	0.2	
	Bbroccoli	0.2	
	Tomato	0.7	

Table 2.1 (*Continued*)

Compounds	Vegetables	Concentrations	References
Putrescine	Lettuce	1.0 mg/100 g FW	Moret et al. (2005)
	Broad bean	6.5	
	Zucchini	4.0	
	Broccoli	1.4	
	Cucumber	2.4	
	Tomato	2.9	
Vitamin B complex			
Thiamine	Broccoli	0.15 mg/100 g FW	FAO (1981)
	Cucumber	0.04	
	Garlic	0.32	
	Leek	1.46	
	Spinach	0.16	
Ribofl vin	Brussels sprout	0.12 mg/100 g FW	FAO (1981)
	Lettuce	0.15	
	Onion	0.17	
	Spinach	0.19	
	Tomato	0.05	
Niacin	Broccoli	0.8 mg/100 g FW	FAO (1981)
	Cabbage	0.5	
	Endive	0.5	
	Leek	1.7	
	Pea	2.4	
	Sweet pepper	0.9	
Pantothenic acid	Broccoli	0.593 mg/100 g FW	USDA (2005)
	Cabbage	0.211	
	Endive	0.9	
	Sweet pepper	0.319	
	Spinach	0.07	
	Tomato	0.17	
Pyridoxine	Broccoli	0.175 mg/100 g FW	USDA (2005)
	Caulifl wer	0.222	
	Carrot	0.11	
	Cucumber	0.05	
	Spinach	0.2	
Folic acid	Broccoli	62.5 mg/100 g FW	USDA (2005)
	Celery	35.8	
	Endive	142	
	Spinach	190	
	Tomato	15	
Organic acids			
Ascorbic acid	Cabbage	58 mg/100 g FW	FAO (1981)
	Caulifl wer	79	
	Onion	30	
	Sweet pepper	146	
	Spinach	56	
	Tomato	20	
Oxalic acid	Broccoli	0.19 g/100 g FW	USDA (2005)
	Brussels sprout	0.36	
	Cabbage	0.10	
	Lettuce	0.33	
	Onion	0.05	
Aconitic acid	Maize corn	2.3 μmol/g FW	Nelson and Rinne (1977)
	Soybean	26.8	

(*Continued*)

Table 2.1 (*Continued*)

Compounds	Vegetables	Concentrations	References
Fatty acids			
Saturated	Broccoli	0.038 g/100 g FW	USDA (2005)
	Caulifl wer	0.032	
	Carrot	0.041	
	Endive	0.048	
	Sweet pepper	0.07	
	Tomato	0.046	
Monounsaturated	Broccoli	0.011 g/100 g FW	USDA (2005)
	Celery	0.03	
	Cucumber	0.003	
	Onion	0.023	
	Spinach	0.01	
Polyunsaturated	Broccoli	0.0375 g/100 g FW	USDA (2005)
	Carrot	0.117	
	Lettuce	0.08	
	Sweet pepper	0.156	
	Spinach	0.17	
	Tomato	0.135	

FW, fresh weight; DW, dry weight; FAO, Food and Agriculture Organization of the United Nations Database; USDA, United States Department of Agriculture National Nutrient Database.

digestible starch. Monosaccharides require no digestion and can be absorbed directly into the blood stream. Unavailable carbohydrates (sugar alcohols, many oligosaccharides, and nonstarch polysaccharides) are not hydrolyzed by endogenous human enzymes. They can be fermented by microorganisms in the large intestine to varying extents and then absorbed (Asp 1996). Fructooligosaccharides and nonstarch polysaccharides are important components of dietary fibe . Sugars are involved in the control of blood glucose and insulin metabolism, intestinal microflor activity, and food fermentation. Monosaccharides bound to protein and lipid molecules (glycoproteins and glycolipids) are involved in cell signaling. The nonenzymatic binding of sugars to proteins produces advanced glycation end products implicated in many age-related chronic diseases, such as type 2 diabetes, cardiovascular diseases, Alzheimer's disease, cancer, and peripheral neuropathy (Jenkins et al. 2002).

Plant components described as dietary fibe typically include nonstarch polysaccharides, resistant oligosaccharides, lignin, and associated substances such as resistant starch, waxes, cutin, and suberin (De Vries 2003). All these materials pass through the gastrointestinal tract as bulk fibe , undergoing modificatio and digestion by microorganisms in the colon (Blaut 2002). Substances produced by intestinal bacteria may be absorbed into the body. Some products, such as vitamin K, biotin, and fatty acids, may be beneficial Other substances, such as alcohols, lactate, and formate, as well as hydrogen gas produced by colon fermentation, may be undesirable. The consumption of high dietary fibe foods has been found to reduce symptoms of chronic constipation, diverticular disease, and some types of colitis (Stollman and Raskin 2004). It has been suggested that diets with low fibe may increase the risk of developing colon cancer, cardiovascular diseases, and obesity (Marlett 2001; McGarr et al. 2005; Slavin 2005). Some researchers believe that dietary fibe improves the ability of diabetics to process blood sugar (Willett et al. 2002). Increasing fibe consumption is a challenge as high-fibe

Table 2.2 Content of selected secondary metabolites in vegetables

	Compounds	Vegetables	Concentrations	References
Carotenoids				
	α-Carotene	Broccoli	1 mg/100 g FW	USDA (2005)
		Carrot	4.6	
		Pea	19	
		Sweet pepper	59	
		Tomato	112	
	β-Carotene	Broccoli	779 mg/100 g FW	
		Brussels sprout	450	
		Carrot	8.8	
		Pea	485	
		Tomato	393	
	β-Cryptoxanthin	Sweet pepper	2.205 mg/100 g FW	
	Zeaxanthin	Carrot	23 mg/100 g FW	
		Celery	3	
		Kale	173	
		Lettuce	187	
		Spinach	331	
	Lycopene	Tomato	3.025 mg/100 g FW	
Quinones				
	Phylloquinone	Broccoli	102 μg/100 g FW	Damon et al. (2005)
		Carrot	8.3	
		Celery	29	
		Cucumber	16.4	
		Lettuce	24.1–127	
		Onion	0.2	
		Sweet pepper	4.9–21.4	
Tocopherols and tocotrienols				
	α-Tocopherol	Broccoli	1.44 mg/100 g FW	Chun et al. (2006)
		Cabbage	0.21	
		Carrot	0.86	
		Celery	0.26	
		Onion	0.04	
		Spinach	1.96	
		Tomato	0.53	
	β-Tocopherol	Carrot	0.01 mg/100 g FW	
		Cucumber	0.01	
		Lettuce	0.01	
	β-Tocopherol	Broccoli	0.31 mg/100 g FW	
		Caulifl wer	0.20	
		Lettuce	0.11–0.74	
		Spinach	0.21	
		Tomato	0.14	
	α-T3	Cabbage	0.04 mg/100 g FW	
		Caulifl wer	0.06	
		Onion	0.12	
	γ-T3	Corn	0.21 mg/100 g FW	
		Pea	0.05	

(*Continued*)

Table 2.2 (*Continued*)

	Compounds	Vegetables	Concentrations	References
Sterols				
	Campesterol	Broccoli	6.9 mg/100 g FW	Normén et al. (1999)
		Brussels sprout	8.0	
		Carrot	2.2	
		Cauliflower	9.5	
		Onion	0.82	
		Tomato	0.28	
	Campestanol	Broccoli	0.10 mg/100 g FW	
		Kale	0.07	
		Leek	0.09	
		Tomato	0.05	
	Stigmasterol	Broccoli	1.1 mg/100 g FW	
		Brussels sprout	0.38	
		Carrot	2.8	
		Cauliflower	3.7	
		Celery	7.0	
		Tomato	1.7	
	β-Sitosterol	Broccoli	31 mg/100 g FW	
		Brussels sprout	34	
		Cauliflower	26	
		Celery	7.3	
		Kale	7.4	
		Tomato	2.4	
	β-Sitostanol	Broccoli	0.08 mg/100 g FW	
		Carrot	0.08	
		Cauliflower	0.06	
		Celery	0.13	
		Tomato	0.23	
Flavonoids				
	Quercetin	Broccoli	3.12 mg/100 g FW	USDA (2005)
		Cabbage	0.01	
		Endive	7.71	
		Lettuce	1.95	
		Onion	13.27	
		Tomato	0.57	
	Apigenin	Cabbage	0.01 mg/100 g FW	USDA (2005)
		Celery	4.61	
		Lettuce	0.01	
	Luteolin	Cauliflower	0.08 mg/100 g FW	USDA (2005)
		Celery	1.31	
		Spinach	1.11	
		Sweet pepper	0.63	
	Myricetin	Lettuce	0.02 mg/100 g FW	USDA (2005)
		Spinach	0.01	
	Cyanidin	Green lettuce	0.3 mg/100 g FW	Harnly et al. (2006)
		Red lettuce	13.7	
Lignans				
	Lariciresinol	Broccoli	972 mg/100 g FW	
		Cauliflower	124	
		Kale	599	
		Lettuce	5	
		Onion	19	
		Sweet pepper	164	

Table 2.2 (*Continued*)

	Compounds	Vegetables	Concentrations	References
	Pinoresinol	Broccoli Cabbage Kale Endive Leek Sweet pepper	315 mg/100 g FW 568 1,691 9 3 1	Milder et al. (2005)
	Secoisolariciresinol	Broccoli Brussels sprout Leek Carrot Lettuce Tomato	38 mg/100 g FW 34 38 93 8 2	
	Matairesinol	Kale	12 mg/100 g FW	
Phenolic acids				
	Chlorogenic acid	Bean Ccarrot Caulifl wer Lettuce Soya bean Tomato	0.29 mg/100 g FW 10 0.14 0.42–23 2.0 0.86	Mattila and Hellström (2007)
	Caffeic acid	Carrot	0.1 mg/100 g FW	
	Ferulic acid	Turnip	0.42 mg/100 g FW	
	p-Coumaric acid	Cabbage Caulifl wer	0.21 mg/100 g FW 0.31	
	Vanillic acid	Soya bean	0.5 mg/100 g FW	
	Sinapic acid	Caulifl wer Turnip	0.15 mg/100 g FW 1.4	
	Protocatechuic acid	Bean Carrot	0.26 mg/100 g FW 0.46	
Tannins				
	Proanthocyanidin monomers	Avocado Kidney bean Lentil Pea Squash	0.96 mg/100 g FW 16.25 0.53 0.02 1.63	USDA (2005)
	Proanthocyanidin dimers	Avocado Kidney bean Lentil Squash	1.46 mg/100 g FW 22.90 1.20 1.98	
	Proanthocyanidin trimers	Avocado Kidney bean Lentil Squash	1.36 mg/100 g FW 23.60 0.11 1.49	
	Proanthocyanidin polymers	Kidney bean Squash	258 mg/100 g FW 3.50	
Alkaloids				
	α-Tomatine	Tomato	521–795 μg/g FW	Kozukue et al. (2004)
	Dehydrotomatine	Tomato	41.6–68.0 μg/g FW	
	α-Solanine	Potato	0.01–0.43 mg/kg FW	Şengül et al. (2004)
	α-Chaconine	Potato	0.7–1.93 mg/kg FW	
	Lactucin	Chicory	178–245 mg/kg FW	Peters et al. (1997)
	Lactucopicrin	Chicory	112–143 mg/kg FW	

(*Continued*)

Table 2.2 (*Continued*)

Compounds	Vegetables	Concentrations	References
Glucosinolates			
Glucoiberin	Broccoli	17.1 μmol/100 g FW	Song and Thornalley (2007)
	Brussels sprout	1.5	
	Caulifl wer	1.34	
	Green cabbage	3.88	
Glucoraphanin	Broccoli	29.4 μmol/100 g FW	
	Brussels sprout	0.55	
	Caulifl wer	0.31	
	Green cabbage	0.35	
Glucoalyssin	Broccoli	3.86 μmol/100 g FW	
	Brussels sprout	0.33	
Sinigrin	Broccoli	1.40 μmol/100 g FW	
	Brussels sprout	8.56	
	Caulifl wer	5.28	
	Green cabbage	5.09	
Gluconapin	Broccoli	2.87 μmol/100 g FW	
	Brussels sprout	2.77	
	Caulifl wer	3.36	
	Green cabbage	0.38	
Progoitrin	Broccoli	3.33 μmol/100 g FW	
	Brussels sprout	2.41	
	Caulifl wer	0.45	
	Green cabbage	0.62	
Gluconasturtiin	Broccoli	4.44 μmol/100 g FW	
	Brussels sprout	1.06	
	Caulifl wer	2.79	

FW, fresh weight; USDA, United States Department of Agriculture National Nutrient Database.

containing vegetables do not always have appealing tastes (Tungland and Meyer 2002).

Amino Acids

Amino acids represent a class of organic compounds containing a basic amino (NH_2) group, an acidic carboxyl (COOH) group, and a side chain attached to an alpha carbon atom (Figure 2.2). In plants, amino acids are produced via the glycolysis pathway, the pentose phosphate pathway, and the citric acid cycle. Amino acids play a role as intermediates in plant and animal metabolism, and join together to form proteins. Proteins provide structural material for the human body and function as enzymes, hormones, and antibodies. Dietary proteins are the major source of amino acids. Most proteins are broken down by enzymes into amino acids and absorbed from the small intestine. Humans can synthesize a range of amino acids, including alanine, asparagine, aspartic acid, cysteine, cystine, glutamic acid, glutamine, glycine, proline, serine, and tyrosine. Nine amino acids, called essential, must come from the diet, including arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, tryptophan, and valine. The amino acids arginine, methionine, and phenylalanine are considered essential for reasons not directly related to lack of metabolic pathway, but because the rate of their synthesis is insufficien to meet the needs of the body (Spallholz et al. 1999). Histidine is considered an essential amino acid in children. Vegetables contain all essential amino acids, but some may be in lower proportions than are required for humans (Young and Pellett 1994). High levels of arginine have been found in asparagus, Brussels

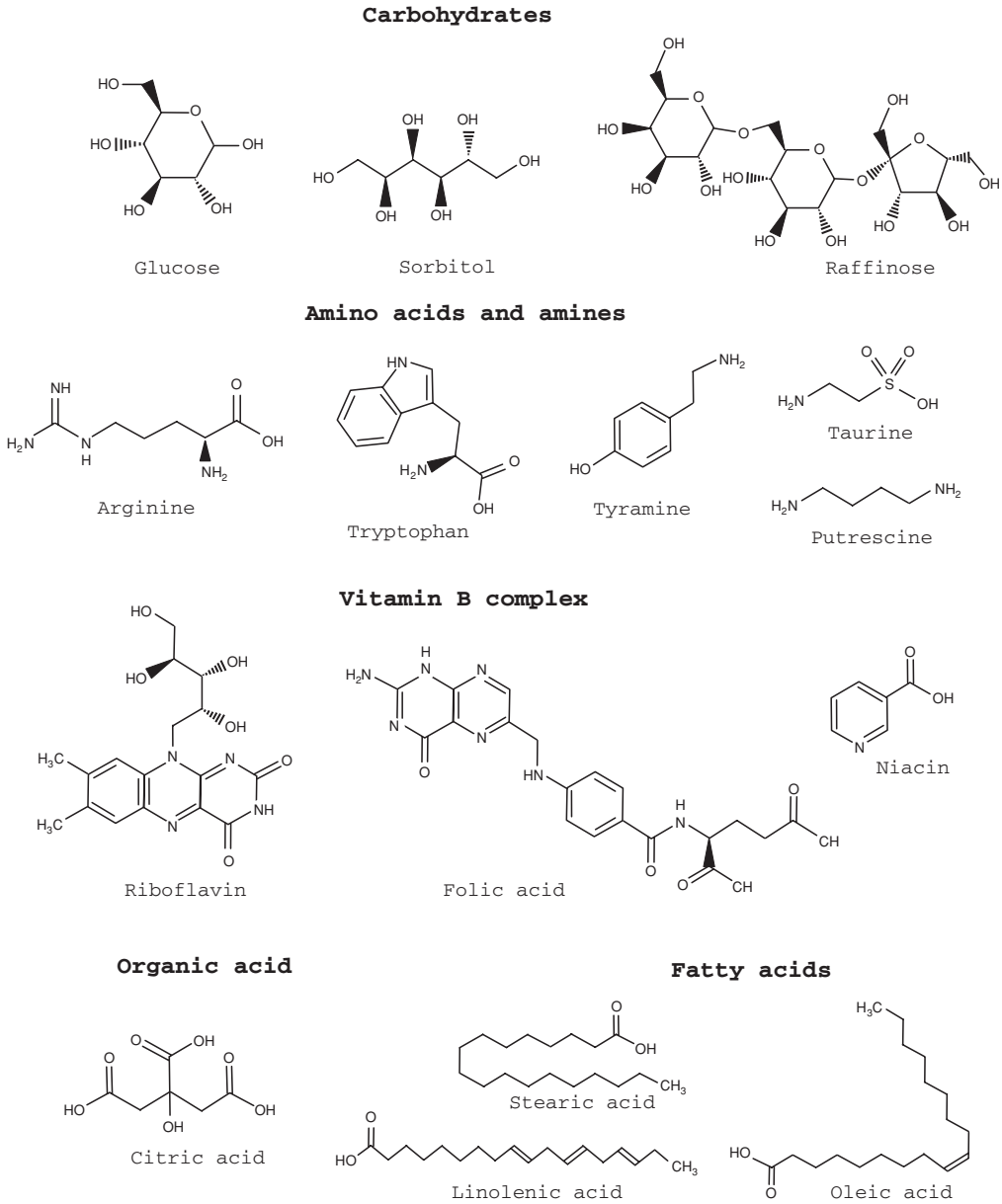

Figure 2.2 Chemical structure of selected primary metabolites.

sprout, potato, and watercress; histidine in broccoli, Brussels sprout, and caulifl wer; phenylalanine in beet, carrot, parsley, spinach, and tomato; methionine in cabbage, caulifl wer, kale, radish, and watercress (FAO 1981). Over 250 nonprotein amino acids (e.g., homoarginine, carnitine, citrulline, taurine, α-aminobutyric acid, and γ-aminobutyric acid) have been identifie in plants. γ-Aminobutyric acid (GABA), present in bean, kale, potato, and spinach (Oh et al. 2003), is an inhibitory neurotransmitter in the

human central nervous system and in the retina. Carnitine, found in pea, potato, and zucchini, is involved in lipid metabolism in heart and skeletal muscles (Demarquoy and others 2004). Taurine, identifie in lentil, maize, and peanuts, is involved in detoxifi cation and membrane stabilization in human cells (Stapleton et al. 1997). Some nonprotein amino acids (e.g., β-cyanoalanine and canavanine found in bean) are reported to be toxic for humans due to inhibition of protein synthesis and immune system (Bell 2003). Besides their importance to the human metabolism, free amino acids contribute to the taste of vegetables. Glycine and alanine are sweet, valine and leucine are bitter, aspartic acid and glutamate have sour and savory tastes (Solms 1969).

Amines and polyamines are synthesized in plants by decarboxylation of amino acids. Amines, such as tyramine, have been found in broad bean, carrot, lettuce, spinach, onion, pepper, potato, and Savoy cabbage; tryptamine in broccoli and carrot; histamine in broad bean, broccoli, spinach, and tomato; 2-phenylethylamine in broccoli, parsley, pepper, onion, and zucchini (Moret et al. 2005). Polyamines putrescine, spermidine, and spermine are ubiquitous in plants, since they play an important role in stress response (Groppa and Benavides 2008). High levels of putrescine were reported in broad bean, broccoli, cucumber, tomato, and zucchini; spermidine in broccoli, caulifl wer, parsley, and spinach; spermine in cabbage, caulifl wer, and potato (Moret et al. 2005). Spoilage of vegetables is usually associated with the accumulation of histamine, tyramine, agmatine, putrescine, cadaverine, spermine, and spermidine, which can be used as indicators of the degree of freshness or spoilage of food (Halász et al. 1994). In humans, amines are essential for maintaining the metabolic activity of cells and the control of blood pressure and allergic responses (Santos 1996; Kalač and Krausová 2005). Polyamines have been shown to protect cells from oxidative damage and reduce lipid peroxidation and inflammatio (Løvaas 1997; Farriol et al. 2003). It has been reported that nitrosable secondary amines (agmatine, spermine, and spermidine) can react with nitrite, forming carcinogenic compounds (e.g., nitrosamines, nitrosopyrrolidines, and nitrosopiperidines). High nitrosamine intake has been linked to gastric cancer (Jakszyn and Gonzalez 2006).

Fatty Acids

Fatty acids are predominantly straight-chain organic molecules, consisting of a hydrophilic carboxylic group attached to a hydrophobic hydrocarbon chain (Figure 2.2). In plants, fatty acids are synthesized from acetyl-COA, which is produced from pyruvate by the glycolysis cycle. Fatty acids are major components of fats, oils, and waxes. They provide the human body with energy and structural material for cell membranes and organ padding. Fatty acids are involved in the absorption of vitamins A and D, blood clotting, and the immune response. Some of them are chemical precursors of prostaglandins and leukotrienes (Nettleton 1995; Yaqoob 2004; Chow 2007). Fatty acid classificatio is based on the number of double bonds. Saturated fatty acids (such as capric, myristic, palmitic, stearic acids) do not contain double bonds. Unsaturated acids with one double bond are called monounsaturated (oleic, palmitoleic); those with two or more double bonds are known as polyunsaturated (docosahexaenoic acid, eicosapentaenoic acid, α-linolenic acid, arachidonic acid) (Gurr et al. 2002). Two unsaturated fatty acids that cannot be made in the body (linoleic acid and α-linolenic acid) must be provided by diet, and are known as essential fatty acids (Innis 1991). α-Linolenic acid can be found in soybean and in most vegetable oils including corn, sunfl wer, and saffl wer oil (Connor 1999). Linolenic acid is present in soybean, wheat germ, and pumpkin seeds (Jakab et al. 2002). Green vegetables, such as Brussels sprout, Chinese cabbage,

parsley, and watercress, are known to contain a relatively high proportion of polyunsaturated fatty acids, primarily in the form of α-linolenic acid (Pereira et al. 2001). The consumption of monounsaturated and polyunsaturated fatty acids has been shown to regulate plasma cholesterol levels (Fernandez and West 2005) and reduce risk factors associated with cardiovascular disease, cancer, and type 2 diabetes (Kris-Etherton et al. 2003; Larsson et al. 2004; Nettleton and Katz 2005).

Vitamin B Complex

The vitamin B complex of vegetables includes the following water-soluble vitamins: B_1 (thiamine and its phosphates); B_2 (riboflavin and riboflavin 5-phosphate); B_3 (nicotinic acid and nicotinamide); B_5 (pantothenic acid); B_6 (pyridoxal, pyridoxamine, pyridoxine, and their 5′-phosphates); B_7 (biotin); and B_9 (folic acid) (Bender 2003). The chemical structure of some B vitamins is shown in Figure 2.2. In plants, these compounds are vital cofactors for enzymes involved in photosynthesis (riboflavin), respiration (thiamine, riboflavin, biotin), synthesis of organic and amino acids (thiamine, folic acid), and regulation of cell division and flowering (niacin). Vitamin B compounds are produced by different metabolic pathways, including the pentose phosphate pathway, glycolysis, and amino acid metabolism (Heldt 2005; Roje 2007). In humans, B vitamins are involved in tissue respiration and carbohydrate, fatty acid, and amino acid metabolism. Deficiency of vitamin B_1 can cause polyneuritis; deficiency of vitamin B_2 can lead to cheilosis, angular stomatitis, and dermatitis; deficiency of vitamin B_3 can result in pellagra, diarrhoea, dermatitis, and dementia; that of vitamin B_6 can cause seborrhoea, glossitis, peripheral neuropathy, and microcytic anaemia; deficiency of vitamin B_7 can lead to nausea and dermatitis; and that of vitamin B_9 can result in anaemia (Combs 1998). Green leafy vegetables, such as asparagus, Brussels sprout, cauliflower, lettuce, spinach, and turnip, are good sources of B vitamins (USDA 2005). Vitamins B_1, B_2, and B_3 have been found in cabbage, carrot, cauliflower, lettuce, potato, spinach, and tomato (Hanif et al. 2006); vitamin B_5 in avocado, carrot, French bean, lentil, pea, and spinach (Pakin et al. 2004); vitamin B_6 in broccoli, Brussels sprout, cabbage, leek, onion, and potato (Kall 2003); vitamin B_7 in bean, broccoli, carrot, cauliflower, spinach, and potato (Staggs et al. 2004); and vitamin B_9 in asparagus, broccoli, leek, and potato (Phillips et al. 2008).

Organic Acids and Vitamin C

Organic acids are a group of organic compounds containing carboxylic groups. In solution, organic acids release protons, which determine their acidic taste. Plants contain acetic, aconitic, ascorbic, citric, fumaric, malic, malonic, oxalic, quinic, shikimic, succinic, tartaric, and other organic acids (Heldt 2005). Malic and citric acids are predominant in plants, while succinic, fumaric, and quinic acids are usually present in lower concentrations. Tartaric acid was found in carrot, celery, chicory, endive, and lettuce (Ruhl and Herrmann 1985); oxalic acid in broccoli, Brussels sprout, cabbage, lettuce, and onion (USDA 2005). Organic acids have important functions as flavor enhancers and natural antimicrobial agents. Organic acids give the vegetables tartness and affect flavor by acting on the perception of sweetness (Kader 2008). The sugar/acid ratio is often used to characterize vegetable ripeness (Sims and Golaszewski 2002). For example, the value of about 7.5 is usually accepted as a beneficial sugar/acid ratio in tomato, although values in the range 3.3–21.7 have been reported (Kmiecik and Lisiewska 2000). Organic acids influence the color of vegetables since many plant pigments are natural pH indicators (Davies 2004). For example, some anthocyanins, found in red cabbages and lettuce, change color from red to blue as pH increases.

Ascorbic and dehydroascorbic acids, known as vitamin C, are organic acids with antioxidant properties. Ascorbic acid is the major form of vitamin C in vegetables, while dehydroascorbic acid represents less than 10% of total vitamin C content (Wills et al. 1984). Vegetables rich in ascorbic acid include bean, broccoli, cabbage, caulifl wer, cress, pea, spinach, spring onion, and sweet peppers (USDA 2005). Vitamin C is involved in the synthesis of neurotransmitters, steroid hormones, and collagen; in the conversion of cholesterol to bile acids; and in the absorption of iron and calcium. It assists in the healing of wounds and burns, in preventing blood clotting and bruising, and in strengthening the walls of the capillaries (Combs 1998). Because vitamin C is a biological antioxidant, it is also linked to the prevention of cataract, certain cancers, and cardiovascular disorders (Carr and Frei 1999). The content of ascorbic acid in vegetables is strongly affected by growth conditions, application of nitrogen fertilizers, as well as by storage conditions and processing (Mozafar 1993; Rickman et al. 2007; Miglio et al. 2008).

Secondary Metabolites

Terpenoids, including Carotenoids

Plant terpenoids include around 25,000 metabolites (Goldberg 2003) derived by repetitive fusion of branched fi e-carbon isoprene units. Terpenoids can be classifie with respect to the number of isoprene units present in the molecule as hemiterpenes (C_5), monoterpenes (C_{10}), sesquiterpenes (C_{15}), diterpenes (C_{20}), sesterterpenes (C_{25}), triterpenes (C_{30}), tetraterpenes (C_{40}), steroids, polyprenols, and polyterpenes. In plants, terpenoids are represented by volatile oils (monoterpenes), gibberellins (diterpenes), limonoids (triterpenes), carotenoids (tetraterpenes), sterols, sapogenins and steroid hormones (steroids), phytol (polyprenols), rubber, gutta, and chicle (polyterpenes) (Goodwin and Mercer 1983; Gershenzon and Kreis 1999). Examples of terpenoids found in vegetables are shown in Figure 2.3.

Terpenoids are synthesized by the polymerization of isopentenyl pyrophosphate (IPP) and its isomer dimethylallyl diphosphate (DMAPP). In plant cells, IPP (DMAPP) are produced via two different pathways, located in separate intracellular compartments. The methylerythritolphosphate pathway takes place in the chloroplasts and forms IPP (DMAPP) for mono- and diterpenoids. The mevalonic acid pathway, found in the cytosol, produces IPP (DMAPP) for sesquiterpenoids. In the second phase of terpene biosynthesis, IPP and DMAPP undergo head-to-tail condensation to produce C_{10}-compound geranyl diphosphate (GDP), C_{15}-compound farnesyl diphosphate (FDP), and C_{20}-compound geranylgeranyl diphosphate (GGDP). In the third phase, GDP, FDP, and GGDP are used to form monoterpenes, sesquiterpenes, and diterpenes, respectively. GGDP generally undergoes further multiple chain extensions to form polyprenylphosphates, which give rise to polyprenols and polyterpenes. Biosynthesis of terpenoids takes place in chloroplasts, mitochondria, and endoplasmic reticulum. For example, carotenoids, phylloquinone, and chlorophylls are synthesized in chloroplasts; ubiquinone in the mitochondria; and sterols in the endoplasmic reticulum. Terpenoids have diverse functional roles in plants as structural components of membranes (sterols), photosynthetic pigments (phytol, carotenoids), electron carriers (ubiquinone, plastoquinone), and hormones (gibberelins, abscisic acid) (Goodwin and Mercer 1983; Seiger 1998; Gershenzon and Kreis 1999). Major groups of terpenoids found in vegetables include carotenoids, tocopherols and tocotrienols, quinones, sterols, sapogenins, and volatile oils.

Carotenoids, such as α-carotene, β-carotene, lycopene, and xanthophylls (e.g., lutein, neoxanthin, violaxanthin, and zeaxanthin) are orange, yellow, and red lipid-soluble

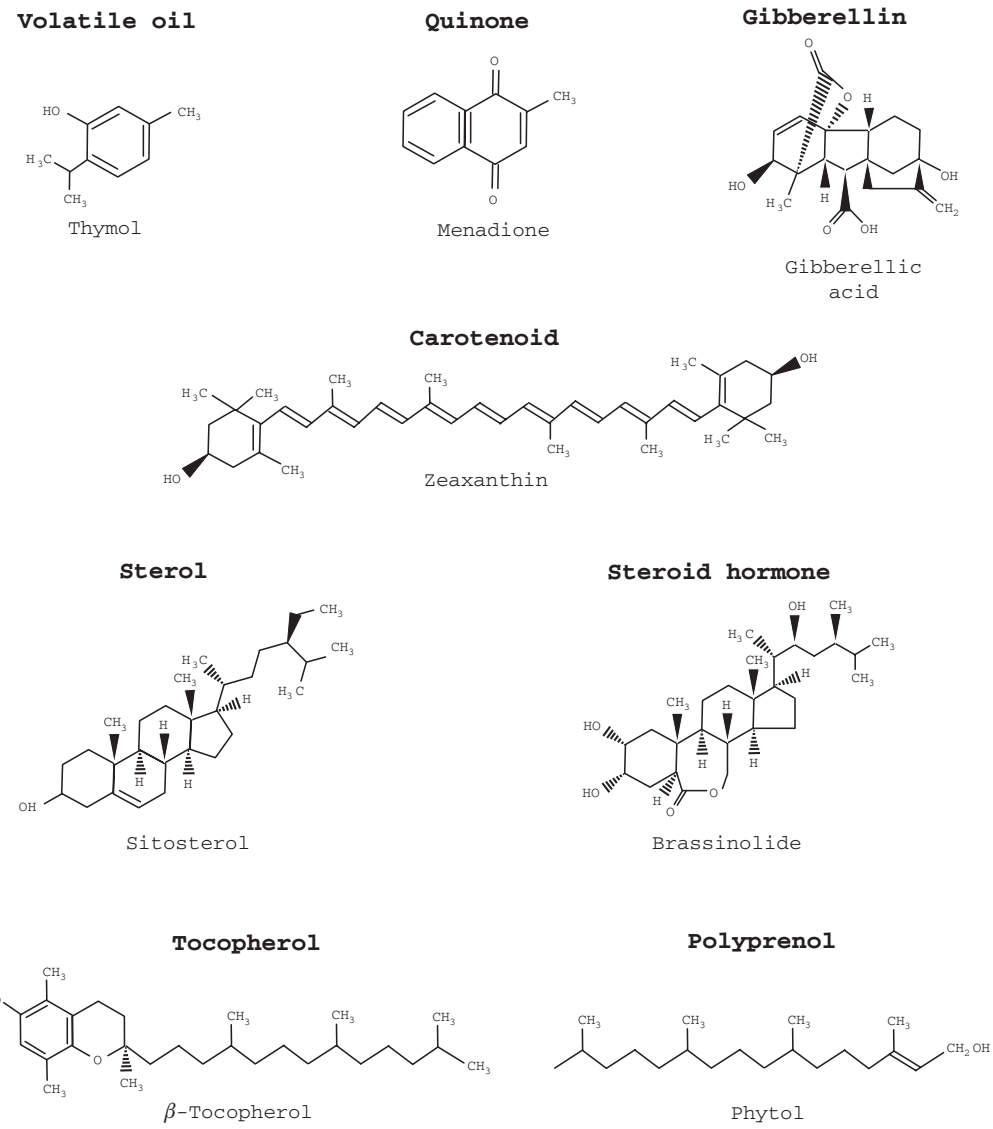

Figure 2.3 Chemical structure of selected terpenoids.

pigments. They are found in all green leafy vegetables such as celery, endive, lettuce, rocket, and watercress (where their color is masked by chlorophyll), as well as in carrot, pumpkin, tomato, and sweet potato (Granado et al. 1992; Crozier et al. 2006; Aizawa and Inakuma 2007). In plants carotenoids protect photosynthetic tissues against photooxidative damage and are precursors of phytohormone abscisic acid, which modulates developmental and stress processes (Demmig-Adams and Adams 1996; Taylor et al. 2000). Carotenoids with pro-vitamin A activity are essential components of the human diet. Vitamin A is involved in hormone synthesis, regulation of cell growth and differentiation, and immune responses (Combs 1998; Bender 2003). It can be produced within the body from

certain carotenoids, notably β-carotene (present in carrot, spinach, and sweet potato) and α-carotene (found in carrot, pumpkins, and red and yellow peppers) (Bureau and Bushway 1986). Lack of carotenoids in the human diet can lead to xerophthalmia (night blindness) and fetal death. Carotenoid-rich diets are correlated with a significan reduction in the risk for certain forms of cancer, coronary heart disease, and some degenerative diseases, such as cataract (Johnson 2002a). Carotenoids act as biological antioxidants, protecting cells and tissues from oxidative damage (Edge et al. 1997).

Tocopherols and *tocotrienols* such as α-tocopherol, β-tocopherol, α-T3, and β-T3 are known as vitamin E. These compounds are found in asparagus, broccoli, Brussels sprout, cabbage, carrot, caulifl wer, kale, lettuce, spinach, sweet potato, tomato, and turnip (Piironen et al. 1986; Eitenmiller and Lee 2004; Chun et al. 2006). In plants, tocopherols protect chloroplast membranes from photooxidation to provide an optimal environment for the photosynthetic machinery (Munné-Bosch and Alegre 2002). In humans, vitamin E is present in all cell membranes and plasma lipoproteins (especially in red blood cells). As the major lipid-soluble chain-breaking antioxidants in humans, tocopherols and tocotrienols protect DNA, low-density lipoproteins, and polyunsaturated fatty acids from free radical-induced oxidation. They also play a role in stabilizing the structure of membranes, haemoglobin biosynthesis, and modulation of immune response (Brigelius-Flohe and Traber 1999).

Quinones possess aromatic rings with two ketone substitutions. Phylloquinone, known as vitamin K_1, is found in asparagus, broccoli, cabbage, caulifl wer, cucumber, celery, kale, lettuce, and spinach (Bolton-Smith et al. 2000; Damon et al. 2005). In plants, phylloquinone is involved in electron transport during photosynthesis and in the generation of the active oxygen species observed as a reaction to pathogen attack or stress (Lochner et al. 2003). In humans vitamin K_1 plays a role in the control of blood clotting, bone formation, and repair. A deficien y of this vitamin results in hemorrhagic disease in newborn babies as well as postoperative bleeding, hematuria, muscle hematomas, and intercranial hemorrhages in adults (Combs 1998; Bender 2003). Menadione, known as vitamin K_3, has been shown to possess cytotoxic activity and inhibit growth of tumors (Taper et al. 2004). Quinones are highly reactive and are responsible for the browning reaction in cut or injured vegetables (Cowan 1999).

Plant sterols, such as sitosterol, sitostanol, campesterol, brassicasterol, and stigmasterol, are found in broccoli, Brussels sprout, carrot, caulifl wer, celery, tomato, soy, and spinach (Normén et al. 1999; Piironen et al. 2003). In plant membranes, sterols regulate the flu idity and the permeability of phospholipid bilayers (Hartmann 1998). Sterols are precursors of plant hormones brassinosteroids, involved in embryonic development, cell division, plant growth, and fertility (Clouse and Sasse 1998). Upon UV irradiation of human skin, these sterols give rise to calciferol (vitamin D_2), which is involved in the absorption of calcium and bone growth. Sterols are essential for the synthesis of prostaglandins and leukotrienes, important components of the immune system. Due to their structural similarity to cholesterol, plant sterols inhibit cholesterol absorption. In addition to their cholesterol-lowering effect, plant sterols may possess anticancer, antiatherosclerosis, anti-inflammation and antioxidant properties (Awad and Fink 2000; Ostlund 2002; Dutta 2003).

Volatile oils include monoterpenes (e.g., linalool, thymol, and fenchol) and sesquiterpenes (e.g., farnesol and carotol). Volatile oils determine the odor of vegetables, since they vaporize at room temperature. Terpenes geraniol and farnesol have been found in tomato, fenchol in fennel, linalool in celery, thymol in thyme, and carotol in carrot (Enfiss et al. 2005; Sowbhagya et al.

2007; Bakkali et al. 2008). Volatile oils possess cytotoxic, antiproliferation, and antimutagenic activities. They inhibit the growth of tumor cells by interacting with the mitochondrial function and inducing oxidative stress (Bakkali et al. 2008). Volatile oils have a pronounced antimicrobial action against food-borne pathogens and spoilage bacteria (Gutierrez et al. 2009), and act as insecticides against mosquitoes and pest insects (Tapondjou et al. 2005; Silva et al. 2008). Although most volatile oils have been found cytotoxic without being mutagenic, some of them (e.g., safrole and estragole) may have secondary carcinogenic effects in animals (Bakkali et al. 2008).

Phenolics

Plant phenolic compounds include around 8,000 metabolites (Goldberg 2003), which contain one or more phenolic residues. Phenolics can be classifie by the number of carbon atoms in their skeleton as phenols (C_6), phenolic acids (C_6–C_1), phenylacetic acids (C_6–C_2), hydrohycinnamic acids, coumarins and chromones (C_6–C_3), naphthoquinones (C_6–C_4), xanthones (C_6–C_1–C_6), stilbenes and anthraquinones (C_6–C_2–C_6), fl vonoids (C_6–C_3–C_6), lignans and neolignans ($[C_6$–$C_3]_2$), bifl vonoids ($[C_6$–C_3–$C_6]_2$), lignins ($[C_6$–$C_3]_n$), melanins ($[C_6]_n$), and condensed tannins ($[C_6$–C_3–$C_6]_n$) (Goodwin and Mercer 1983). Plant phenolics are synthesized through two major pathways: the shikimic acid pathway and the malonic acid pathway. The shikimic acid pathway is involved in the biosynthesis of most plant phenolics, while the malonic acid pathway (typical for fungi and bacteria) is of less significanc in higher plants. The shikimic acid pathway converts intermediates from glycolysis (phosphoenolpyruvate and erythrose 4-phosphate) to chorismate, the precursor of aromatic amino acids and many phenolic compounds (Herrmann and Weaver 1999). The general scheme of phenolic biosynthesis via the shikimate pathway is shown in Figure 2.4.

The major groups of phenolic compounds found in vegetables include phenolic, hydroxycinnamic, and phenylacetic acids; coumarins; fl vonoids; lignans; lignins; and tannins. Hydroxycinnamic and phenylacetic acids are often referred to as phenolic acids.

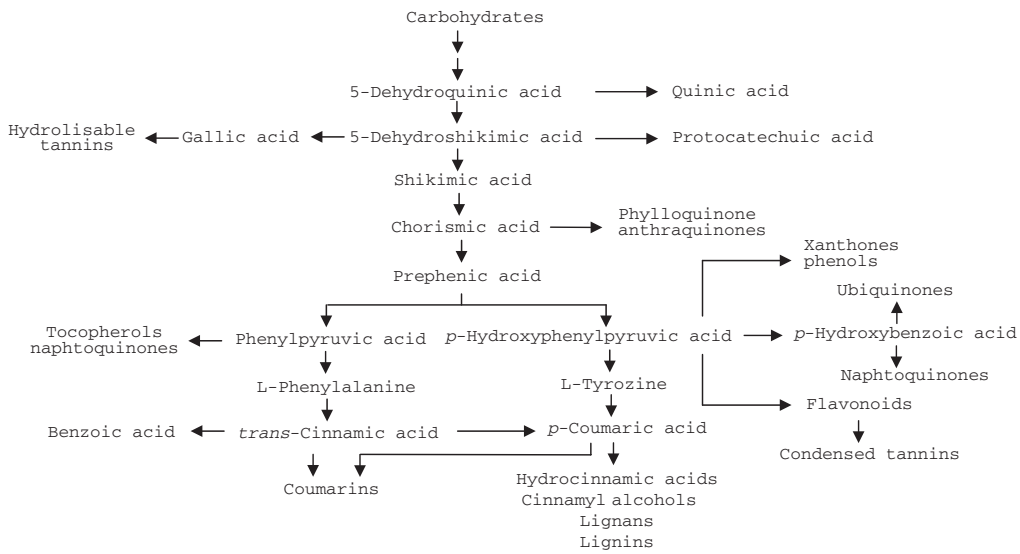

Figure 2.4 General scheme of synthesis of plant phenolic compounds via the shikimic acid pathway.

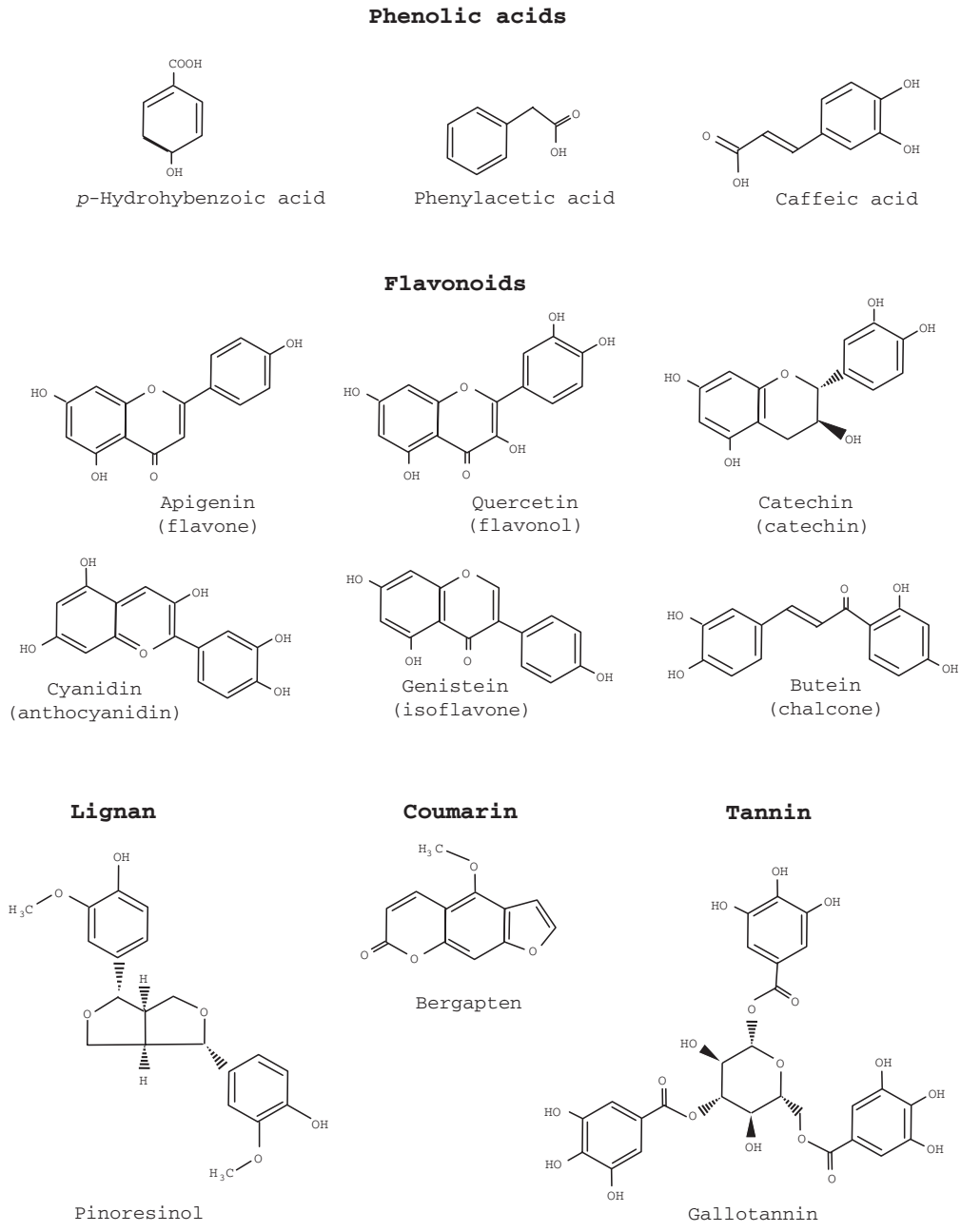

Figure 2.5 Chemical structure of selected phenolic compounds.

Flavonoids, coumarins, lignans, lignins, and hydroxycinnamic acids are also classifie as phenylpropanoids, since they originate from phenylalanine. The chemical structure of representative phenolic compounds is shown in Figure 2.5.

Phenolic compounds are feeding deterrents for many insects and other plant-eating

animals. High concentrations of phenolic compounds are often associated with increased resistance to fungal pathogens (Nicholson and Hammerschmidt 1992). Some phenolics determine the color and smell of plants, attracting pollinators. Phenolics are involved in cold acclimation and protection against UV radiation. In plant cells most phenolic compounds are coupled to sugars to reduce their endogenous toxicity. External stimuli such as microbial infection, ultraviolet radiation, temperature, and chemical stressors induce their synthesis (Parr and Bolwell 2000).

Phenolic acids are chemical compounds with at least one aromatic ring bearing one or more hydroxyl groups. These compounds include phenolic acids (e.g., hydroxybenzoic, gallic, and vanillic), hydroxycinnamic acids (e.g., ferulic, coumaric, and caffeic), and phenylacetic acids (e.g., phenylacetic and hydroxyphenylacetic). Chlorogenic acid has been found in bean, carrot, caulifl wer, and lettuce; coumaric in cabbage and caulifl wer; protocatechuic in bean and carrot; and sinapic in caulifl wer and turnip (Mattila and Hellström 2007). In plants, these compounds fulfil antipathogen, antiherbivore, and allelopathic roles (Nicholson and Hammerschmidt 1992; Chou 1999). Salycilic acid plays an important role in cell signaling under stress conditions (Klessig and Malamy 1994). Dietary phenolic acids, such as benzoic, hydrobenzoic, vanillic, and caffeic, were reported to have antimicrobial and antifungal action, probably due to enzyme inhibition by the oxidized compounds (Cowan 1999). Hydroxycinnamic acid derivatives, such as caffeic, chlorogenic, sinapic, ferulic, and *p*-coumaric acid, possess strong antioxidant activity due to the inhibition of lipid oxidation and scavenging reactive oxygen species (Sroka and Cisowski 2003; Cheng et al. 2007). Some phenolics such as syringic acid may contribute to the bitter and astringent taste of vegetables (Drewnowski and Gomez-Carneros 2000).

Flavonoids represent the most numerous (~4,000 compounds) group of plant phenolics (Harborne 1993). Flavonoids are classifie as fl vones (e.g., apigenin, luteolin, and chrysoeriol), fl vonols (e.g., quercetin, kaempferol, and isorhamnetin), fl vanones (e.g., naringenin and hesperetin), catechins (e.g., catechin and epigallocatechin), anthocyanidins (e.g., pelargonidin, cyanidin, delphinidin, and malvidin), isofl vones (e.g., genistein and daidzein), and chalcones (e.g., butein and phloretin). Flavonols quercetin, kaempferol, and isorhamnetin have been found in bean, broccoli, endive, leek, onion, and tomato; fl vones apigenin and luteolin in bean, red peppers, parsley, and thyme; anthocyanidins cyanidin, delphinidin, and malvidin in onion, radish, red cabbage, and red lettuce; and isofl vones in soy (Hertog et al. 1992; Song et al. 1998; Yao et al. 2004; Horbowicz et al. 2008). Most of the fl vonoids present in plants are attached to sugars (glycosides) (Ross and Kasum 2002). Many fl vonoids, such as anthocyanidins, chalcones, and fl vones, are plant pigments, which determine the color of vegetables. Dietary fl vonoids possess antiviral, antiinflammator , antihistamine, and antioxidant properties. They have been reported to inhibit lipid peroxidation, to scavenge free radicals, to chelate iron and copper ions (which can catalyze production of free radicals), and to modulate cell signaling pathways (Heim et al. 2002; Rice-Evans and Packer 2003). Flavonoids protect low-density lipoprotein cholesterol from being oxidized, preventing the formation of atherosclerotic plaques in the arterial wall. They stimulate enzymes involved in detoxificatio of cancerogenic substances and inhibit inflammatio associated with local production of free radicals (Hollman and Katan 1999). A number of bifl vonoids have been shown to possess antituberculosis activity (Lin et al. 2001). Most fl vonoids have a bitter or astringent taste, or a bitter taste with sweet aftertaste (Drewnowski and Gomez-Carneros 2000).

Coumarins include about 1,300 phenolic compounds made of fused benzene and α-pyrone rings. Coumarins are often classifie into four major groups: simple coumarins (e.g., coumarin and hydroxycoumarin); furanocoumarins (e.g., bergapten, xanthoxin, and isopimpinellin); pyranocoumarins (e.g., decursin and xanthyletin); and phenylcoumarins (e.g., indicanine and 5,7,3′,4′-tetrahydroxy-4-phenylcoumarin). In vegetables coumarins are widely distributed among the *Umbelliferae* family, which includes carrot, celery, fennel, and parsley (Zobel 1997; Cherng et al. 2008). These vegetables contain coumarins apigravin, apimentin, apimoside, bergapten, celerin, isopimpinellin, and xanthoxin. Coumarins daphnetin, scopoletin, and umbelliferone have been also found in pea; coumarin, aesculetin, scopoletin, and umbelliferone in maize; aesculin, coumarin scopoletin, and umbelliferone in potato (Zobel 1997; Cherng et al. 2008). In humans plant coumarins possess antibacterial, anti-inflammator , vasorelaxant, and immunomodulatory activities. With respect to antioxidant activities, coumarins have been shown to react with hydroxyl radicals and superoxide anion radicals, and to chelate iron ions (Hoult and Payá 1996).

Lignans are diphenolic compounds, derived from monolignols (*p*-coumaryl, coniferyl, and sinapyl alcohols). Lignans and lignin share monolignols as common precursors. Lignans (e.g., lariciresinol, pinoresinol, secoisolariciresinol, and matairesinol) have been found in broccoli, Brussels sprout, cabbage, carrot, kale, leek, and sweet pepper (Milder et al. 2005). Lignans play a role in the defense of plants against insects, acting as regulators of insect feeding and development (moulting) (Harmatha and Dinan 2003). Some plant lignans such as lariciresinol, matairesinol, pinoresinol, and secoisolariciresinol can be converted into enterolignans by the intestinal microflora and absorbed into the human body (Heinonen et al. 2001). In humans, lignans possess antioxidant and (anti)oestrogenic properties, and may reduce the risk of certain cancers. It has been postulated that, compared to the semivegetarian diet in many Asian countries, the Western diet may alter hormone production, metabolism, or action at the cellular level, increasing incidences of breast, colorectal, and prostate cancer (Adlercreutz and Mazur 1997). Reduced cancer risks have been associated with higher urinary lignan excretion (Webb and McCullough 2005).

Lignins are phenolic polymers with molecular mass >10,000 Da, and are hydrophobic constituents of plant cell walls. Lignins are composed of phenilpropanoid monolignol units *p*-coumaryl, coniferyl, and sinapyl alcohols, which give rise to *p*-hydroxyphenyl, guaiacyl, and syringyl lignins, respectively. Natural lignins significantl vary in their subunit composition and intermolecular linkages (Campbell and Sederoff 1996). Vegetable lignins mainly consist of guaiacyl and syringyl units with guaiacyl/syringyl ratios ranging from 39 to 0.2 (Bunzel et al. 2005). Lignins from asparagus, carrot, kale, radish, and spinach have been classifie as guaiacyl-rich, lignins from rhubarb as syringyl-rich, while lignins from kohlrabi and radish have been define as balanced (Bunzel et al. 2005). In plants lignins play an important role in mechanical support, water transport, and defense. With respect to human nutrition, lignin is often define as nonhydrolysable component of dietary fibe (De Vries 2003). Lignin is thought to be involved in the adsorption and excretion of bile acids and a reduction of serum cholesterol (Eastwood 2005). The potential antioxidant and cytotoxic activities of different types of lignins have been demonstrated (Ugartondo et al. 2008). Lignins have been shown to adsorb copper and cadmium ions (Guo et al. 2008) involved in the production of reactive oxygen species (Valko et al. 2006).

Tannins are phenolic metabolites with molecular weights between 500 and 30,000

Da. Tannins include hydrolysable tannins gallotannins (e.g., tannic acid and gallotannin) and ellagitannins (e.g., pedunculagin, casuarictin); condensed tannins (e.g., procyanidin A_1, procyanidin B_2); and complex tannins (e.g., acutissimin A) (Khanbabaee and van Ree 2001). Tannic acid has been found in cabbage, sweet potato, and turnip (Mosha et al. 1995). Condensed tannins have been found in bean, broccoli, carrot, lentil, rhubarb, and spinach (Gu et al. 2004; Serrano et al. 2009). Tannins have long been regarded as antinutrients, since they cause decreases in feed intake, protein digestibility, and iron absorption in animals (Mueller-Harvey 2006). Tannins inhibit growth of many fungi, yeasts, bacteria, and viruses, and act as antioxidants (Chung et al. 1998). In humans, tannins have also been reported to accelerate blood clotting, reduce blood pressure, decrease the serum lipid level, and modulate immunoresponses (Chung et al. 1998; Hayashi et al. 2008).

Alkaloids

Alkaloids are a group of basic nitrogen-containing metabolites (~12,000 compounds; Goldberg 2003), mainly derived from amino acids. Amino acid-derived alkaloids containing heterocyclic rings are frequently called true alkaloids, while those without rings are called protoalkaloids. Alkaloids that are not derived from amino acids are called pseudoalkaloids. True alkaloids and protoalkaloids are classifie either according to their heterocyclic ring structure (pyrrolidine, piperidine, pyridine, etc.) or according to amino acids from which they are derived (L-lysine, L-tyrosine, L-ornithine, etc.). Pseudoalkaloids consist of isoprenoid residues in which the nitrogen atom is inserted. They can be classifie as monoterpenoid, sesquiterpenoid, diterpenoid, triterpenoid, and steroid alkaloids. Examples of plant alkaloids are pyridine derivatives nicotine and coniine, tropane alkaloids atropine and cocaine, isoquinone alkaloids morphine and codeine, purine alkaloid caffeine, and steroid alkaloid solanine (Goodwin and Mercer 1983). The chemical structure of selected vegetable alkaloids is shown in Figure 2.6.

Alkaloids have traditionally been of great interest because of their pronounced physiological and medicinal properties (e.g., caffeine, nicotine, morphine, atropine, quinine). The importance of alkaloids in the metabolism of plants is still being debated. Most alkaloids are very toxic and have a potential role in providing chemical defenses against herbivores and microorganisms (Wittstock and Gershenzon 2002). It has also been suggested that these compounds serve as protectants against damage by UV light (Jansen et al. 1998). Plant alkaloids such as berberine, palmatine, and mahanine are reported to have antimicrobial and cytotoxic activities (Facchini 2001). Some vegetable alkaloids can be toxic for humans. Unripe tomato and potato exposed to light contain two major alkaloid fractions, solanine and chaconine (Jadhav et al. 1981). Solanine is a cholinesterase inhibitor and can cause neurological and gastrointestinal symptoms, including depression of the activity of the central nervous system (Dalvi and Bowie 1983). However, it has not been proven that consumption of these vegetables would be toxic unless they comprised an excessively high proportion of the diet. Most alkaloids (e.g., lactucin and lactucopicrin, present in lettuce and chicory) have a bitter and acrid taste (Van Beek et al. 1990).

Plant glucoalkaloids solanine, tomatine, and chaconine are called saponins since these compounds have surfactant properties and form foam in aqueous solutions (Hostettmann and Marston 2005). Saponins are found in asparagus, bean, garlic, onion, pea, potato, tomato, and spinach (Sparg et al. 2004). Saponins defend plants against microorganisms and herbivores due to their insecticidal and molluscicidal activity, and have allelopathic effects on many weeds (Haralampidis

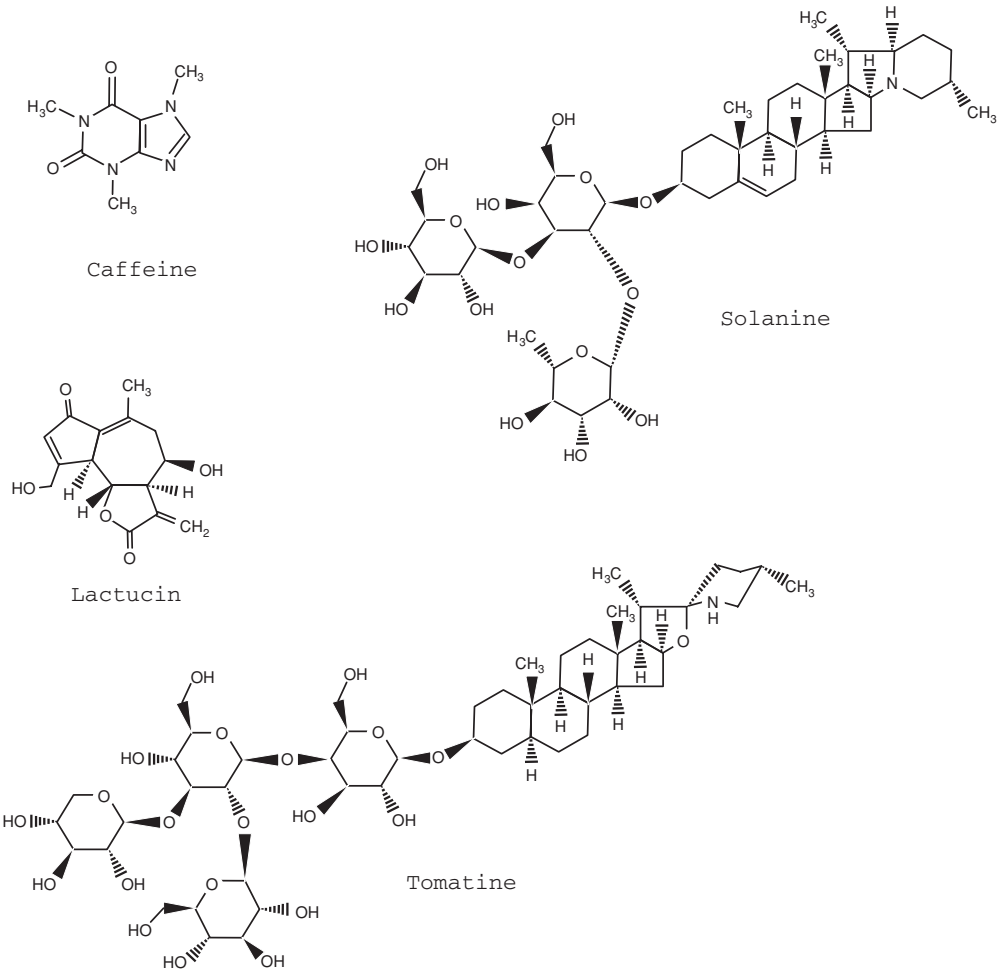

Figure 2.6 Chemical structure of selected alkaloids.

et al. 2001). Dietary saponins cause a reduction of blood cholesterol, inhibit growth of cancer cells, and stimulate the immune system (Francis et al. 2002). Saponins contribute to the bitter and acrid taste of vegetables (Drewnowski and Gomez-Carneros 2000). However, sweet saponins, like periandrin V, are 100 times sweeter than sucrose (Kinghorn et al. 1998). Some saponins, such as sapotoxin, can be toxic for humans. They cause irritation of membranes of the respiratory and digestive tracts, increase the membrane permeability of red blood cells, and may lead to urticaria (skin rash) (Francis et al. 2002).

Sulfur-Containing Compounds

Sulfur-containing compounds are a relatively small group of plant secondary metabolites (around 200 compounds). They include glucosinolates and their breakdown products (thiocyanates, isothiocyanates, epithionitriles, and oxazolidinethiones); cysteine sulfoxides; diallyl sulfides and dithiolthiones. The chemical structure of some

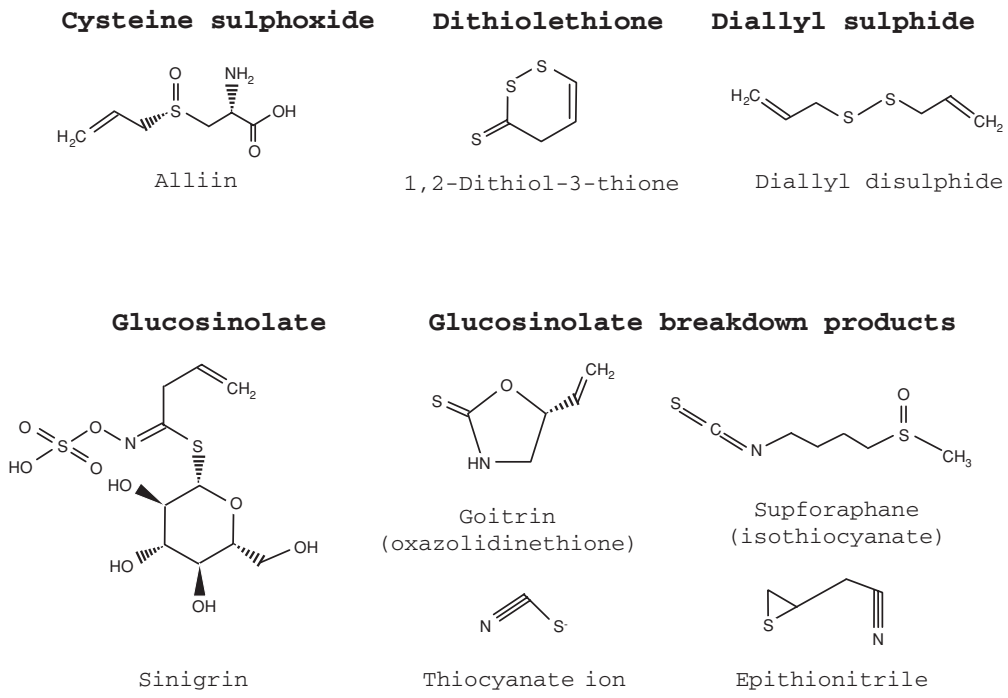

Figure 2.7 Chemical structure of selected sulfur-containing metabolites.

representative sulfur-containing compounds is shown in Figure 2.7.

Glucosinolates are a small but diverse family of sulfur-containing amino acid derivatives containing a group derived from glucose. These include ~120 compounds, which are largely limited to species of the *Brassicaceae* family. Glucosinolates progoitrin and sinigrin are found in white and red cabbage, Brussels sprout, and caulifl wer; glucoiberin and glucoraphenin in broccoli, daikon, and red radish; sinigrin and gluconasturtiin in horseradish and mustard; glucoalyssin and gluconapoleiferin in turnip (Fahey et al. 2001; Johnson 2002b; Padilla et al. 2007).

Glucosinolates are derived from protein amino acids (alanine, isoleucine, leucine, methionine, phenylalanine, tryptophan, tyrosine, and valine). Biosynthesis of glucosinolates proceeds in three stages: (1) side-chain elongation of amino acids; (2) development of core structure; and (3) secondary side-chain modifications In the firs stage precursor amino acids are elongated via transamination, condensation, isomerization, and oxidative decarboxylation. In the second stage (common to all glucosinolates), the amino acid moiety (whether elongated or not) undergoes modification via oxidation, C–S cleavage, glucosylation, and sulfation to produce a core structure. Secondary modifi cations of the side chain include various kinds of oxidation, alkylations, and esterifications Glucosinolates are synthesized in cytosol and later sequestered in vacuoles. Upon tissue disruption, glucosinolates are rapidly hydrolyzed by the enzyme myrosinase. Breakdown products include thiocyanates, isothiocyanates, nitriles, epithionitriles, and oxazolidinethiones (Grubb and Abel 2006; Halkier and Gershenzon 2006). Some of these compounds act as allelochemicals, protecting plants against herbivores, pests, and pathogens (Bennett and Wallsgrove

1994; Bones and Rossiter 1996). Some glucosinolates are important precursors for fl vor compounds. Isothiocyanates, such as allylisothiocyanate and benzylisothiocyanate, commonly termed "mustard oils," have a pungent or lachymatory taste, and an acrid smell (Drewnowski and Gomez-Carneros 2000). Other glucosinolates are unwanted as their breakdown products have undesirable sensory or physiological characteristics. Sinigrin and its degradation product have a bitter taste. Progoitrin and gluconapoleiferin are tasteless, but their hydrolytic products are very bitter (Van Doorn et al. 1998). Overconsumption of glucosinolate-rich food can disrupt synthesis of thyroid hormones and cause inflammatio of the mucous membranes of the stomach (Fenwick and Heaney 1983). However, these cases are rare. Certain glucosinolates (glucoraphanin, glucobrassin, glucotropaeolin) and their breakdown products have been linked to a reduction in the prevalence of certain types of cancer (Das et al. 2000). The anticarcinogenic effect of glucosinolates is explained by the activation of enzymes involved in the detoxificatio of carcinogens, inhibition of enzymes modifying steroid hormone metabolism, and protection against oxidative damage (Johnson 2002b). Isothiocyanates, resulting from glucosinolate hydrolysis, possess antiproliferative activities (Zhang et al. 2006).

Alkyl cysteine sulfoxides such as methiin, alliin, isoalliin, and propiin are fl vor precursors in *Allium* species including chive, garlic, leek, and onion (Jones et al. 2004; Fritsch and Keusgen 2006). Upon tissue disruption these precursors are cleaved by the enzyme alliinase to produce pyruvate, ammonia, and thiosulfinate The latter undergoes further reactions so that the smell of *Allium* changes over time. Although compounds from onion and garlic have been reported to have a range of health benefits including anticarcinogenic, antiplatelet, antithrombotic, antiasthmatic, and antibiotic properties (Griffith et al. 2002), the role of alkyl cysteine sulfoxides in humans has not been scientificall investigated due to the instability of these compounds.

Diallyl sulfide such as allyl methyl disulfide diallyl sulfide diallyl disulfide and diallyl trisulfid are found in chive, garlic, leek, and onion (Lanzotti 2006; Rattanachaikunsopon and Phumkhachorn 2008). Diallyl sulfide are breakdown products of allicin, which is converted from alliin when tissues of *Allium* plants are disrupted. Diallyl sulfide possess antioxidant, antimicrobial, antithrombotic, and antiangiogenic properties. They reduce the production of proinflammator cytokines, platelet aggregation, and DNA damage by genotoxic compounds, and protect low-density lipoprotein against oxidation and glycation (Chan et al. 2002; Ou et al. 2003; Belloir et al. 2006; Thejass and Kuttan 2007; Rattanachaikunsopon and Phumkhachorn 2008).

Dithiolethiones are well known as cancer chemopreventive agents (Zhang and Munday 2008). Natural dithiolethione (1,2-dithiole-3-thione) has been found in cabbage (Marks et al. 1991). Synthetic dithiolethiones, such as D3T, anethole dithiolethione, and oltipraz, have been shown to inhibit the toxicity and carcinogenicity in animal models (Kensler et al. 2000). The key mechanism of action of dithiolethiones involves induction of phase II detoxificatio enzymes, such as glutathione S-transferase (Kensler et al. 2000; Zhang and Munday 2008).

Antioxidants

Vegetables are a rich source of dietary antioxidants, and links between vegetable consumption and a lower risk of coronary heart diseases, diabetes, cataract, degenerative diseases, and different types of cancer have been extensively reported (Goldberg 2003; Valko et al. 2007). Dietary antioxidants are define as food compounds that significantl decrease the adverse effects of reactive oxygen species, reactive nitrogen species, or both, on the normal physiological function in humans (SEDRI 1998). Reactive oxygen species (e.g.,

oxygen ions, free radicals, and peroxides) and reactive nitrogen species (e.g., nitrous anhydride, peroxynitrite, and nitrogen dioxide radical) cause oxidation, nitration, halogenation, and deamination of biomolecules of all types, including lipids, proteins, carbohydrates, and nucleic acids, with the formation of toxic and mutagenic products (Patel et al. 1999; Castro and Freeman 2001).

Antioxidants delay the start or slow the rate of free radical formation. These compounds are characterized by the ability to donate the hydrogen atom (or electron/proton), or to chelate metal ions involved in formation of reactive oxygen species. In most cases antioxidant action involves a combination of different mechanisms; therefore, antioxidant properties cannot be attributed to a certain class of chemical compounds or to certain functional groups in these compounds. Antioxidants have been found among many classes of primary and secondary plant metabolites, such as amino acids, amines and polyamines, organic acids, terpenoids, phenolics, alkaloids, and organosulfur compounds. Table 2.3 summarizes the information about the main metabolic groups of antioxidants found in plants.

A number of studies have demonstrated synergistic interactions between different antioxidant compounds. It has been shown that mixtures of antioxidants have higher antioxidant activity than the sum of individual compounds. Mixtures of carotenoids were more effective against oxidative damage compared to single carotenoids (Stahl et al. 1998). Synergistic interactions have been demonstrated between phenolic acid, β-carotene, and ascorbic acid, as well as between fl vonoids and tocopherols (Trombino et al. 2004; Marinova et al. 2008).

Conclusions

Renewed interest in the role of vegetable consumption in maintaining and enhancing human health has highlighted the importance of considering the chemical composition of vegetables available to consumers. This chapter provides an overview of the large variety of primary and secondary metabolites found in vegetables. It includes information about the classificatio and biochemistry of major groups of metabolite compounds, and their role in plants and in human health.

Studying the metabolite composition of vegetables remains a difficul task. Levels of plant metabolites are strongly affected by genetic and environmental factors, as well as transportation and storage conditions. Growth factors such as light, temperature, humidity, type of soil, application of fertilizers, damage caused by microorganisms and insects, stress induced by UV radiation, heavy metals, and pesticides, all alter the metabolite composition of plants (Orcutt and Nilsen 2000). Before vegetables appear on a supermarket shelf, they have been handled by plant growers, transporters, packagers, storehouse operators, distributors, and/or processors. The chemical and physical changes that occur in vegetables during these stages can lead to loss of potentially beneficia components (MacEvilly and Peltola 2003).

Existing studies usually focus on a certain group or class of chemical compounds, rather than providing an overall picture of the metabolites present in vegetables. Plant metabolomics, or large-scale phytochemical analysis, is a new research discipline, which aims to develop a comprehensive approach to metabolite detection and identificatio in plants (Fiehn 2002; Schauer and Fernie 2006). Mass spectrometry, nuclear magnetic resonance, and infrared spectrometry are the most common metabolomics platforms. Metabolite profilin and metabolite fingerprintin are fast-growing technologies for phenotyping and diagnostic analyses of plants (Roessner et al. 2001; Krishnan et al. 2004).

While a large volume of information is now available about the occurrence and content of different chemical compounds in vegetables, it has yet to be effectively systemized. Classificatio of plant metabolites should be rationalized. Future studies should

Table 2.3 A list of plant metabolites with reported antioxidant properties.

Metabolic category	Antioxidant compound	References
Amino acids and amines	Cystationine	Wada et al. (1996)
	Homocysteine	Meucci and Mele (1997)
	Methionine	Meucci and Mele (1997)
	Tyrosine	Meucci and Mele (1997)
	Agmatine	Lee et al. (2003_
	Glucosamine	Yan et al. (2006)
	Tyramine	Yen and Hsieh (1997)
	Putrescine	Das and Misra (2004)
	Spermidine	Das and Misra (2004)
Organic acids	Acetoacetic acid	Mallet and Sun (2003)
	Aconitic acid	Sousa et al. (2007)
	Adipic acid	Papadopoulos et al. (2001)
	Ascorbic acid	Otero et al. (1997)
	Citric acid	Papadopoulos et al. (2001)
	Dehydroascorbic acid	Otero et al. (1997)
	Lactic acid	Groussard et al. (2000)
	Malic acid	Puntel et al. (2007)
	Pyruvic acid	Mallet and Sun (2003)
	Shikimic acid	Sousa et al. (2007)
	Succinic acid	Naylin et al. (2006)
	Tartaric acid	Papadopoulos et al. (2001)
Pyridines	Nicotinamide	Crowley et al. (2000)
	Nicotinic acid	Crowley et al. (2000)
	Pyridoxamine	Jain and Lim (2001)
	Pyridoxine 5-phosphate	Jain and Lim (2001)
Terpenoids	α-,β-,γ-,δ-Tocopherols	Yoshida et al. (2007)
	α-,β-,γ-,δ-Tocotrienols	Yoshida et al. (2007)
	β-Carotene	Böhm et al. (2002)
	β-Sitosterol	Yoshida and Niki (2003)
	Apiole	Singh et al. (2005)
	Campesterol	Yoshida and Niki (2003)
	Geraniol	Choi et al. (2000)
	Limonene	Gerhäuser et al. (2003)
	Lycopene	Böhm et al. (2002)
	Phylloquinone	Rhodes et al. (2000)
	Stigmasterol	Yoshida and Niki (2003)
	Zeaxanthin	Böhm et al. (2002)
Phenolics	Catechol	Arts et al. (2003)
Phenols	Eugenol	Reddy and Lokesh (1992)
	Hydroquinone	Arts et al. (2003)
Coumarins	Bergapten	Yu et al. (2005)
	Coumarin	Kostova (2005)
	Decursin	Kang and Kim (2007)
	Fraxetin	Fernandez-Puntero et al. (2001)
	Scopoletin	Shaw et al. (2003)
	Xanthotoxin	Fylaktakidou et al. (2004)
Phenolic acids	Benzoic acid	Weitzman and Stossel (1982)
	Caffeic acid	Gülçin (2006)
	Cinnamic acid	Kanski et al. (2002)
	Coumaric acid	Kanski et al. (2002)
	Dihydrocaffeic acid	Huang et al. (2004)
	Ellagic acid	Meyer et al. (1998)
	Gallic acid	Yilmaz and Toledo (2004)
	Gentisic acid	Ashidate et al. (2005)

Table 2.3 (*Continued*)

Metabolic category	Antioxidant compound	References
	Hydroxybenzoic acid	Gadow et al. (1997)
	Phenylacetic acid	Kim and Lee (2004)
	Protocatechuic acid	Saito and Kawabata (2004)
	Syringic acid	Schmeda-Hirschmann et al. (2004)
	Vanillic acid	Kanski et al. (2002)
	Veratric acid	Miyazawa et al. (2003)
Flavonoids	Arbutin	Hong et al. (2008)
	Artemetin	Dugas et al. (2000)
	Betanidin	Kanner et al. (2001)
	Butein	Chen et al. (2006)
	Butin	Zhang et al. (2008)
	Catechin	Yilmaz and Toledo (2004)
	Chrysin	Harris et al. (2006)
	Cyanidin	Meyer et al. (1998)
	Dihydroquercetin	Dok-Go et al. (2003)
	Epicatechin	Yilmaz and Toledo (2004)
	Epigallocatechin	Luo et al. (2002)
	Equol	Arora et al. (1998)
	Flavidin	Jayaprakasha et al. (2004)
	Gallocatechin	Luo et al. (2002)
	Kaempferol	Brown et al. (1998)
	Luteolin	Brown et al. (1998)
	Naringenin chalcone	Calliste et al. (2001)
	Nobiletin	Murakami et al. (2000)
	Pelargonidin	Pietta (2000)
	Purpurogallin	Sugiyama et al. (1993)
	Rubiadin	Tripathi et al. (1997)
	Quercetin	Meyer et al. (1998)
Lignans	Hinokiresinol	Song et al. (2007)
	Honokiol	Park et al. (2003)
	Lariciresinol	Pietarinen et al. (2006)
	Lyoniresinol	Tomosaka et al. (2008)
	Magnolol	Park et al. (2003)
Phenylpropanoid intermediates	Cinnamaldehyde	Kim et al. (2007)
	Coniferin	Kayano et al. (2004)
	Coniferyl alcohol	Barclay et al. (1997)
	Coumaryl alcohol	Ly et al. (2003)
	Syringin	Es-Saf et al. 2007
Alkaloids	Caffeine	Devasagayam et al. (1996)
	Koenigine	Rao et al. (2007)
	Mahanimbine	Rao et al. (2007)
	Tetrahydro-β-carboline alkaloids	Herraiz and Galisteo (2003)
Organosulfur compounds	Alliin	Chung (2006)
	Anethole dithiolethione	Drukarch et al. (2006)
	Butiin	Dini et al. (2008)
	Diallyl disulfid	Koh et al. (2005)
	Dipropyl disulfid	Munday et al. (2003)
	Etiin	Dini et al. (2008)
	Glutathione	Noctor and Foyer (1998)
	Methiin	Dini et al. (2008)
	Propiin	Dini et al. (2008)

focus on the development of a comprehensive database, accumulating all available data about metabolites found in vegetables.

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Chapter 3

Flavor and Sensory Characteristics of Vegetables

Peter K. C. Ong and Shao Quan Liu

Introduction

Vegetables are referred to as the edible portions of plants, excluding fruits and seeds, and are normally consumed as part of the main course of a meal. For the purpose of this chapter, vegetables have been broadly categorized as (1) leafy and leafstalk vegetables; (2) stem vegetables; (3) fl wer and immature inflorescenc vegetables; (4) fruit as vegetables; (5) tuber vegetables; (6) root vegetables; (7) bulb vegetables; (8) herbs and spices; (9) edible fungi; (10) fresh-cut vegetables; and (11) fermented vegetables.

Flavor is one of the important quality attributes that determine consumer acceptance and repeat purchase of a food product. It is contributed by various odor-active, taste-active, and chemethestic components. Although fl vor is one of the most important sensory characteristics of foods, other sensory parameters such as appearance (e.g., color) and texture are also important in the consumers' perception of the food.

Fresh, raw vegetables are the major vegetable types that consumers purchase for consumption, while processed vegetables in the dried, frozen, and canned forms are also readily available. Furthermore, minimally processed vegetables have also gained popularity in recent years. While the focus of this chapter is on the fl vor and sensory characteristics of raw vegetables, the effects of processing, for example, cutting, and the unique impact of fermentation on vegetable fl vor and sensory attributes are discussed. Edible fungi and herbs and spices, which are considered to be a major part of the vegetarian diet and have not been reviewed earlier in much detail, are discussed in detail here. The general adverse effects of drying, freezing, and thermal processing on vegetable fl vor, color, and texture are well studied over the past few decades and these will not be reviewed in this chapter.

The volatile compounds in a diverse range of vegetables have been previously reviewed in great detail (Whitfiel and Last 1991; Christensen et al. 2007). However, the nonvolatile taste components of vegetables have not been reviewed. Therefore, this chapter will focus on both nonvolatile taste components and volatile odor-active compounds of vegetables, as well as the color and texture of vegetables.

Biogenesis of Flavors in Vegetables

The formation of major fl vor compounds in vegetables is well understood and comprehensively detailed in books and review articles (Fisher and Scott 1997; Cheetham 2002; Reineccius 2006; Christensen et al. 2007; Lindsay 2007).

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

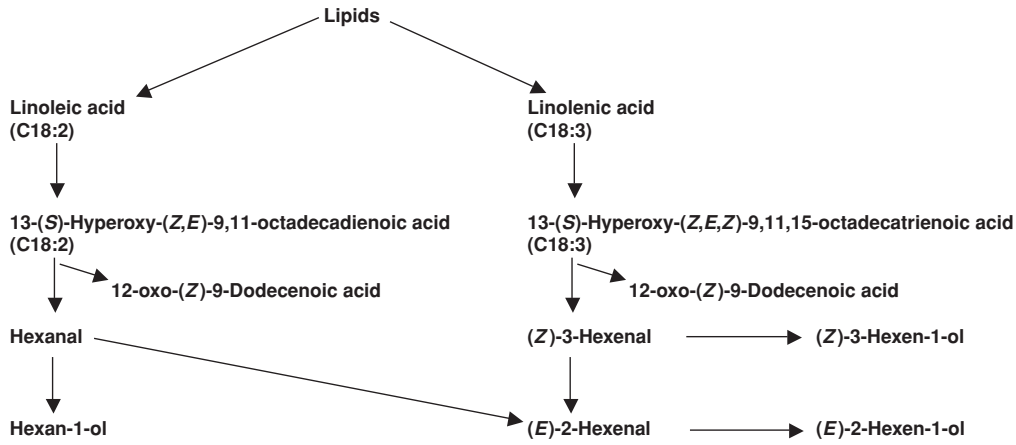

Figure 3.1 Formation of flavor compounds from fatty acids via the lipoxygenase pathway. (Modified after Fisher and Scott 1997; Christensen et al. 2007.)

The major substrates for the biogenesis of fl vors in vegetables are lipids and fatty acids, amino acids, glucosinolates, terpenoids, and phenolics (Figures 3.1–3.4) (Reineccius 2006; Christensen et al. 2007; Lindsay 2007). The specifi types of fla vor compounds formed and the pathways involved are dependent upon a number of factors such as vegetable type (plant or edible fungi), edible parts of plants (e.g., fruit, leaf, stem, fl wer, tuber, root, or bulb), and stage of maturity and processing methods (e.g., fermentation, drying, freezing, or canning).

Most fresh and raw vegetables do not have strong aroma when they are in their intact states. The odor compounds are formed

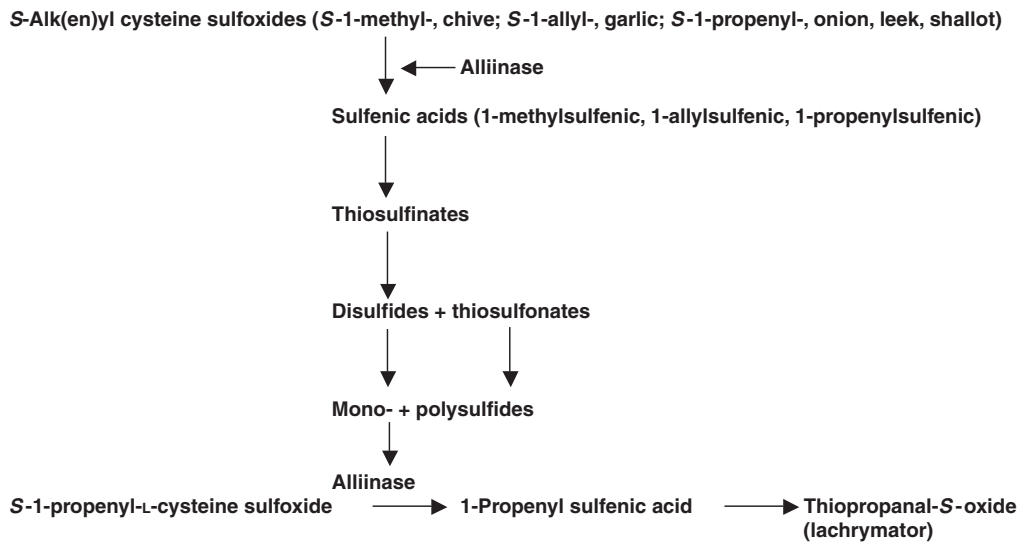

Figure 3.2 Formation of volatile sulfur flavor compounds in *Allium* (bulb) vegetables from amino acid precursors. (Modified after Fisher and Scott 1997; Christensen et al. 2007.)

Figure 3.3 Formation of volatile flavor compounds from glucosinolates. (Modified after Fisher and Scott 1997; Christensen et al. 2007; Lindsay 2007.)

during vegetable preparations such as cutting, shredding, and heating. Tissue disruption due to preparations allows mixing and interaction of enzymes and substrates that are usually not in contact. This results in the formation and release of volatile fl vor compounds that contribute to the characteristic fl vors of the various vegetables.

Oxidative degradation of unsaturated fatty acids such as linoleic ($C_{18:2}$) and linolenic acids ($C_{18:3}$) is catalyzed by lipoxygenase, and gives rise to C_6 aldehydes and alcohols that are responsible for the green fl vor notes in certain vegetables, such as leafy vegetables and cucumber (Figure 3.1). Enzymatic hydrolysis of S-alk(en)yl cysteine sulfoxide by alliinase produces a range of volatile sulfur fl vor compounds that are responsible for the odor in bulb vegetables such as garlic and onion (Figure 3.2). The odorous compounds of cut *Brassica* vegetables such as cabbages are formed as a result of hydrolysis of glucosinolates catalyzed by thioglucosidase (myrosinase) (Figure 3.3). Terpenoid fl vor compounds in vegetables such as tomato are primarily derived from oxidative degradation of carotenoids (Figure 3.4).

The formation of fl vor compounds in fermented vegetables is complicated due to the involvement of complex microflor of bacteria, yeasts, and molds. This topic will not be discussed here.

Flavors and Sensory Characteristics of Vegetables

Leafy and Leafstalk Vegetables

Leafy vegetables are numerous while the number of leafstalk vegetables is limited: the former include cabbage, Brussels sprouts, lettuce, parsley, watercress, and spinach; the latter includes celery and rhubarb. Information is lacking on the fl vor and sensory attributes of many of these vegetables, but the fl vor compounds of some of these vegetables were reported by Whitfiel and Last (1991).

Cabbage and Brussels Sprouts

The key fl vor compounds of cabbage and Brussels sprouts are characterized by the dominance of sulfur volatiles. The main sulfur volatiles in Brussels sprouts are dimethyl

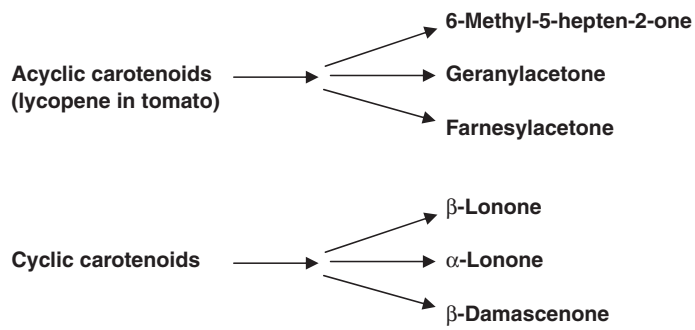

Figure 3.4 Formation of flavor compounds from carotenoids. (Modified after Christensen et al. 2007.)

sulfide dimethyl disulfide dimethyl trisulfide and 2-propenyl isothiocyanate, whereas the major sulfur volatiles in cabbage are methanethiol, dimethyl trisulfide 2-propenyl isothiocyanate, and 3-butenyl isothiocyanate (Christensen et al. 2007). Quantitatively, 3-butenyl cyanide and 3-butenyl isothiocyanate are the major fl vor compounds in wild cabbage *Brassica cretica*, and 2-phenylethyl cyanide and 2-phenylethyl isothiocyanate are the main fl vor compounds in another wild cabbage *Brassica insularis*. Also, organonitrogen compounds such as skatole were reported to contribute to the odor profil of the cabbage due to their high odor activity values (Breme et al. 2009).

In Brussels sprouts, sinigrin and progoitrin were reported to be responsible for the bitter taste typically experienced (Engel et al. 2002).

Spinach

Cooked spinach leaves are characterized not only by the classical C_6 aldehydes and alcohols that exhibit green notes, but also by some unusual volatiles such as (*E*)-3-methyl-2-nonen-4-one, (*Z*)-3-(3-hexenyloxy)-hexanal, (*E*)-3-(2- hexenyloxy)-hexanal, and (*E*)-6-methyl-6-(5-methyl-2-furyl)-3-hepten-2-one, which impart meaty, smoky, phenolic, typical cooked spinach notes (Naf and Velluz 2000).

Celery

The characteristic odors of raw and boiled celery are mainly ascribed to phthalides such as 3-*n*-butylphthalide, sedanenolide, and *trans*- and *cis*-sedanolides, and to a lesser extent attributed to terpenes such as myrcene and γ-terpinene (Kurobayashi et al. 2006; Christensen et al. 2007). The compounds (*Z*)-3-hexenal and (*Z*)-3-hexenol are dominant in raw celery, while 2-methylbutanoic acid, sotolon, β-damascenone, and β-ionone dominate in boiled celery and reduce the green note of the celery (Kurobayashi et al. 2006). Interestingly, a recent study showed that 3-*n*-butylphthalide, sedanenolide, and sedanolide enhanced the fl vor complexity of chicken broth and the perceived intensities of umami and sweet fl vor characteristics (Kurobayashi et al. 2008).

Rhubarb

The stalk of vegetable rhubarb (*Rheum rhabarbarum* L.) has a fresh, sour taste attributed to malic, oxalic, and citric acids, as well as C6 saturated and unsaturated aldehydes and acids. A recent study has revealed a total of 78 volatiles in raw rhubarb, including alcohols, aldehydes, esters, ketones, acids, terpenes, and others (Dregus and Engel 2003). According to this study, unsaturated C_6 aldehydes and alcohols, typically (*E*)-2-hexenol, hexanal, (*Z*)-3-hexenal, and (*E*)-2-hexenal, are the major odor compounds of raw rhubarb. (*E*,*Z*)-2,6-nonadienal and β-ionone are also important to the aroma of raw rhubarb and contribute to the flora notes.

Stem Vegetables

Asparagus is the most studied and commercially important stem vegetable and will be the focus of this section. There is little or no information available on the fl vor and sensory characteristics of other stem vegetables such as bamboo shoot and mung bean shoot. These could be considered for future study.

The volatile fl vor compounds in asparagus have been previously reviewed (Whitfiel and Last 1991). Sulfur-containing compounds are an important feature of the raw asparagus aroma and the major components based on concentration are methyl 1,2-dithiolane-4-carboxylate and 1,2-dithiolane-4-carboxylic acid. The major volatile components of cooked asparagus are hexanol, methyl 1,2-dithiolane-4-carboxylate, 3-hydroxy-2-butanone, dimethyl sulfide pentanol, and vanillin. It is believed that these volatiles contribute to the aroma of raw and cooked

asparagus. Ulrich et al. (2001) reported key volatiles of cooked asparagus as dimethyl sulfide methyl thioacetate, pentanedione, hexanal, octanedione, 2,6-dimethyl pyrazine, 2-methoxy-3-isopropyl pyrazine, 3-ethyl-2,5-dimethyl pyrazine, and methional.

Flowers (Immature Inflorescence) as Vegetables

Broccoli and caulifl wer are the two major vegetables belonging to this category. The volatile fl vor compounds in broccoli and caulifl wer have been discussed elsewhere (Whitfiel and Last 1991; Christensen et al. 2007) and are briefl touched upon in this section.

The odors of broccoli and caulifl wer are characterized by a diverse range of sulfur-containing volatiles. Broccoli odor is mainly attributed to the influenc of dimethyl sulfide dimethyl disulfide dimethyl trisulfide 4-methylthio-butyl isothiocyanate, butyl isothiocyanate, and 2-methylbutyl isothiocyanate. In caulifl wer, the main sulfur-containing volatiles are methanethiol, dimethyl sulfide dimethyl trisulfide 3-methylthio-propyl isothiocyanate, and 2-propenyl isothiocyanate. Nonsulfur volatiles such as aldehydes hexanal and nonanal also contribute to the odor of broccoli and caulifl wer.

Caulifl wer contains significan levels of glutamic and aspartic acids (Slupski et al. 2009), which likely play a part in its savory taste. Mouthfulness- and complexity-enhancing compound glutathione, one of the so-called kokumi taste compounds, has been found in broccoli (Ueda et al. 1997). This sulfur-containing peptide derivative, when combined with an umami (savory) solution of monosodium glutamate (MSG) and disodium inosinate (IMP), significantl enhances the umami fl vor of the solution (Ueda et al. 1997). Also, bitterness of cooked caulifl wer has been reported to be due to its content of bitter glucosinolates (Engel et al. 2002).

Fruits as Vegetables

A variety of fruits are consumed as vegetables and only a few selected ones are considered in this section with respect to their fl vors and sensory characteristics.

Avocado

The unique consistency and special taste of avocado are attributed to its high oil content. Volatiles of fresh avocado fruit include β-caryophyllene as the major sesquiterpene, and α-humulene, caryophyllene oxide, α-copaene, and α-cubebene as the main hydrocarbons (Sinyinda and Gramshaw 1998). Storage (2 hours) of avocado fruit at room temperature results in some fl vor changes with β-caryophyllene present as the main sesquiterpene, followed by α-copaene, a cadinene isomer, α- and β-cubebene, α-farnesene, and octane as the major hydrocarbons, and decenal and heptenal as the principal aldehydes (Sinyinda and Gramshaw 1998). Information on the relative importance of these volatiles to the avocado aroma is lacking, as GC-O (gas chromatography-olfactometry) analysis has not been performed.

Tomato

Tomato is consumed fresh or processed. The fl vor of tomato has been subjected to intensive research (see reviews by Whitfiel and Last 1991 and Christensen et al. 2007). The most important aroma compounds in fresh tomato are 3-methylbutanal, hexanal, (*Z*)-3-hexenal, (*E*)-hexenal, 3-methylbutanol, 1-hexanol, (*Z*)-3-hexenol, 1-penten-3-one, 6-methyl-5-hepten-2-one, β-ionone, β-damascenone, 2-phenylethanol, methyl salicylate, guaiacol, benzyl alcohol, furaneol, and 2-isobutylthiazole (Christensen et al. 2007; Markovic et al. 2007; Ortiz-Serrano and Gil 2007). Using GC-O analysis, *cis*-3-hexenal, β-ionone, and hexanal were reported

with the most odor activity, while guaiacol, benzyl alcohol, and furaneol were not detected (Yilmaz 2001). The key difference in fl vor of fresh and processed tomato is almost complete loss of *cis*-3-hexenal and the presence of furfural in processed tomatoes (Markovic et al. 2007).

Much research has been directed at the fl vor compounds, with little focus on the taste components that play a significan role in the fl vor characteristics of tomatoes. Glutathione, one of the so-called kokumi taste compounds, has been identifie in tomato and is believed to enhance the mouthfeel and fla vor perception (Ueda et al. 1997). Glutamic and aspartic acids, the major free amino acids present in tomato, are reported to act synergistically with the major 5′-nucleotide, 5′-adenosine monophosphate (AMP), to contribute to the umami taste of tomato. These compounds are unevenly distributed in the tomato and are present in larger amounts in the inner pulp (Oruna-Concha et al. 2007).

Cucumber

Cucumber is consumed raw, cooked, or pickled. The key aroma compounds of raw cucumber after cutting are (*E*,*Z*)-2,6-nonadienal and (*E*)-2-nonenal. Both compounds are formed as a result of enzymatic catabolism of linoleic and linolenic acids (Figure 3.1) (Whitfiel and Last 1991; Christensen et al. 2007). During fermentation, (*E*,*Z*)-2,6-nonadienal and (*E*)-2-nonenal decrease to barely detectable levels, while linalool increases to levels well above its odor threshold (Zhou and McFeeters 1998), resulting in a dramatic reduction of the fresh cucumber aroma. Tissue softening is an issue of pickled cucumber and can be effectively mitigated by adding calcium ions (McFeeters and Fleming 1989).

Winter Gourd

Winter gourd or winter melon, also known as wax gourd, is a common vegetable in Asia. The major volatiles found in cooked winter gourd are (*E*)-2-hexenal, hexanal, hexyl formate, (*E*,*E*)-2,4-decadienal, (*Z*)-3-hexenal, (*E*)-2-heptenal, 1-octen-3-ol, (*E*,*E*)-2,4-heptadienal, (*E*,*E*)-2,4-nonadienal, and ethyl acetate (Whitfiel and Last 1991).

Peppers

Bell (or sweet) pepper and chili pepper (or hot chili) are considered peppers in this chapter. The most important odor compounds in raw sweet pepper are 2-(2-methylpropyl)-3-methoxypyrazine, (*E*,*Z*)-2,6-nonadienal, and (*E*,*E*)-2,4-decadienal, while the major aroma compounds in cooked sweet pepper are 2-(2-methylpropyl)-3-methoxypyrazine, 1-nonen-4-one, 2-nonen-4-one, (E,Z)-2,6-nonadienal, (E,E)-2,4-decadienal, and linalool, as reviewed by Whitfiel and Last (1991).

It is well known that the "hotness" or pungency of chili pepper is caused by the nonvolatile capsaicinoids, of which capsaicin is present in the highest proportion. The type and content of capsaicinoids vary with chili pepper varieties. In Szechuan chili pepper, natural alkylamides or sanshools are responsible for the "hotness" sensations. The main alkylamide, α-hydroxysanshool causes a tingling sensation while other alkylamides consisting of α-, β-, γ-, and δ-sanshools also contribute burning, numbing, pungent, and tingling sensations (Menozzi-Smarrito et al. 2009).

The fl vor of fresh chili pepper is believed to be due to 2-(2-methyl-propyl)-3-methoxy pyrazine, while aliphatic esters including 1-(4-methylpentyl)-4-methylpentanoate, 1-(4-methylpentyl)-2-methylbutanoate, 1-(3-methylpentyl)-3-methylbutanoate, and 1-(4-methylpentyl)-2-methylpropanoate are the main contributors to the fruity aroma of Tabasco chili pepper (Whitfiel and Last 1991). Two recent studies demonstrate that esters are the major aroma compounds of Habanero chili pepper, with several other compounds such as (*E*)-2-hexenal and 3,3-dimethylcyclohexanol also suggested to be important components of its fl vor (Pino et al. 2006, 2007).

Sweet Corn

The major odor compounds in the volatile oil by vacuum distillation of the "uncooked" sweet corn kernels are 2-nonanol, 2-heptanol, (*Z*)-4-hepten-2-ol, 2-undecanol, nonanol, and 3-nonenol, while that of cooked kernels are dimethyl sulfide ethanol, and acetaldehyde (Whitfiel and Last 1991). In cooked sweet corn, dimethyl sulfid is the most odor-active compound, followed by ethanol, acetaldehyde, hydrogen sulfide ethanethiol, and methanethiol (Flora and Wiley 2007).

Beans

Beans and peas are commonly consumed as vegetables, whereas soybeans are usually consumed after processing. The fl vor volatiles in beans, peas, and soybeans, as reviewed by Whitfiel and Last (1991), are briefl summarized with the inclusion of more recent information on their aroma and taste characteristics.

The fl vor volatiles in beans vary with the bean type and form (raw or processed). The major fl vor volatiles in canned snap beans are linalool, 1-octen-3-ol, furfural, α-terpineol, (*Z*)-3-hexenol, and pyridine. The major volatile fl vor components of uncooked dry red bean seeds include 1-octen-3-ol, (Z)-5-octen-2-ol, (*Z*)-5-octen-2-one, (*Z*)-3-hexenol, hexanol, and 3,5-octadien-2-one, with 1-octen-3-ol and (*Z*)-3-hexenol believed to be the most important contributors to its aroma. Thialdine, 2-methoxy-4-vinylphenol, 2,4-dimethyl-5-ethylthiazole, and 2-acetylthiazole are considered important to the aroma of cooked dry beans.

A recent study using HS-SPME-GC (headspace solid phase microextraction gas chromatography olfactometry) and SDE-GC-MS (simultaneous distillation extraction gas chromatography mass spectrometry) (Barra et al. 2007) has identifie 104 known and new volatiles in thawed and cooked French beans, including alcohols, aldehydes, ketones, hydrocarbons, terpenoids, heterocyclic compounds, esters, sulfur compounds, and fatty acids. Among the 104 volatiles, 1-octen-3-ol, (*Z*)-3-hexenol, hexanol, 3-octanol, octan-3-one, linalool, α-terpineol, nerolidol, geraniol, 3-ethyl-4-methylpentanol, and (*Z*)-hex-3-enylacetate are believed to be more important to the typical "green odor" of French beans.

The so-called "kokumi" taste compounds have been discovered in both raw and thermally processed beans (Dunkel et al. 2007). The key molecules that induce the taste-modifying effect are identifie as γ-L-glutamyl peptides (γ-L-glutamyl-L-leucine, γ-L-glutamyl-L-valine, and γ-L-glutamyl-L-cysteinyl-β-alanine) isolated from beans. Aqueous solutions of these γ-L-glutamyl peptides possess a faint astringent sensation. When added to a savory matrix such as sodium chloride and MSG solutions or chicken broth, the taste thresholds of these peptides decrease dramatically, while the savoriness is greatly enhanced.

Peas

The major volatile compounds in raw peas are alcohols, carbonyls, and esters. Compounds at high levels are hexanol, propanol, 2-methylpropanol, pentanol, 2- and 3-methylbutanols, and (*Z*)-3-hexenol. GC-O analysis indicates the following most important contributors to the raw pea odor: alkanals, 2-alkenals, 2,4-alkadienals, 2,6-nonadienal, 3,5-octadien-2-one, 2-alkyl-3-methoxylpyrazines, and hexanol. The volatiles are likely to be responsible for the "green" fl vor note of raw pea. In contrast, the major volatiles in blanched/cooked peas are ethanol, dimethyl sulfide (*Z*)-3-hexenol, propanol, hexanol, pentanal, acetaldehyde, 2- and 3-methylbutanals, and 2- and 3-methylbutanols.

Soybeans

Raw soybeans are known to have a beany, bitter, and astringent fl vor, which is generally considered as undesirable. The bitter and

astringent taste is typically attributed to the phenolic acids and flavonoids that naturally occur in soybeans (Marshall 1990).

According to Whitfield and Last (1991), the major classes of volatiles in raw soybeans are alcohols, carbonyls, and monoterpenoids. Volatiles present at high levels are acetic acid, hexanol, pentanol, 3-methylbutanol, acetone, 2-propanol, and α-pinene. In addition, hexanal, nonanal, decanal, 2,4-decadienal, 2-pentylfuran, and 3-(4-methyl-3-penentyl)furan, though present at lower amounts, are also believed to be contributors to the soybean aroma.

A more recent study using SPME-GC-MS has found 49 known and new volatiles and semivolatiles in soybeans, including aldehydes, esters, lactones, alcohols, ketones, terpenoids, and furans (Boue et al. 2003). Hexanal, (*E*)-2-heptenal, (*E*)-2-octenal, ethanol, 1-hexanol, 1-octen-3-ol, 3-hexanone, 3-octanone, and (*E*)-2-hexenal were the most abundant in the volatile extract odor-active volatiles. It is generally accepted that the saturated and unsaturated aldehydes are the key contributors to the green bean-like flavor of raw soybeans.

Processed soybeans in various forms are more commonly consumed than the unprocessed counterparts as part of the main meal in East Asia. Soybeans are processed into various ingredients and products such as soy protein isolates, soy protein hydrolysates, soymilk, tofu (soybean curd), and fermented soy products (sour soymilk, soy yoghurt, soy nuggets, soy sauce, sufu, soybean paste, miso, natto, tempeh) (Liu 2004).

GC-MS and GC-O analyses indicate that the major contributors to the beany odor of soymilk and tofu are hexanal, 1-octen-3-one, (E,Z)-2,6-nonadienal, 2-nonenal, 2,4-decadienal, methional, and β-damascenone (Feng et al. 2001). The beany odor of soymilk and tofu is mainly due to the oxidation of polyunsaturated lipids catalyzed by lipoxygenase during processing and can be reduced or even eliminated by minimum exposure to air and light (Torres-Penaranda et al. 1998; Feng et al. 2001; Min et al. 2005). The beany volatiles can also be decreased by direct steam injection, cyclodextrin trapping, and fermentation with lactic acid bacteria (Suratman et al. 2004; Blagden and Gilliland 2005; Yuan and Chang 2007).

Based on GC-MS and GC-O analyses, the most important odor components of soy protein isolates and hydrolysates include dimethyl trisulfide (*E*,*E*)-2,4-decadienal, 2-pentylpyridine, hexanal, pentanal, octanal, nonanal, 2-pentylfuran, 2-heptanone, (*E*,*E*)-2,4-nonadienal, acetophenone, 1-octen-3-one, and two unidentified volatiles with burnt soy sauce-like and charred sweaty feet-like characters (Boatright and Lei 1999).

Fermentation of soymilk with lactic acid bacteria transforms the flavor and texture of soymilk, resulting in the production of sour soymilk and soy yoghurt (Liu 2004) with lactic acid, acetic acid, ethanol, diacetyl, and other aroma compounds being formed. Lactic acid bacteria can also reduce the levels of beany odor volatiles such as hexanal (Blagden and Gilliland 2005).

The flavor profile of soy sauce is extremely complicated due to its unique manufacturing process involving complex microflora (molds, bacteria, and yeasts) and heat treatment (Huang and Teng 2004). Many flavor compounds are produced during fermentation and heat treatment. Browning of soy sauce is due to Maillard (nonenzymatic) browning, caramelization, and oxidation. In general, soy sauce contains 1.00–1.65% total nitrogen (w/v) (45% as simple peptides and 45% as amino acids), 2–5% reducing sugars (mainly glucose), 1–2% organic acids (mainly lactic acid), 2.0–2.5% ethanol, 17–19% NaCl (w/v) (Huang and Teng 2004). Glutamic and aspartic acids together with NaCl are the major contributors to the umami (savory) taste of soy sauce. Other amino acids such as L-phenylalanine and L-tyrosine can enhance the umami taste of soy sauce in the presence of NaCl and MSG (Lioe et al. 2004).

The chemical nature of soy sauce aroma is very complex, consisting of nearly 300

Table 3.1 Major flavor compounds in soy sauce

Classes	Compounds	Precursors
Alcohols	Isobutanol	Valine
	n-Butanol	Isoleucine
	Isoamyl alcohol	Leucine
	Acetol	Phenylalanine
	Acetoin	Ferrulic acid
	Ethanol	
	Methionol	Methionine
	2-Phenylethanol	
	4-Ethyl guaiacol	
Acids	Acetic acid	Pentoses
	Lactic acid	Hexoses
	Succinic acid	Citric acid
	2-Methylbutanoic acid	Isoleucine
	3-Methylbutanoic acid	Leucine
	2-Phenylacetic acid	Phenylalanine
	Butanoic acid	
	Glutamic acid	
	Aspartic acid	
Aldehydes	2-Methylbutanal	Isoleucine
	3-Methylbutanal	Leucine
	Methional	Methionine
	2-Phenylacetaldehyde	Phenylalanine
	4-Hydroxyl-3-methoxybenzaldehyde	
Esters	Ethyl lactate	Lactic acid
	Diethyl succinate	Succinic acid
	Ethyl 2-methylpropanoate	Fatty acid
	Ethyl 2-methylbutanoate	Valine
	Methyl 2-methylpropanoate	
Furanones	Sotolone	Amino acids and reducing sugars
	HEMF, HDF	
Pyrazines	Methylpyrazine	Threonine
	2,6-Dimethylpyrazine	
Others	2,3-Diethyl-5-pyrazine	
	4-Vinyl-2-methoxylphenol	
	1-Octen-3-one	
	2-Acetyl-1-pyrroline	
	2-Methoxy phenol	
	Bis(2-methyl-3-furyl)disulfide	

Source: Adapted from Huang and Teng (2004) and Steinhaus and Schieberle (2007).

compounds (hydrocarbons, alcohols, acids, esters, aldehydes, terpenes, ketones, acetals, lactones, furanones, pyrones, pyrazines, furans, thiazoles, sulfur compounds, and other compounds) (Huang and Teng 2004). GC-O analyses, odor activity value calculation, and aroma reconstitution have demonstrated 12 key aroma compounds in soy sauce: 3-methylbutanal, 3-hydroxyl-4,5-dimethyl-2(*5H*)furanone (sotolone), 4-hydroxy-5-ethyl-2-methyl-3(*2H*)furanone (4-HEMF), 2-methylbutanal, methional, ethanol and ethyl 2-methylpropanoate, 4-hydroxy-2,5-dimethyl-3(*2H*)-furanone (4-HDF), phenylacetaldehyde, acetic acid, 3-methylbutanoic acid, 2-phenylethanol, and 2-acetyl-1-pyrroline (Steinhaus and Schieberle 2007). The major fl vor compounds in soy sauce are summarized in Table 3.1.

Fermented whole soybean products in China and Japan include soy nuggets or douchi (fermented with molds), and natto (fermented with bacteria, *Bacillus natto*) (Teng et al. 2004a). The taste of douchi is

characterized as being predominantly salty with a moderate umami taste and slight bitterness, where free amino acids (Arg, Glu, Phe, Leu, and Lys) responsible for the bitter and umami taste were found to be the most abundant(Qin and Ding 2007a, 2007b). A total of 122 volatiles are found in douchi, including alcohols, esters, acids, aldehydes, ketones, phenols, sulfur compounds, heterocyclic compounds, alkanes, bezenes, and terpenoids (Qin and Ding 2007b). The major volatiles are ethanol, 1-octen-3-ol, acetic acid, 3-methylbutanoic acid, ethyl acetate, acetaldehyde, 2-phenylpropanal, 2-butanone, diacetyl, guaiacol, dimethyl disulfide methional, propyl disulfide anethole, 2,5-dimethylpyrazine, 2,3,5-trimethylpyrazine, and tetramethylpyrazine. However, the key aroma compounds have not been identifie because studies of the odor activity of these components have not been performed.

Natto from Japan has a fruity/nutty aroma characterized by a strong hydrolyzed protein fl vor without the noticeable ammonia note (Owens et al. 1997). The aroma compounds of natto consist mainly of aldehydes, ketones, and pyrazines (Owens et al. 1997). The major volatiles present are acetoin, 2,5-dimethylpyrazine, and trimethylpyrazine, while other compounds such as nonanal, decanal, 1-octen-3-ol, diacetyl, 3-octanone, 3,6-dimethyl-2-ethylpyrazine, 2-pentylfuran, dimethyl sulfide benzaldehyde, and 2-methoxylphenol are also present in concentrations above their respective odor threshold values. As olfactory information is lacking, the most odor-active compounds are not yet known.

Miso is a type of fermented soybean paste made in Japan. The taste of miso is characterized by peptides, amino acids, and glucose produced by enzymatic hydrolysis of protein and starch, while the brown pigment of miso (melanoidine) is generated during aging as a result of the amino–carbonyl reaction (Ohata et al. 2009). The most odor-active compounds in miso are 4-hydroxy-2(or 5)-ethyl-5(or 2)-methyl-3(*2H*)-furanone, 3-hydroxy-2-methyl-4*H*-pyran-4-one, 2-phenylethanol, 3-methyl butanoic acid, 4-hydroxy-2,5-dimethyl-3(*2H*)-furanone, 3-methylthiopropanal, benzaldehyde, 1-hexanol, 2-methoxylphenol, and 2-furanmethanethiol (Ohata et al. 2009).

A total of 91 volatiles, including aldehydes, alcohols, acids, esters, ketones, pyrazines, sulfur compounds, vinyl phenols, and other compounds were identifie in Korean fermented soybean pastes (Lee and Ahn 2009). The following compounds are quantitatively more important: ethyl hexadecanoate, 2-methylbutanoic acid, 3-methylbutanoic acid, benzacetaldehyde, 2,3,5,7-tetramethyl pyrazine, butanoic acid, 2-furancarboxaldehyde, 2-methylpropanoic acid, and 3-methyl-1-butanol (Lee and Ahn 2009). Quantitatively minor volatiles may be aroma active, but there is a lack of odor activity information identifying the compounds contributing to the odor character of fermented soybean.

Chinese fermented soybean curds (tofu) include sufu (fermented mainly with molds) and stinky tofu (fermented with mainly lactic acid bacteria and bacilli) (Han et al. 2001; Teng et al. 2004b). Sufu has a smooth and sticky texture and is characterized by its salty taste, whereas stinky tofu has a characteristic strong odor of ammonia.

The volatile components of Chinese fermented soybean curds have been the subject of several studies. A total of 111 compounds are found in three commercial fermented soybean curds, with alcohols and esters being the major classes of volatile compounds that dominate with a sweet and fruity fl vor, and with aldehydes, ketones, sulfur compounds, pyrazines, pyridines, and others being present in smaller amounts (Chung 1999; Hwan and Chou 1999). The high levels of alcohols and esters in fermented soybean curds are likely the result of adding rice wine or ethanol to the brine solution, a general practice for maturation of fermented soybean curds (Hwan and Chou 1999).

GC-O analysis and odor activity values determined the most odor-active compounds in red fermented soybean curds to be ethyl 2-methylpropanoate, diacetyl, ethyl butanoate, ethyl 2-methylbutanoate, 3-(methylthio)propanal, benzacetaldehyde, and ethyl 3-phenylpropionate (Chung 2000). In plain (white) fermented soybean curd, the most aroma-active components are acetic acid, methional, ethyl (*Z,Z*)-9,12-octadecadienoate, ethyl (*Z*)-9-octadecenoate, and 3-methylbutanoic acid, according to GC-O, odor activity values, and omission analyses (Chung et al. 2005).

Tempeh is a fermented soybean cake originating from Indonesia. *Rhizopus oligosporus* is the major fermenting mold of tempeh. During fermentation, the fungus produces a range of volatiles that contribute to the aroma of tempeh. Ethanol, acetone, 2-butanone, and 3-methyl-1-butanol were present in the highest concentrations, while other odor-active compounds such as 3-octanone, 1-octen-3-ol, and β-caryophyllene were also detected in smaller amounts (Feng et al. 2007). Further research is required to elucidate the aroma profil of tempeh.

Tuber Vegetables

A number of high-starch plant foods fall into the category of tuber vegetables, and examples are potato, sweet potato, taro, yam, arrowroot, and Jerusalem artichoke. However, this section focuses on potato and sweet potato due to either a lack of space or scant information.

Potato

Raw, intact potato has little odor; once cut, odor develops due to the oxidation of unsaturated fatty acids by lipoxygenases (Figure 3.1). This results in the formation of major odor components such as (*E*,*Z*)-2,4-decadienal, (*E*,*E*)-2,4-heptadienal, (*E*,*Z*)-2,6-nonadienal, (*E*)-2-octenal, hexanal, heptanal, 1-penten-3-one, 2-pentyl furan, and 1-pentenol (Christensen et al. 2007). Methional and (*E*,*Z*)-2,6-nonadienal are regarded as representing the typical raw potato odor (Christensen et al. 2007). Detailed information on potato aroma compounds is available elsewhere (Whitfiel and Last 1991; Christensen et al. 2007). A recent study suggests that the umami character is also an important component of potato fl vor, characterized by high contents of glutamate, aspartate, and 5′-nucleotides GMP and AMP (Morris et al. 2007).

Sweet Potato

Sweet potato is well known for its sweetness, which is due to the presence of sucrose, glucose, and fructose, as well as maltose that results from starch degradation during cooking (Truong et al. 1986; Horvat et al. 1991). Of all the sugars, maltose is the principal sugar produced during cooking (Horvat et al. 1991). A recent study has identifie seven new aminoacyl sucrose derivatives in sweet potato (Dini et al. 2006). Some aminoacyl sugars are known to be sweet and further work is required to evaluate the taste characteristic and potency of these newly discovered aminoacyl sucrose derivatives and to assess their contribution to the sweetness of sweet potato.

Raw sweet potato possesses little aroma. However, baked or roasted sweet potatoes emit a pleasant aroma, especially during cooking. The quantitatively major components of this characteristic aroma are 2-furaldehyde, 2-furanmethanol, benzaldehyde, phenylacetaldehyde, 5-methyl-2-furaldehyde, 3-hydroxy-2-methyl-4*H*-pyran-4-one (maltol), 2,3-dihydro-3,5-dihydroxy-6-methyl-4*H*-pyran-4-one, and 5-hydroxymethyl-2-furancarboxaldehyde (Purcell et al. 1980; Tiu et al. 1985; Sun et al. 1993, 1995). Further research using GC-O is required to establish the relative importance of each aroma compound to the aroma of baked sweet potatoes.

Root Vegetables

Root vegetables are diverse, including such vegetables as carrots, beetroot, radish, horseradish, parsnip, rutabaga (or Swedish turnip), turnip, and cassava. However, only carrots and radish are considered in this section as they are the more common of the root vegetables and recent studies on them have not been reviewed in the literature. Information on other root vegetables can be obtained elsewhere (Whitfiel and Last 1991).

Carrot

Carrot, raw or cooked, has a pleasant fl vor. Fructose, glucose, and sucrose are the main sugars that contribute to the sweetness of carrot, while some minor carbohydrates are also present (inositol, mannitol, and sedoheptulose or D-*altro*-2-heptulose) (Soria et al. 2009).

Potential bitter compounds in carrot are polyacetylenes, isocoumarins, and phenolic acids, which contribute varying extents of bitterness (Kreutzmann et al. 2008a). For example, falcarindiol and a di-caffeic acid (both present in the peel) have more significan bitter taste perceptions in comparison to falcarinol (distributed in the root) and other potential bitter compounds (Kreutzmann et al. 2008a).

A recent study showed that disruption of carrot matrix by freeze treatment resulted in a change in texture and decrease in carotene content (Berger et al. 2008). In another interesting study, it was found that carrot colors relate to their sensory profiles with orange carrots exhibiting more intense carrot fl vor and aroma in comparison to yellow carrots, whereas purple carrots display stronger sweet taste and nutty aroma, and red carrots impart higher intensities of green odor and a bitter and burning aftertaste (Kreutzmann et al. 2008b).

The carrot aroma is contributed mainly by terpenoids, which consist of monoterpenes, sesquiterpenes, and irregular terpenes. The key aroma compounds in carrot are *p*-cymene, limonene, β-myrcene, sabinene, terpinolene, γ-terpinene, β-caryophylene, (*E*)-γ-bisabolene, β-bisabolene, and α-pinene (Christensen et al. 2007; Kreutzmann et al. 2008b; Soria et al. 2008). The main non-terpenoid volatiles in carrot are 3-hydroxy-2-butanone, ethanol, hexanal, acetic acid, and *erythro*- and *threo*-2,3-butanediol (Soria et al. 2008) which are odor active and may also contribute to the carrot aroma.

Radish

White radish, otherwise known as Luo Bo in Chinese (Chinese white radish) or daikon in Japanese, is consumed raw, cooked, brined, fermented, or dried in East Asia. It is generally accepted that 4-methylthio-3-*trans*-butenyl isothiocyanate, derived from the hydrolysis of 4-methylthio-3-*trans*-butenyl glucosinolate by myrosinase, is primarily responsible for the characteristic pungent aroma of white radish (Coogan et al. 2001; Suzuki et al. 2006).

A recent study shows that the major sulfur-containing aroma components in black, white, and red radishes are 4-methylthio-butyl isothiocyanate, rather than the previously reported 4-methylthio-3-*trans*-butenyl isothiocyanate (Blazevic and Mastelic 2009). This discrepancy could be due to varietal differences, as different radish varieties likely contain different glucosinolates, which in turn can produce different volatiles upon degradation. Other relatively minor sulfur-containing aroma components identifie by this study are 5-methylthio-pentyl isothiocyanate, dimethyl trisulfide 2-phenylethyl isothiocyanate, and 5-methylthio-(*E*,*Z*)-4-pentenenitrile.

Bulb Vegetables

Garlic, onion, leek, shallot (scallion), and chive in *Allium* species are the major bulb vegetables, which also include Chinese shallot (Chinese spring onion or Welsh onion, *A. fistulosu*) and Chinese chive (*A. tuberosum*).

Table 3.2 Key sulfur-containing flavor compounds in bulb vegetables

Occurrence	Compounds
Onion	Dipropyl disulfide methyl (*E*)-propenyl disulfide propyl (*E*)-propenyl disulfide methyl propyl trisulfide dipropyl trisulfide propyl methanethiosulfonate, thiopropanal-*S*-oxide, γ-glutamyl-*trans*-*S*-propenyl-L-cysteine sulfoxide
Garlic	Methyl 2-propenyl disulfide di-2- propenyl disulfide dimethyl trisulfide di-2- propenyl trisulfide methyl 2-propenyl trisulfide alliin, γ-glutamyl-*S*-allyl-L-cysteine sulfoxide, 3-(*S*)-methyl-1,4-thiazane-5-(*R*)-carboxylic acid 1-oxide
Leek	1-Propanethiol, dipropyl disulfide methyl (*E*)-propenyl disulfide propyl (*E*)-propenyl disulfide dipropyl trisulfid
Shallot	Dipropyl disulfide propyl (*E*)-propenyl disulfide methyl propyl trisulfide dimethyl trisulfide dipropyl trisulfid
Chive	Dipropyl disulfide methyl propyl disulfide 1-propenyl propyl disulfid (*E*/*Z*), dimethyl disulfide 2-propenyl propyl disulfide dipropyl trisulfid

Source: Adapted from Ueda et al. (1990), Whitaker and Mazelis (1991), Whitfiel and Last (1991), Leino (1992), Ueda et al. (1994), and Christensen et al. (2007).

The volatile fl vor compounds and the biochemistry of their formation in bulb vegetables (Figure 3.2), garlic and onion in particular, have been studied intensively and have been reviewed previously (Whitaker and Mazelis 1991; Whitfiel and Last 1991; Fisher and Scott, 1997) and more recently by Christensen et al. (2007). The major fla vor precursors are mainly sulfur-containing amino acid derivatives and peptides, which vary from one *Allium* species to another. However, due to their similarities in properties and modes of genesis, they will be discussed together in this section.

The major precursors in onion and leek are *S*-1-propenyl-cysteine sulfoxide and *S*-1-propenyl-γ-glutamyl sulfoxide, whereas the main fl vor precursor in chive is *S*-1-methyl-cysteine sulfoxide and *S*-1-methyl-γ-glutamyl sulfoxide. On the other hand, the principal fl vor precursor in garlic is *S*-2-propenyl-cysteine sulfoxide (*S*-allyl-L-cysteine sulfoxide). The fl vor precursors in Chinese shallot and Chinese chive are presumably similar to those in shallot and chive, but further study is required to verify this.

Upon maceration of bulb vegetables, the enzymes alliinases that are released act on the precursors to produce unstable intermediate sulfenic acids, which rearrange or condense to form numerous odorous sulfur-containing compounds (Figure 3.2). The key odor compounds in bulb vegetables are the sulfur-containing volatiles, which are summed up in Table 3.2. Similar sulfur-containing aroma compounds are assumed to be present in Chinese shallot and Chinese chive, but confirmatio studies are needed.

The lachrymatory factor thiopropanal-*S*-oxide present in raw onion, but not in garlic, is assumed to be absent in shallot (Whitfiel and Last 1991; Christensen et al. 2007). Cut Chinese shallots cause tears and thus likely contain thiopropanal-*S*-oxide or similar lachrymatory compounds. Further research is needed in this area.

Much research attention has been directed at the odor components of bulb vegetables, while taste components generally attract less research interest. Onion contains significan levels of sugars fructose, glucose, and sucrose, which contribute to the sweetness (Davis et al. 2007). Onion also contains signifi can concentrations of glutamic, citric, and malic acids, which contribute to the umami taste and acidity (Galdon et al. 2008). Information on taste compounds in other bulb vegetables is scarce.

The so-called kokumi taste compounds, which enhance mouthfeel, continuity, and thickness, have been identifie in garlic and onion (Ueda et al. 1990, 1994). These

Table 3.3 Character-impact flavor compounds in herbs and spices

Occurrence	Compounds
Aniseed	*trans*-Anethole, methyl chavicol
Basil	Estragole (methylchavicol), linalool
Caraway	D-carvone
Cardamom	α-Terpinyl acetate, linalool, 1,8-cineole
Cinnamon	*trans*-Cinnamaldehyde, eugenol
Clove	Eugenol, eugenyl acetate
Coriander	D-linalool, *trans*-dodecenal, geraniol
Cumin	Cuminaldehyde, *p*-1,3-menthadien-7-al
Dill	(*S*)-α-Phellandrene, 3,9-epoxy-*p*-menth-1-ene
Eucalyptus	1,8-Cineole (eucalyptol)
Fennel	*trans*-Anethole, fenchone
Fenugreek	Sotolone
Ginger	Gingerols
Horseradish	1-Peten-3-one, 4-pentenyl isothiocyanate
Lavender	Linalool, linalyl acetate
Laurel	Methyleugenol, eucalyptol
Mace	α-Pinene, sabinene
Marjoram	Terpinen-4-ol, sabinene
Mustard	Allyl isothiocyanate
Oregano	Carvacrol, linalool
Black pepper	α-*trans*-, *cis*-Bergamotene
Nutmeg	Sabinene, α-pinene, myristicin
Parsley	p-Mentha-1,3,8-triene, (*Z*)-hex-3-enal, myrcene, 2-sec-butyl-3-methoxypyrazine, myristicin, linalool, (Z)-dec-6-enal
Peppermint	L-Menthol, menthone
Rosemary	Verbenone, 1,8-cineole, camphor, linalool
Spearmint	L-carvone
Saffron	Safranal, 2-hydroxy-4,4,6-trimethyl-2,5-cyclohexadien-1-one
Sage	α-Thujone, 1,8-cineole, camphor
Tarragon	Methylchavicol, *trans*-anethole
Turmeric	Turmerone, zingeriberene, 1,8-cineole
Thyme	Thymol, carvacrol, *p*-cymene
Wintergreen	Methyl salicylate
Vanilla	Vanillin

Source: Adapted from Blank et al. (1992), Venskutonis (1997), Masanetz and Grosch (1999), McGorrin (2002), Diaz-Maroto et al. (2005), Lachowicz et al. (1997), Zeller and Rychlik (2006), Carmona et al. (2007), Lindsay (2007), Perez et al. (2007), and Da Porto et al. (2009).

compounds are sulfur-containing peptide derivatives such as alliin, γ-glutamyl-*S*-allyl-L-cysteine sulfoxide, and 3-(*S*)-methyl-1,4-thiazane-5-(*R*)-carboxylic acid 1-oxide in garlic, and *trans*-*S*-propenyl-L-cysteine sulfoxide and its γ-glutamyl peptide in onion. These sulfur-containing peptide derivatives significantl enhance the kokumi fl vor of an umami (savory) solution of MSG and IMP (for garlic and onion), and soups (only garlic).

Herbs and Spices

Herbs and spices often contain character-impact fl vor compounds that impart unique sensory attributes (Table 3.3). Some herbs and spices do not have a specifi character-impact compound and their sensory identity is contributed by a mixture of several fl vor compounds. For example, the aroma of mango ginger is composed of a mixture of character-impact fl vor compounds of raw mango and turmeric including *cis*- and *trans*-dihydroocimene, ocimene, and myrcene (Rao et al. 1989).

Herbs and spices also contain other volatiles that collectively and synergistically contribute to their balanced and more rounded fl vor. For example, the dill fl vor is mainly contributed by (*S*)-α-phellandrene, but is

Table 3.4 Major flavor compounds in some edible fungi

Occurrence	Compounds
Agaricus bisporus	1-Octen-3-ol, 1-octen-3-one, 3-octanone, (*E*)-2-octenol
Garlic *Marasmius*	Dimethyl disulfide 2,3,5-trithiahexane, dimethyl trisulfide benzaldehyde, 3-methylbutanal
Pine mushrooms	1-Octen-3-one, ethyl 2-methylbutyrate, linalool, methional, 3-octanol, 1-octen-3-ol
Agaricus subrufecens	Benzyl alcohol, benzaldehyde, benzonitrile, methyl benzoate
Oyster mushroom	1-Octen-3-ol, 1-octen-3-one, benzaldehyde, anisaldehyde, 3-methyl-1-butanol, 3-methyl-1-propanol
Polyporus tuberaster	Benzaldehyde, 3-methylbutanol
Shiitake mushroom	Lenthionine, 1,2,4,5-tetrathiane, 1,2,4-trithiolane, 1-octen-3-ol
White truffl	Methyl sulfid
Beefsteak fungus	1-Octen-3-one, 1-octen-3-ol, linalool, phenylacetaldehyde, phenylacetic acid, butanoic acid, bisabolol oxide B, (E)-methyl cinnamate, (E)-2-methyl-2-butenoic acid, methyl (Z)-9-hexadecenoic acid

Source: Adapted from Whitfiel and Last (1991), Kawabe and Morita (1993), Rapior et al. (1997), Venkateshwarlu et al. (2000), Venkateshwarlu et al. (2001), Wu et al. (2005), Cho et al. (2006), Cho et al. (2007), and Chen and Wu (2007).

rounded off by an additive effect of dill ether (Blank et al. 1992).

Herbs and spices are commonly sold in dried forms. The drying process and methods have a dramatic effect on the fl vor quality of herbs and spices. Drying decreases certain fl vor compounds, while increasing the levels of other compounds due to loss and chemical transformation. For example, drying the spearmint decreases the herbaceous and flora notes due to substantial losses in oxygenated terpenes and sesquiterpenes, and increases the minty odor due to the release of higher quantities of monoterpenes and carvone from the affected cell structure (Diaz-Maroto et al. 2003). Microwave drying allows a better retention of color and aroma than traditional drying methods, as demonstrated with basil (Di Cesare et al. 2003). The extent of loss and chemical changes due to drying is dependent on the botanical structure of herbs and spices, as shown by drying thyme and sage (Venskutonis 1997).

An alternative to drying is the extraction of essential oils from herbs and spices. Essential oils provide microbiological stability and fla vor profile that resemble but are not identical to those of fresh herbs and spices. An example is the volatile components of ginger oil in which β-zingiberene is most abundant (Chen and Ho 1988). The plant parts from which essential oils are extracted influenc the volatile composition and preference of the resultant oils such as basil essential oil (Sheen et al. 1991).

The composition of essential oils is greatly affected by extraction methods, both qualitatively and quantitatively, as in the case of lavender oil (Da Porto et al. 2009), fennel, and thyme oil extracts (Diaz-Maroto et al. 2005). High temperature during hydrodistillation can result in the formation of high levels of certain volatiles such as 1-octen-3-ol, which is only present at low levels in the herbal plant of *Melittis melissophyllum* L. subsp. *melissophyllum* (Lamiaceae) (Maggi et al. 2009).

Edible Fungi

Edible fungi include mushrooms and nonmushrooms; examples of the latter include truffle and beefsteak fungus (or ox-tongue fungus). The major classes of fl vor compounds found in edible fungi are alcohols, carbonyls, hydrocarbons, sulfur compounds, nitrogen-containing heterocyclic compounds, and the *N*-formyl-*N*-methylalkanal hydrazones (Whitfiel and Last 1991). This section focuses on the fl vor of mushrooms while touching briefl on nonmushrooms. The major fl vor compounds in some edible fungi are summed up in Table 3.4.

The fl vor of mushrooms is composed of both nonvolatile taste components and volatile aroma components. The characteristic mushroom aroma compound is 1-octen-3-ol with some contributions from 1-octen-3-one and 3-octanone (Hadar and Dosoretz 1991; Whitfiel and Last 1991; Zawirska-Wojtasiak 2004). However, some mushrooms such as *Polyporus tuberaster* and *Agaricus subrufecens* contain low levels of 1-octen-3-ol but high levels of aromatic compounds (benzaldehye, benzyl alcohol, etc.) with an almond-like aroma (Kawabe and Morita 1993; Chen and Wu 2007).

Interestingly, high-quality pine mushrooms are closely associated with ethyl 2-methylbutyrate, (*E*)-2-decenal, α-terpineol, and 2-phenylethanol, while low-quality pine mushrooms are strongly linked with 1-octen-3-one, 1-octen-3-ol, 3-octanone, 3-octanol, (E)-2-octen-1-ol, and methional (Cho et al. 2006, 2007), suggesting the positive role of "nonmushroom aroma compounds" in mushroom fl vor.

The sulfur-containing lenthionine is considered the character-impact aroma compound of shiitake mushroom, whereas methylenebis (methyl sulfide is the principal odor component of the white truffl (Whitfiel and Last 1991). The strong garlicky odor of a small mushroom (garlic *Marasmius*) is characterized by high concentrations of volatile sulfur fl vor compounds of dimethyl disulfide 2,3,5-trithiahexane, and dimethyl trisulfide plus relatively high levels of benzaldehyde and 3-methylbutanal (Rapior et al. 1997).

The characteristic odor compounds of the fruiting bodies of wild beefsteak fungus contain not only the typical mushroom aroma compounds 1-octen-3-ol and 1-octen-3-one, but also some sweet, fruity, and flora compounds such as linalool, phenylacetaldehyde, phenylacetic acid, bisabolol oxide B, and (*E*)-methyl cinnamate (Wu et al. 2005), indicating the importance of "nonmushroom fl vor compounds" in the fl vor of edible fungi.

Much research attention has been directed at the nonvolatile taste components of edible mushrooms. The taste of mushrooms is mainly attributed to several classes of water-soluble compounds including carbohydrates, organic acids, amino acids, and 5′-nucleotides, which collectively contribute to the sweetness and umami taste of mushrooms. The profil and concentration of taste-active nonvolatile components vary with mushroom species and are generally found at low concentrations.

The taste of mushrooms is the result of interactions among carbohydrates, amino acids, 5′-nucleotides, and organic acids. Among the amino acids, L-glutamic acid and L-aspartic are the most important umami taste contributors, and 5′-nucleotides exert a taste-enhancing effect. A recent study has identifie two umami taste-contributing compounds, (*S*)-malic acid 1-*O*-D-glucopyranoside and γ-aminobutyric acid (GABA), in morel mushrooms (Rotzoll et al. 2005). GABA has a very low taste threshold concentration of 0.02 mmol/L for its mouth-drying and mouth-coating oral sensations. It is likely that Glu, Asp, and GABA interact in synergy to impart the umami taste to mushrooms. Indeed, GABA is widely present in mushrooms (Chiang et al. 2006; Tsai et al. 2007, 2009; Kalac 2009; Kim et al. 2009).

Detailed information on the nonvolatile taste components of edible mushrooms is available elsewhere and will not be discussed in detail (Chang et al. 2001; Mau et al. 2001a, 2001b; Yang et al. 2001; Tseng et al. 2005; Huang et al. 2006; Tsai et al. 2006; Guo et al. 2007; Lee et al. 2009).

Fresh-cut Vegetables

Flavor and sensory characteristics are an integral part of the quality parameters of fresh-cut vegetables. To date, little fl vor and sensory research has been done specificall on this category of vegetables. Thus, there is a lack of information on compounds or compound

classes of fresh-cut vegetables. The fl vor and textural aspects of fresh-cut vegetables have been reviewed (Beaulieu and Baldwin 2002; Lamikanra 2002), and much information on fl vor discussed discussed in the two review articles are derived from those compounds considered as naturally occurring (i.e., endogenous). Fresh-cutting is a form of processing and is expected to impact on secondary compound production and, consequently, fla vor and texture of fresh-cut vegetables. The focus of this section is on the impact of fresh-cutting on the fl vor and sensory attributes of fresh-cut vegetables based on the review articles by Beaulieu and Baldwin (2002) and Lamikanra (2002).

Enzymes and substrates are normally compartmentalized in plant tissues. Cutting results in tissue disruption and allows mixing of enzymes and substrates. The interactions between enzymes and substrates cause changes to fl vor, color, and texture of fresh-cut vegetables, such as formation of off-odor, discoloration, and loss of firmnes (softening of tissue). A well-known example is aroma generation upon cutting onion and shallot.

The main enzymes that affect fl vor, color, and texture of fresh-cut vegetables are lipoxygenase (LOX), peroxidase (POD), polyphenol oxidase (PPO), and pectolytic enzymes (PEs). LOX catalyzes the oxidation of polyunsaturated fatty acids (PUFA) in the presence of oxygen, leading to the formation of volatile aldehydes of C6 to C9 with "green" and "grassy" fl vor notes. LOX is particularly notable in cucumber, tomato, broccoli, and green leafy vegetables. POD is widely distributed in vegetables and is believed to cause fl vor changes in vegetables based on an empirical relationship between residual POD activity and off-fl vors. Surprisingly, little information is available on the reactions involved. POD also causes browning by its affinit to accept a wide range of hydrogen donors such as phenolic compounds. PPO is well known to cause browning in vegetables such as lettuce and mushroom in the presence of oxygen by oxidizing polyphenols to quinones. PEs consist of polygalacturonase, lyases, and pectinesterase. Together these enzymes are responsible for the breakdown of pectins, resulting in tissue softening and loss of firmnes in vegetables such as tomato.

Many factors can affect fl vor and sensory properties of fresh-cut vegetables such as storage temperature, packaging, sanitation, and processing techniques. In light of the role of oxygen in off-fl vor formation and discoloration, modifie atmosphere packaging (MAP) is expected to improve fl vor and color of fresh-cut vegetables. Indeed, MAP is widely used for fresh-cut vegetables, although occasionally it can cause off-fl vor and discoloration due to undesirable gaseous composition. A recent study demonstrates that irradiation of up to 1 kGy has no adverse effects on the appearance, texture, and aroma of 13 common fresh-cut vegetables while improving microbial safety (Fan and Sokorai 2008).

As discussed above, enzymes play a crucial role in the changes in fl vor, color, and texture of fresh-cut vegetables, and consequently, inactivation of enzymes is expected to help maintain or delay changes to these sensory quality parameters. Heat treatment such as blanching is not desirable as it can cause damages to sensory properties. Chemical treatments such as applying calcium salts have been proposed as a way of inhibiting enzymatic browning, but this can impart off-fl vors. On the other hand, to the best of our knowledge, little research has been done on the application of nonthermal processes such as high-pressure and pulsed-electric fiel to fresh-cut vegetables with regard to enzyme inactivation. This area should be fruitful for future research.

Fermented Vegetables

This section is not designed to provide detailed information on the microorganisms involved in and the principles and processes of vegetable fermentation. Rather, this section

intends to summarize the effects of fermentation on the fl vor and sensory properties of vegetables. For simplicity and due to the commonality of fermentations involved, fermented leafy vegetables and pickles are listed under this single heading.

Fermented leafy vegetables include well-known sauerkraut and kimchi, as well as less-known pickled (fermented) Chinese leafy vegetables such as leaf mustard, potherb mustard, and pak choi or Chinese cabbage (Chiou 2004; Li 2004; Zhao et al. 2007; Harbaum et al. 2008). Pickles refer mainly to fermented cucumber and table olives. The common feature of these fermented vegetables is that fermentation is carried out by lactic acid bacteria (LAB), resulting in significan biotransformation of fl vor and sensory characteristics of raw vegetables.

The major LAB involved in vegetable fermentation include homo- and heterofermentative lactobacilli, heterofermentative leuconostocs, and homofermentative pediococci (Li 2004). The four LAB most frequently associated with vegetable fermentation are *Leuconostoc mesenteroides*, *Pediococcus cerevisiae*, *Lactobacillus brevis*, and *Lb. plantarum*. Vegetable fermentation is usually initiated by *Leu. mesenteroides* and ends with *Lb. plantarum*.

Vegetables contain sufficien amounts of fermentable sugars, organic acids, and amino acids for the growth and metabolism of LAB (Li 2004). For example, cabbage contains about 4.7% total sugars (2.38% glucose, 2.05% fructose, and 0.25% sucrose) (Hang 2004). The biotransformation of these substrates by LAB impacts significantl on the fl vor and sensory properties of vegetables.

Sugars are converted into lactic acid, the major organic acid that imparts a sharp tart taste to fermented vegetables, in addition to the production of aroma compounds acetic acid and ethanol, and CO_2. Citrate degradation results in the formation of lactic acid, acetic acid, diacetyl (buttery), and CO_2. Malate decarboxylation to lactate and CO_2 can cause undesirable bloating in fermented cucumbers (Li 2004).

Fructose, whether in free form or derived from sucrose, is converted by heterofermentative LAB such as *Leu. mesenteroides* into not only lactic acid, but also CO_2, acetic acid, and mannitol, which is a sweetener (Yun and Kim 1998; Wisselink et al. 2002; Li 2004). However, mannitol is a fermentable substrate for *Lb. plantarum*, which can metabolize mannitol into lactic acid, as well as acetic acid, succinic acid, and ethanol in the presence of citrate (Chen and McFeeters 1986a, 1986b; McFeeters and Chen 1986). The amount of mannitol accumulated in fermented vegetables is dependent on the extent of growth of *Lb. plantarum*. In kimchi, where there is no overgrowth of this LAB, mannitol is accumulated up to 0.4–0.5% of kimchi (Yun et al. 1996; Li 2004). In sauerkraut and pickle, where overgrowth of *Lb. plantarum* occurs, mannitol is accumulated to a lesser extent (Li 2004; Hang 2004; Johanningsmeier et al. 2007).

Yeasts may be present in significan numbers in the later stages of vegetable fermentation (Park and Cheigh 2004), producing pectic enzymes that soften vegetable tissues, affecting texture. Yeasts can also produce volatile compounds, influencin fl vor. However, little research has been done in this area.

Volatiles in fermented vegetables have been relatively understudied, given the availability of SPME-GC-MS and GC-O in recent years. The greatest impacts on kimchi and sauerkraut fl vors are the sour and sulfur notes. The major aroma components of kimchi include acetic acid, ethanol, methyl allyl sulfide dimethyl disulfide camphene, 1-phellandrene, diallyl disulfide methyl allyl trisulfide amongst several others (Park and Cheigh 2004). The main aroma compounds in sauerkraut are hydrogen sulfide methanethiol, dimethyl sulfide carbon disulfide dimethyl disulfide allyl isothiocyanate, dimethyl trisulfide methanol, ethanol, *n*-propanol, 2-propanol, acetaldehyde, and ethyl

acetate (Trail et al. 2007). Zhao et al. (2007) detected a wide range of volatile components in fermented potherb mustard, including acids, sulfides alkenes, aldehydes, ketones, alcohols, phenols, esters, isothiocyanates, nitriles, and heterocyclic compounds.

The volatile odor components of fermented cucumber are far more complex than those of its fresh counterpart, containing not only aldehydes, but also alcohols, sulfides and esters (Zhou et al. 2000; Palma-Harris et al. 2002). Exposure of fermented cucumber to oxygen increases production of both saturated and *trans*-unsaturated aldehydes such as hexanal, heptanal, pentanal, (*E*)-2-pentenal, (*E*)-2-hexenal, (*E*)-2-heptenal, and (*E*)-2-octenal (Zhou et al. 2000; Cleary and McFeeters 2006), resulting in the formation of oxidized off-odors. Thus, exclusion of oxygen is crucial to minimize the formation of oxidized off-odors by packaging fermented cucumbers in oxygen-impermeable containers.

Table olives are fermented olives consumed as vegetables popular in the Mediterranean countries. Glucose and fructose (and mannitol) are the main sugars in fresh olives, which are greatly reduced in table olives due to the transformation by lactic acid bacteria and yeasts into lactic and acetic acids (Lopez-Lopez et al. 2007). Olive fruit has a bitter component—oleuropein, a glucoside, which can be degraded by fermentation or oxidation (Garcia et al. 2008).

Good quality table olives have a pleasant fruity aroma, which is affected by many factors. The key influenc arises from the metabolic activities of microflor involved in olive fermentation—predominantly lactic acid bacteria and yeast (Arroyo-Lopez et al. 2008; Sabatini et al. 2008). The major volatile compounds in table olives are 2-butanone, ethanol, ethyl acetate, propyl acetate, ethyl propanoate, 2-butanol, 1-propanol, isopentanol, *cis*-3-hexen-1-ol, and acetic and propionic acids (Panagou and Tassou 2006; Sabatini and Marsilio 2008; Sabatini et al. 2008).

In another recent study involving GC-O analysis, it was found that the main contributors to the aroma of table olives were (*Z*)-3-hexenal, methional, guaiacol, (*E*)-2-decenal, (*E*,*Z*)-2,4-decadienal, and (*E*,*E*)-2,4-decadienal (Collin et al. 2008). This study also identifie 2-methyl-3-furanthiol, 2,3-dimethylpyrazine, ethyl decanoate, δ-deca lactone, γ-decalactone, and γ-dodecalactone as the additional key aroma compounds in black table olives (Collin et al. 2008).

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Chapter 4

Genetic Engineering of Vegetable Crops

Jiwan S. Sidhu and Sudarshan Chellan

Introduction

According to the World Health Organization (WHO), low intake of vegetables and fruits is one of the top ten risk factors for diseases leading to nearly 2.6 million deaths worldwide every year (Clemens and Dubost 2008). Increased nutritional importance of vegetables has generated interest in improving agricultural practices including use of biotechnology and genetic engineering to enhance yield, drought resistance, insect resistance, and quality (Southon and Faulks 2002; Dalal et al. 2006; Yonekura-Sakakibara and Saito 2006). The use of genetic engineering has, however, led to controversies and opposition to genetically modifie (GM) foods (Varzakas et al. 2007; Dona and Arvanitoyannis 2009). Among the commercialized GM foods, soybeans, maize, cotton, and canola are the important crops being grown widely. In addition, GM varieties of rice, squash, cucumber, onion, cabbage, papaya, sugar beets, sweet pepper, hot pepper, eggplant, carrot, potato, and tomato are in various trial phases. The firs generation of genetically engineered crops improved resistance to herbicides, insects, viruses, and diseases. The second-generation GM foods have improved nutritional quality and lowered allergen levels. The third-generation GM plants have focused on the production of antibodies, vaccines, and pharmaceuticals. This chapter will discuss the main aspects and issues related to genetic engineering of vegetables.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Genetic Engineering

Improvement of crops by the conventional plant breeding techniques has been taking place for many years. However, often these techniques have limitations and are time consuming. Genetic engineering is a molecular biology approach to improve crops by transforming their genetic makeup and producing unique varieties or traits that are not easily obtained through conventional breeding techniques. These products are often referred to as transgenic, bioengineered, or genetically modifie (GM) because they contain foreign genetic material. The products of transgenetic engineering are often called genetically modifie organisms, or GMOs. GM/GMOs refer to the methods by which biologists splice genes from one or more species into the DNA of crops in an attempt to transfer chosen genetic traits. The method is known as recombinant DNA technology. Genes are segments of DNA that contain information that in part determines the end function of a living organism. Genetic engineers direct DNA typically by taking genes from one species and inserting them into another species, such as an agricultural crop. An intermediate organism or virus can be used to "infect" the host DNA with the desired genetic material. Microparticle bombardment technology and electroporation technique can also be used to transfer the genes into the

plant cells. Genetic engineering can play an important role in achieving food security.

The genetic engineering technology can reduce the time required for the development of new varieties of crops from a normal cycle of 10–15 years to about 2–3 years (Rommens 2007). However, to be acceptable, there is a need for proper scientifi enquiry and testing and safety validation of newly expressed proteins for toxicity, allergen, and other safety concerns (Paoletti and Pimentel 1996).

As the world population is expected to reach 9 billion by 2050, traditional agricultural technologies will be inadequate to feed the growing human population (Ramon et al. 2008). Genetic engineering will likely become the main engine of growth of sustainable agriculture and human-friendly environment.

Abiotic Stress Tolerance Improvement

Globally, approximately 22% of the agricultural land is saline (FAO 2004), and areas under drought are expected to increase (Burke et al. 2006). Abiotic stresses such as drought, salinity, and extreme temperatures have adverse effects on the growth and productivity of crops including vegetables. Drought and salinity are becoming particularly widespread in many regions and may cause serious salinization of more than 50% of all arable lands by the year 2050 (Bray et al. 2000). Drought and salt stress, together with extreme temperatures, lead to a series of morphological, biochemical, and molecular changes affecting plant growth and productivity (Wang et al. 2001). To achieve tolerance for abiotic stresses, three interconnected aspects of plant activities must be taken care of, namely, damage must be prevented or alleviated, homeostatic conditions must be reestablished in the new environment, and growth must be resumed (Zhu 2001). Recent molecular and genetic studies have revealed that the stress-induced expression of a variety of genes functions not only in stress tolerance but also in the regulation of gene expression and signal transduction (Yamaguchi et al. 2002; Shinozaki et al. 2003).

Drought Resistance

Drought resistance refers to the ability of a plant to produce in a water-defici environment. The signal transduction events that occur during drought stress have been reviewed (Shinozaki et al. 2003). In contrast to ion homeostasis, a plant's adaptation to drought is to a greater extent under transcriptional control regulated by abscisic acid (ABA). The mechanism of drought resistance can be grouped into three categories: (1) drought escape, (2) drought avoidance, and (3) drought tolerance (Levitt 1972). However, plants use more than one mechanism at a time to resist drought. Drought escape is the ability of the plant to complete its life cycle before severe soil and water deficit develop. Drought avoidance is the ability of plants to maintain relatively high tissue water potential despite a shortage of soil moisture, whereas drought tolerance is the ability to withstand water defici with low tissue water potential. Mechanisms for improving water uptake, storing in plant cell, and reducing water loss confer drought avoidance. The responses of plants to tissue water defici determine their level of drought tolerance.

The mechanisms of drought tolerance are maintenance of turgor through osmotic adjustment, increase in elasticity and decrease in cell size, and desiccation tolerance by protoplasmic resistance (Sullivan and Ross 1979). Unfortunately, most of these adaptations to drought have disadvantages. A genotype of short duration usually yields less compared to that of normal duration. The mechanisms of drought avoidance usually result in reduced assimilation of carbon dioxide. Osmotic adjustment increases drought resistance by manipulating plant turgor, but the increased solute concentration responsible for osmotic adjustment may have detrimental effect in addition to energy requirement for osmotic

adjustment. Consequently, crop adaptation must reflec a balance among escape, avoidance, and tolerance while maintaining adequate productivity.

Many genes are involved in drought resistance (Wang et al. 2003). The identifica tion of genes responsible for morphological and physiological traits and their location on chromosomes have not been possible, but their inheritance pattern and nature of gene action have been reported. Polygenic inheritance of drought resistance is reported in rice, and drought resistance controlled by a single gene in cowpea is also reported (Tomar and Prasad 1996; Mai Kodomi et al. 1999). Metabolic pathways involving the synthesis of different metabolites such as polyamine, carbohydrate, proline, glycine betaine, and trehalose have been shown to be associated with drought resistance.

In response to drought stress, both RNA and protein expression profile change. Approximately 130 drought-responsive genes have been identifie using microarrays (Reymond et al. 2000; Seki et al. 2001). These genes are involved with transcription modulation, ion transport, transpiration control, and carbohydrate metabolism. *DREB1A* and *CBF*, and *HSF* genes are transcription factors implicated in drought and heat response, respectively (Sakuma et al. 2002; Sung et al. 2003). Cell wall invertase (*INV*) and sucrose synthase (*SUSY*) play key roles in carbohydrate partitioning in plants (Déjardin et al. 1999), and this regulation of carbohydrate metabolism in leaves may represent part of the general cellular response to acclimation and contribute to osmotic adjustment under stress. The *ERECTA* gene regulates plant transpiration efficien y in *Arabidopsis thaliana* (Masle et al. 2005), and the *NHX* and *AVP1* genes are associated with ion transport (Zhang and Blumwald 2001).

There are many more genes implicated with stress response and the current challenge is to identify the ones that confer a tolerant phenotype in the crop of interest. Although the function of these genes has been elucidated, particularly in *A. thaliana*, only a few genes have contributed to a tolerant phenotype when overexpressed in vegetables (Zhang et al. 2004). Expression of *AVP1*, a vacuolar H^+ pyrophosphatase from *A. thaliana*, in tomato resulted in enhanced performance under soil water defici (Park et al. 2005). The engineered tomato has a stronger, larger root system that allows the roots to make better use of limited water. The control plants suffered irreversible damage after fi e days without water as opposed to transgenic tomatoes, which began to show water-stress damage only after 13 days but recovered completely as soon as water was supplied. The *CBF/DREB1* genes have been used successfully to engineer drought tolerance in tomato and other crops (Hsieh et al. 2002).

Salinity Resistance

Currently, elevated soil salinity affects agricultural production in a large part of the world. It is estimated that more than a third of all irrigated land is affected, exclusive of regions classifie as arid and desert lands, which comprise 25% of total land surface. The conventional plant breeding for imparting salt tolerance is not very successful and there is a need to investigate the potentials of transgenic salt-tolerant crops (Kumar and Bhatt 2006).

Halophytes that survive under high salinity have high intracellular salt levels (Blumwald and Grover 2006). A major component of the osmotic adjustment in these cells is accomplished by ion uptake. The utilization of inorganic ions for osmotic adjustment would suggest that salt-tolerant plants must be able to tolerate high levels of salts within their cells. However, enzymes extracted from these plants show high sensitivity to salt, suggesting that these plants are able to keep Na^+ ions away from the cytosol.

Plants can use three strategies for the maintenance of a low cytosolic sodium concentration: (1) sodium exclusion, (2) compartmentation, and (3) secretion. One mechanism for sodium transport out of the cell

is through operation of plasma membrane-bound Na^+/H^+ antiports, as confirme by the characterization of SOS1, a putative plasma membrane Na^+/H^+ antiport from *Arabidopsis thaliana* (Shi et al. 2000). The efficien compartmentation of sodium is likewise accomplished through operation of vacuolar Na^+/H^+ antiports that move potentially harmful ions from cytosol into large, internally acidic, tonoplast-bound vacuoles (Apse et al. 1999). These ions, in turn, act as an osmoticum within the vacuole to maintain water fl w into the cell (Glenn et al. 1999). Antiports use the protonmotive force generated by vacuolar H^+-translocating enzymes, H^+-adenosine triphosphatase (ATP*ase*) and H^+-inorganic pyrophosphatase (PP_i*ase*), to couple downhill movement of H^+ (down its electrochemical potential) with uphill movement of Na^+ (against its electrochemical potential).

In 1999, Eduardo Blumwald and coworkers successfully engineered transgenic *Arabidopsis* plants that overexpress *AtNHX1,* a vacuolar Na^+/H^+ antiport, which allowed the plants to grow in 200 mM NaCl (Glenn et al. 1999). Zhang and Blumwald (2001) have reported the genetic modificatio of tomato plants to overexpress the *Arabidopsis thaliana AtNHX1* antiport, which allowed those plants to grow in the presence of 200 mM NaCl.

A salt concentration of 200 mM is equivalent to 40% of the salt concentration of seawater and can inhibit the growth of almost all crops. The growth of the wild-type plants in this study was severely inhibited by the presence of 200 mM NaCl in the growth solution, and most of the plants died or were severely stunted (Zhang and Blumwald 2001). On the other hand, the transgenic plants grew, fl wered, and produced fruit. The high sodium and chloride content in the leaves of transgenic plants grown in salty water demonstrated that enhanced vacuolar accumulation of Na^+ ions, mediated by the Na^+/H^+ antiport, allowed transgenic plants to ameliorate the toxic effects of Na^+. Most notable was the production of fruit by these transgenic plants grown in the presence of 200 mM NaCl. While the transgenic leaves accumulated Na^+ to almost 1% of their dry weight, the fruits displayed only a marginal increase in Na^+ content and a 25% increase in K^+ content.

Epstein (1983) argued for development of crops in which the consumable portion is botanically a fruit, such as grain, berries, or pomes, which have a truly halophytic response to salinity. In these plants, Na^+ ions would accumulate mainly in leaves, and since water transport to fruits and seeds is primarily through the phloem pathway (i.e., the intercellular connections), much of the salt from these organs would be screened. The results obtained with transgenic salt-tolerant tomato clearly support Epstein's argument.

In addition to the transgenic method, somaclonal variation via plant tissue culture method can also be used for the development of salt-resistant variants. Potato is one of the most salt-sensitive crops, which gives potential yield in up to 1,000 ppm soil salinity. But at higher salinity concentrations the plants wilt and die. Recently, a potato variant tolerant toward salinity has been developed for cultivation in Kuwait (Sudhersan et al. 2007) through plant tissue culture method. Experiments to determine performance of the plantlets of this salt-tolerant potato inside a greenhouse showed characteristics similar to in vitro conditions (Figure 4.1). The potato tubers produced from the salt-tolerant variant under brackish water irrigation appeared like normal tubers (Figure 4.2) and had similar taste. Further study and fiel evaluations of this new salt-tolerant potato variant for commercial cultivation are in progress.

Cold Resistance

Cold is an environmental factor that limits the geographical distribution and growing season of many crops (Thomashow 1999). Plants from tropical and subtropical regions are sensitive to low temperatures while plants

Figure 4.1 Salt-tolerant variant potato growing under brackish water irrigation.

from temperate regions tolerate low temperatures. Each year, worldwide crop production loss due to low temperature damage amounts to approximately US$2 billion (Kumar and Bhatt 2006). Due to limited understanding of the chilling regulating mechanism in plants, the traditional breeding methods had limited success in this field With the advent of molecular genetics and biotechnology, it is now possible to genetically engineer plants to be more tolerant to cold temperatures.

Cold-responsive genes encode a diverse array of proteins such as enzymes involved in respiration and metabolism of carbohydrates, lipids, phenylpropenoids, and antioxidants, and the intolerance to dehydration caused by freezing (Kumar and Bhatt 2006).

Plants vary greatly in their ability to withstand low temperature stress. As an adaptation strategy, most plants native to the temperate climates develop freezing tolerance during cold acclimatization processes that

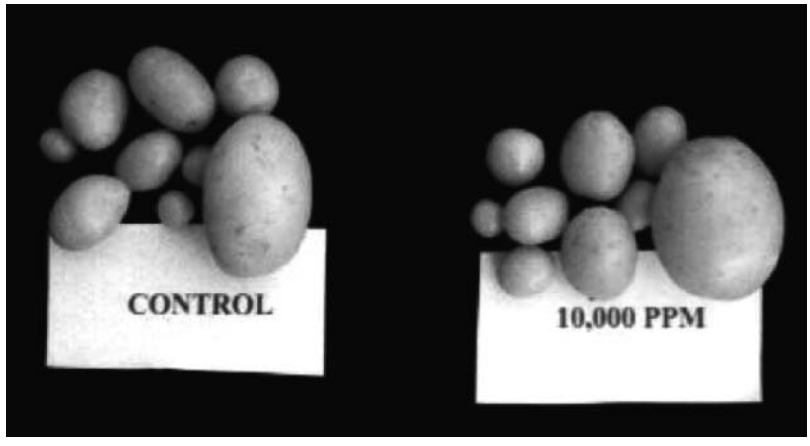

Figure 4.2 Minitubers obtained from salt-tolerant variant.

occur prior to freezing. Many biochemical and physiological changes are known to occur during cold acclimatization (Guy 1990). With the onset of low temperature, putative temperature sensors at the cell membrane generate stress signals which are transmitted and amplifie through many steps and a chain reaction termed the kinase cascade. The message evenly reaches the nucleus and the regulators of gene expression called transcription factors, which act as master switches to regulate the expression of genes, resulting in the increase of proteins and other organic molecules that protect the cell from freezing damage. Some reports also identifie cold regulated (CR) genes *Aradbidopsis thalina* (Kumar and Bhatt 2006). However, plants' response to cold acclimatization is complex and diverse, and the biochemical and physiological changes at the molecular level are poorly understood.

The C-repeat binding factor (CBF) genes represent a significan discovery in the fiel of low temperature adaptation and signal transduction. All important crops and a few vegetable plants contain this gene. The transgenic canola plants containing this gene are able to survive at a temperature 4–5°C lower than the nontransgenic controls (Jaglo et al. 2001). Tomato plants have also been successfully engineered using the CBF genes to achieve chilling tolerance (Hsieh et al. 2002). Thus, the CBF technology has a great potential for improving the cold and freezing tolerance in plants. Many other important genes that have an effective role for cold tolerance in plants have also been isolated recently and introduced in cucumber, pea, and eggplant to produce transgenic plants. Thus, by transgenic technology, several vegetable crops can be grown in temperate regions (Kumar and Bhatt 2006).

Prerequisite for Transgenic Technologies

In spite of significan advances in the genetic stress tolerance, efficien transformation and plant regeneration technologies which are the prerequisites for release of genetically improved vegetable crops are yet to be developed (Sharma et al. 2006). Success of genetic transformation for abiotic stress tolerance depends on two important factors: molecular biology, and plant cell and tissue culture. The prerequisites for the successful release of abiotic stress-tolerant transgenic are: identificatio of the genes for a particular trait; preparation of gene construct and transformation with suitable vectors; development of efficien transformation technique for the introduction of selected genes into the targeted crop plant; development of an efficien plant regeneration protocol through plant cell and tissue culture; recovery, plant regeneration, and multiplication of transgenic plants; characterization of transgenic plants; efficien and stable gene expression; fiel evaluation of transgenic crops for tolerance toward the particular plant stress; evaluation of the transgenic crop performance under particular stress condition; assessment of biosafety over the transgenic crop; and commercialization and marketing.

Current Status of Transgenic Technologies

Globally, the area planted with transgenic crops increased from 1.7 million hectares in 1996 to 90 million hectares in 2005 (James 2005); the United States, Argentina, and Canada account for more than 90% of the total area under transgenic crops. The major crops occupying more than 80% area are herbicide-tolerant soybeans and canola, Bt-corn, and Bt-cotton. Several transgenic cultivars of soybeans, maize, canola, potato, and papaya resistant to biotic stress like herbicides, insects, bacteria, fungi, and viruses have been commercially released. According to Manjunath (2005), transgenic varieties of four fiel crops, three vegetables, one fruit, and tobacco are presently produced commercially across the world. However, no transgenic crop tolerant to abiotic (water, temperature,

salt) stresses has been released for commercial cultivation. Seven transgenic crops exhibiting tolerance to a range of abiotic stresses have undergone fiel testing in Bolivia (frost-resistant potato), China (cold-tolerant tomato), India (moisture-tolerant *Brassica* vegetables), Egypt (salt-tolerant wheat), and Thailand (salt- and drought-tolerant rice) (Kumar and Bhatt 2006).

End-product Quality Improvement

Nutritional Quality

Commonly consumed vegetables contain a number of antioxidants such as fl vanols, phenolic acids, ascorbic acid, vitamin E, and carotenoids (Table 4.1). Broccoli and green peppers are good sources of vitamin C and β-carotenes (Hussein et al. 2000). Among the carotenoid antioxidants, β-carotene and lutein dominate in spinach, and lycopene in tomato (Van Den Berg et al. 2000). With the help of genetic engineering, foreign genes have been incorporated into vegetables to enhance their micronutrients (DellaPenna 1999; Anon. 2008a).

One important class of phytochemicals present in fruits and vegetables is the carotenoids (Kopsell and Kopsell 2006). Carotenoids are synthesized through the isoprenoid biosynthetic pathway. Roemer et al. (2000) inserted into tomato a bacterial gene that encodes for the phyoene-desaturase enzyme for the production of lycopene. These transgenic tomato plants produced threefold more β-carotene than the control plants. Sandmann et al. (2006) and Frazer et al. (2009) have recently reviewed the need to understand carotenoid metabolism as a necessity for genetic engineering of crop plants to enhance their bioactive phytochemical contents. Attempts have been made to improve the biosynthetic pathway to enhance the preexisting carotenoids and to incorporate carotenoid activity in plant tissues that are devoid of such activity (Sandmann 2001). However, genetic manipulation of carotenoid pathway resulted in stunted growth of tomato plants due to competition for the production of growth hormone, gibberellin (GA), as both the carotenoid pigments and GA originate from the same precursor, geranylgeranyl diphosphate (GGPP) (Fray et al. 1995). By using a bacterial phytoene synthase (crtB) and a tissue-specifi promoter, a two- to threefold increase in carotenoids in tomato has been achieved (Frazer et al. 2002).

Table 4.1 Rich vegetable sources of selected nutrients

Compounds	Rich sources
Ascorbic acid (vitamin C)	Green leafy vegetables, potatoes, turnip leaves
Tocopherols (vitamin E)	Vegetable oils, avocado, tomato seeds
Pro-vitamin A (α- and β-carotenes)	Green leafy vegetables, carrots, pumpkin, sweet potato
Folates	Green leafy vegetables, potatoes
Vitamin K	Green leafy vegetables
Minerals (Ca, Fe, Mg, K)	Green leafy vegetables
Mono-unsaturated fatty acids	Avocado
Lutein	Yellow and green vegetables
Lycopene	Tomatoes
Flavonoids	Onions, green beans
Anthocyanins	Sugar beet
Glucosinolates	*Brassica* spp. (Mustard green, turnip leaves)
Alkenyl cysteine sulphoxides	Garlic and onions
Glycoalkaloids	Potato, eggplant
Furanocoumarins	Parsnip, celery
Cyanogenic glycosides	Cassava tubers, butter beans
Proteins	Green peas, green seeded beans
Dietary fibe	All vegetables

Source: Adapted from Herbers (2003) and Morris et al. (2006).

Table 4.2 Metabolic engineering approaches for increased β-carotene levels in transgenic plants

Genes	Source	Promoter	Plant	Tissue	Main products
Phytene synthase	Daffodil	Rice glutelin	Rice	Endosperm	Lutein, zeaxanthin, β-carotene (small amount of α-carotene)
Phytoene desaturase	*E. uredovora*	CAMV 35S	Rice	Endosperm	Lutein, zeaxanthin, β-carotene (small amount of α-carotene)
Lycopene β-cyclase	Daffodil	Rice glutelin			
Phytoene synthase (crtB)	*E. uredovora*	*Brassica napin*	Rapeseed	Embryo	β-Carotene, α-carotene
Phytoene synthase (crtB)	*H. pluvialis (bkt1)*	Patatin	Potato	Tubers	Increased levels of violaxanthin and lutein
β-Cyclase	*Arabidopsis*	Tomato Pds	Tomato	Fruit	β-Carotene

Source: Adapted from Herbers (2003) and Morris et al. (2006).
CaMV, caulifl wer mosaic virus; Pds, phytoene desaturase.

To enhance the carotenoid content of potato tubers, transgenic plants expressing an *Erwinia uredovora* crtB gene encoding phytoene synthase have been engineered (Ducreux et al. 2005). They achieved a total carotenoid content of 78 μg/g dry weight of tubers in transgenic lines. In these tubers, the major carotenoids were violaxanthin, lutein, antheraxanthin, and β-carotene.

Zeaxanthin is an important dietary carotenoid pigment that accumulates in the human macula lutea and provides protection to the retina from the damaging blue UV light. Depending upon the transgenic lines and tuber development, Roemer et al. (2002) achieved a zeaxanthin content of 4- to 130-fold, reaching up to 40 μg/g dry weight. In addition to zeaxanthin, most transgenic lines also showed higher levels (up to 5.7-fold) of total carotenoid. The tubers in these transgenic lines showed two- to threefold higher levels of α-tocopherol. The consumption of zeaxanthin-rich potatoes significantly increased the zeaxanthin levels in chylomicrons, suggesting that these genetically engineered potatoes could be a good dietary source of carotenoids (Bub et al. 2008).

De la Garza et al. (2007) have used genetic engineering techniques to produce tomato with enhanced (up to tenfold) folate content. As in the control samples, most of the folate in genetically engineered tomatoes was in the form of 5-methyltetrahydrofolate polyglutamates and 5,10-methtetrahydrofolate polyglutamates. Herbers (2003) reviewed the use of genetic engineering techniques for enhancing the levels of vitamins in plants to create functional foods with enhanced health benefit (Table 4.2). Hitherto scientists have succeeded in producing transgenic plants with elevated levels of provitamin A, vitamin C, and vitamin E.

Many plants including certain vegetables (such as peas and beans) produce storage proteins of considerable nutritional importance. However, these vegetable proteins are defi cient in essential amino acids such as lysine and methionine. Genetic engineering techniques can be used to improve the essential amino acid makeup of vegetable proteins (Nikiforova et al. 2002). Chakraborty et al. (2000) inserted an *Amaranthus* seed protein gene (*AmA1*) in transgenic potato tubers and produced a nonallergenic protein rich in essential amino acids to meet WHO standards for human diet. Egnin and Prakash (1997) introduced a 292 bp artificia gene (*asp-1*) in sweet potato that encoded a storage protein rich in essential amino acids. One of their transgenic lines had a fourfold increase in protein content than the storage roots of the control plants. A comprehensive review on nutritionally improved sweet potato has

recently been published by the Institute of Food Technologists, USA (Anon. 2008b).

Processing Quality and Functional Foods

A "functional food" can be define as food providing health benefit beyond the basic nutrition. It may include whole, fortified enriched, or enhanced foods which have beneficia effect on health when consumed as part of varied diet on a regular basis (Hasler 2000; Heinonen and Meyer 2002; Kalt 2005). Use of biotechnology has a great potential to produce novel functional foods (Mermelstein 2008; Pleniz et al. 2009). However, the lengthy procedure adopted by the regulatory agencies for the approval of GM foods and slow pace of consumer acceptance have led to a lack of investment in this area (Powell 2007). The US government's mandate to remove *trans* fats from the diet has resulted in an increased use of genetic engineering techniques to develop vegetable oils with healthier fatty acid profiles

Grusak (2002) has reviewed both the traditional breeding techniques as well as modern biotechnological tools for enhancing the mineral contents of plant foods to ensure adequate dietary minerals for all individuals. Schijlen et al. (2004) reviewed the current knowledge of the molecular regulation of the fl vonoid pathways and the role of genetic engineering to improve these crops (fruits, vegetables, nuts, and seeds) nutritionally and make them a part of various functional foods.

Tomatoes are an excellent source of lycopene and a number of fl vonoids such as naringenin chalcone and rutin. Muir et al. (2001) have genetically transformed tomato with *Petunia chi-a* gene that encodes for chalcone isomerase. The transgenic lines were found to have up to 78-fold increase in fl vonols, rutin being the main compound. They did not fin any change in the phenotypes of the transgenic lines and observed stable inheritance pattern over four subsequent generations. The fl vonol levels of these transgenic lines were as high as those found in onions, a vegetable known to be naturally rich in fl vonol compounds. Compared with fresh tomatoes, about 65% of fl vonols were present in the processed tomato paste. Le Gall et al. (2003) have analyzed the tomato fruits from two genetically modifie lines and reported the fl vonoid glycoside contents of these GM lines to be ten-fold higher than the controls. Production of healthy and tasty snacks based on fruits, vegetables, and whole grains has been reviewed recently (Anon. 2007).

Using genetic engineering, Gonzali et al. (2009) have produced purple tomato fruits which have high anthocyanin content. The genetically modifie purple tomatoes prolonged the life of cancer-susceptible mice, suggesting that they have additional health-promoting effects. Kushad et al. (1999) reported a wide natural variation in glucosinolates content in various groups and accessions of vegetable crops of *Brassica oleracea* (broccoli, Brussels sprouts, cabbage, caulifl wer, and kale) and suggested use of genetic engineering techniques to enhance the glucosinolates levels in these vegetables.

Sensory Quality

Wang et al. (1996) incorporated a gene from yeast encoding Δ-9 desaturase into tomato and achieved higher levels of unsaturated fatty acids but a reduced level of saturated fatty acids in tomato fruits. They found a change in certain fl vor compounds (such as *cis*-3-hexenol, 1-hexanol, hexanal, and *cis*-3-hexenal) derived from fatty acids and concluded that change in the profil of fatty acids in a plant could result in change in its profil of fl vor compounds. Speirs et al. (1998) modifie the fl vor profil of ripening tomatoes through genetic manipulation of alcohol dehydrogenase (ADH), and reported that fruits with elevated ADH activity and higher levels of alcohols had a more intense

"ripe" fl vor. In another study, Lewinsohn et al. (2001) inserted a heterologous Clarkia breweri S-linalool synthase (LIS) gene under the control of late-ripening-specifi E8 promoter into tomatoes. The transgenic tomato fruits had higher levels of S-linalool and 8-hydroxylinalool during ripening. The ripened tomato fruits showed no phenotypic alterations or a change in the levels of tocopherols, β-carotene, and lutein.

Enzymatic browning due to polyphenol oxidase enzyme (PPO) in potatoes and loss of the fl vor compound (methional) are the two major challenges for the potato processing industry. Coetzer et al. (2001) developed Russet Burbank potato transgenic lines through inhibition of PPO activity by sense and antisense PPO RNAs expressed from tomato PPO cDNA under the control of the 35S promoter from caulifl wer mosaic virus. Their results showed that the expression of closely related heterologous genes can be used to prevent enzymatic browning in potatoes without the application of food additives.

Di et al. (2003) introduced *Arabidopsis thaliana* CGS cDNA under transcriptional control of the caulifl wer mosaic virus 35S promoter into Russet Burbank potato by *Agrobacterium*-mediated transformations. The objective was to enhance the level of cystathionine γ-synthase (CGS) activity, a key enzyme regulating methionine biosynthesis in plants. The transgenic lines of potato had six-fold more methionine than the control. Zeh et al. (2001) employed antisense inhibition of threonine synthase (TS) to produce higher contents of methionine in transgenic potato plants.

Monellin, a protein, is nearly 100,000 times sweeter than sucrose on molar basis. This protein exists naturally as a heterodimer, but loses its sweetness upon denaturation. Penarrubia et al. (1992) introduced a single-chain monellin gene to transgenic tomato and lettuce that resulted in the accumulation of this protein in fruit and leaf of these transgenic plants. Production of this protein in transgenic fruits and vegetables opens up another possibility to enhance their fl vor and consumer quality.

Parthenocarpic Attributes

Some of the plant hormones such as auxin, gibberellins (GA), abscisic acid (ABA), and ethylene play an important role in the growth and development of plants. To replace synthetic hormones and growth regulators, application of genetic engineering techniques has now made it possible to manipulate hormone concentration and tissue sensitivity to these chemicals to achieve desirable qualities in fruits and vegetables (Li et al. 2004). One of the commercial applications of auxin-overproducing transgenic plants is the production of seedless fruits and vegetables (parthenocarpy—fruit development without pollination). Traditional seedless fruit technologies mainly concentrated on watermelon, citrus fruits, grapes, and cucumber. Traditionally, seedless fruits and vegetables are produced from mutants, triploid plants, or with the use of exogenous plant hormones. The triploid plants and seedless fruit and vegetable mutants have one major disadvantage that these are difficul to breed.

Use of genetic engineering of parthenocarpy of fruits and vegetables helps in producing fruits under those environmental conditions which otherwise curtail fruit productivity and quality. Use of *DefH9-iaaM* gene that induces auxin synthesis in plants has made it possible to produce several parthenocarpic vegetables of commercial importance such as tomato and eggplant (Molesini et al. 2009). Varoquaux et al. (2000) have reviewed the application of modern biotechnological techniques in producing seedless fruits and vegetables. Recently, Kikuchi et al. (2008) produced hybrids between Japanese and European parthenocarpic eggplants, and the hybrids had desired quality characteristics. The new hybrids gave higher fruit set even under hot cultural conditions. Donzella et al.

(2000) have produced transgenic hybrid eggplants with *DefH9-iaaM* gene and compared their performance under various greenhouse conditions. They obtained about 25% higher yields and a 10% reduction in cultivation cost (through reduction in cost of hormone sprays). Similar results of improved fruit productivity under both greenhouse and open fiel cultivation for transgenic eggplant have also been reported by Acclarri et al. (2002). Both the fresh transgenic eggplant fruits and those stored at −20°C for 15 months when compared with hybrid controls showed a slower browning of pulp with respect to controls (Maestrelli et al. 2003). As compared with hybrid controls, lower molecular weight fragments of pectic substances were observed in transgenic eggplants.

Fruit set in tomato is severely affected by both high and low temperatures as well as low humidity affecting the pollen viability (de Jong et al. 2009a). Under such conditions, tomato fruits have poor quality or sometimes there is no fruit set at all. Genetic or transgenic parthenocarpy that gives fertilization-independent fruit setting and development provides a good solution to these environmental problems (Shabtai et al. 2007).

Ficcadenti et al. (1999) used DefH9-iaaM chimeric gene to engineer parthenocarpy in tomato fruits. The seedless parthenocarpic fruits from emasculated fl wers and fruits with seeds from pollinated fl wers did not differ in processing quality (pH and soluble solids). Carmi et al. (2003) induced parthenocarpy in tomato fruit with ovary-specifi expression of the *Agrobacterium rhizogenes*-derived gene *rolB* and young-fruit-specifi promoter TPRP-F1. Pandolfin et al. (2009) have reviewed the mechanism of the expression of Aucsia genes responsible for auxin biosynthesis in ovary and placenta that uncouples tomato fruit development and fertilization processes, thus producing parthenocarpic fruits. Their results demonstrated that Aucsia genes encode a family of 53-amino acid long plant peptides that control fruit initiation and fruit development in tomato plants. de Jong et al. (2009b) have also reviewed the role of auxin response factor 7 (SlARF7) in regulating auxin signaling during tomato fruit initiation and development in tomato plants. According to them, a tomato ARF gene, homologous to Arabidopsis NPH4/ARF7, designated as SlARF7 is expressed at a high level in unpollinated mature ovaries. The SlARF7 transcript increased during fl wer development, remained constant at high levels in mature fl wers, but is then down-regulated within 48 hours after pollination. The transgenic plants with suppressed SlARF7 mRNA levels produce parthenocarpic fruits.

Food Safety

Although the use of genetic engineering has resulted in a number of GM foods with improved shelf life, drought and salt tolerance, higher nutritive value, insect resistance, etc., consumers are still reluctant to accept these foods. The long-term impacts of GM foods on the environment and human health have not been established and that makes consumers suspicious of the safety of GM foods. The genetic modification of plants could be either beneficia if there are improved economic benefits or harmful if there are adverse environmental or toxicological effects (Kappell and Auberson 1998). The supporters of GM foods highlight the increased nutrient contents to combat human malnutrition and hunger of the growing world population. The major concern of the opponents is the risk of allergenicity in humans and the potentials for negative environmental effects (Bachas-Daunert and Deo 2008; Daunert et al. 2008; Knight 2009).

A number of cross-cultural surveys have been conducted regarding the acceptance of GM food in different countries. In contrast to US consumers, Europeans were less favorable toward first-generatio GM foods but both equally perceived a direct benefi from second-generation GM foods (Le Marre

et al. 2007; Anon. 2008c; Costa-Font and Gil 2009). Many consumers look to GM foods as an attractive solution to counter rising food costs and the risks of increasing food shortages around the world. The Indian government encourages biotechnological research and development on a wide range of food crops, and China and India may authorize GM food production to improve their food supply (Knight and Paradkar 2008). Polymerase chain reaction (PCR) based analytical techniques are now available to detect the presence of GM foods in a number of processed food products (Gaudron et al. 2009).

A number of foods such as milk, egg, soy, nuts, and wheat are known to cause allergic reactions in some individuals. However, with the introduction of GM foods, the food allergy issue has taken center stage (Buchanan 2001). Although genetic engineering of plants has the potential to introduce new allergenic proteins into GM foods, it can also be used to remove established allergenic proteins.

A number of approaches have been proposed to remove allergens from the food supply by allergen gene silencing strategies that operate at post-transcriptional level (Bhalla and Singh 2004; Singh and Bhalla 2008). Le et al. (2006a, 2006b) designed tomato fruits with reduced allergenicity by down-regulating the ns-LTP (Lyc e 3) gene expression by dsRNAi-mediated inhibition. Domingo (2007), who reviewed the toxicity assessment of various GM potatoes, corn, soybeans, rice, cucumber, tomatoes, sweet pepper, peas, and rapeseeds, concluded that there was insufficien scientifi information to be certain about the safety of these GM foods.

Promoting GM foods without sufficien testing about their safety and possible allergenic potential to consumers is not a good regulatory practice (Ho et al. 2007; Goodman et al. 2008). Chembezi et al. (2008) carried out a survey among US farmers about their preference for mandatory labeling of GM food products. Most producers were in favor of mandatory labeling. The Codex Alimentarius Commission of the FAO/WHO (Anon. 2009) reported on the status of the labeling of GM foods and ingredients. The problem of allergies from GM foods may be effectively addressed through development and use of animal models as a reliable indicator of allergies in humans (Buchanan 2001).

Food Applications

Jany and Greiner (2000) reviewed the applications of genetically engineered products including use of genetic engineering in food production and processing, enzymes and additives from GMO, production of new starter and protective cultures, GM yeasts, development of transgenic plants and animals, use of GM feeds in animal production, and regulatory aspects. Van der Meer et al. (1994) modifie a normal non-fructan-storing potato plant by introducing the microbial fructosyltransferase genes so that it can accumulate higher amounts of this polymer. They created constructs by fusing these genes either from *Bacillus subtilis* (*sacb*) or *Streptococcus mutans* (*ftf*) with the yeast carboxypeptidase Y (cpy) gene, and these constructs were put under the control of constitutive caulifl wer mosaic virus 35S promoter and introduced into the target potato tissues. The bioengineered potato plants accumulated over fi e times more of higher molecular weight fructans (with 25,000 fructose units) than the control. The total nonstructural neutral carbohydrate content in soil-grown plants increased from 7% in the wild type to 35% in transgenic potatoes. As high-amylose starch is in great demand by the starch industry for its unique functional properties, Schwall et al. (2000) have bioengineered a very high amylase potato starch by simultaneously inhibiting two isoforms of starch branching enzymes to below 1% of the activity of the wild-type potato. This genetically engineered starch with its high amylose, low

amylopectin, and high phosphorus contents offers novel characteristics for food and industrial applications.

Starch is one of the major carbohydrate constituent used for food and feed purposes. Higher starch content in grains or tubers offers important strategy to increase crop yields. By altering adenylate pools in transgenic plants, Regierer et al. (2002) increased the level of starch to 60% above that in wild-type plants. Their transgenic plants also gave higher tuber yield because of this genetic manipulation. Granule size is an important parameter that determines the use of starch in industrial applications. Ji et al. (2004) succeeded in reducing granule size from 15.2 μm in control to 7.8 μm by expression of an engineered tandem starch-binding domain in bioengineered potato plant. The small granule starches can fin applications in the manufacture of biodegradable plastic films

Low-calorie, noncariogenic sweeteners are in great demand by the food industry. Palatinose (isomaltulose, 6-O-α-D-glucopyranosyl-D-fructose) is a structural isomer of sucrose with quite similar physicchemical properties. It is currently produced industrially by the enzymatic rearrangement of sucrose using immobilized bacterial cells. Bornke et al. (2002) introduced a chimeric sucrose isomerase gene from *Erwinia rhapontici* under control of a tuber-specifi promoter and produced a transgenic potato plant. Expression of the pall gene within the apoplast of transgenic tubers led to nearly quantitative conversion of sucrose to palatinose. Although the soluble carbohydrates have increased in the transgenic potato, no phenotypic changes were observed. Inulin is a highly water-soluble polysaccharide consisting of linear β (2→1)-linked fructose units attached to a sucrose molecule. As a prebiotic it has many applications in the food industry as it positively influence the gut microflor and has benefi cial effects on mineral absorption, lipid profile and prevention of colon cancer. Hellwege et al. (2000) bioengineered potato plants via constitutive expression of the *1-SST* (sucrose: sucrose 1-fructosyltransferase) and the *1-FFT* (fructan: fructan 1-fructosyltransferase) genes of globe artichoke (*Cynara scolymus*). The fructan pattern of tubers from transgenic potato plant represented full spectrum of fructan molecules of the original artichoke roots. The inulin content was 5% of the dry weight of transgenic tubers. The inulin accumulation in tubers did not alter the sucrose concentration but starch content was decreased in tubers. Beaujean et al. (2000) have achieved direct fructose production in bioengineered potato tubers by expressing a bifunctional α-amylase/glucose isomerase gene complex. They constructed a fusion gene encoding the thermostable enzymes: α-amylase (*Bacillus stearothermophillus*) and glucose isomerase (*Thermus thermophillus*). This chimeric gene was placed under the control of the granule-bound-starch synthase promoter. The fructose and glucose in transgenic tubers increased by a factor of 16.4 and 5.7, respectively, compared to the control. Their finding offered a novel and viable strategy for starch-processing industries via a system where the enzymes are produced directly in the plants and these enzymes are active only at high temperature. This will also eliminate the need for external source of microbial enzymes for starch degradation.

The common bean (*Phaseolus vulgaris* L.) is one of the most cultivated species in the Leguminosae family, but its genetic improvement through conventional breeding has not been successful. In addition to being time consuming and labor intensive, a number of problems including low genetic variation, low survivability of interspecifi hybrids, inheritance of some traits such as yield, disease and pest resistance, and harvesting characteristics are the other major constraints. Veltcheva et al. (2005) have reviewed the problems and progress related to in vitro regeneration and the genetic transformation of this common bean, and have suggested that genetic

engineering techniques offer different strategies to overcome the above difficulties

Biofarming

Biofarming or medical molecular farming is the production of proteinaceous biomolecules in genetically engineered plants. Such biomolecules may include antibodies, antigens, and enzymes. Currently, many of these biomolecules are being produced using bacteria, fungi, or other animals, but the use of plants can offer many advantages. Growing of plants at farms is ecofriendly and less costly for mass production as it utilizes sunlight, water, and some minerals. As plants usually do not have human pathogens, this offers another advantage. Tomato and potato are the commonly employed host vegetables for the purpose of biofarming.

Enzymes and Plant-Based Antibodies

Scheller et al. (2001) have produced spider silk proteins in tobacco and potato plants. Spider dragline silk is a proteinaceous fibe with remarkable mechanical strength that lends to it many technical applications. The recombinant spider silk proteins exhibited extreme heat stability and had a molecular weight of up to 100 kDa. Chong and Langridge (2000) have succeeded in expressing a full-length bioactive antibacterial human lactoferrin protein in potato plants. They used a cDNA fragment encoding human lactoferrin (hlf) linked to a plant microsomal retention signal peptide (SEKDEL) that was integrated into the potato genome by *Agrobacterium tumefaciens*-mediated leaf disk transformation methods. The lactoferrin gene was expressed under the control of both the auxin-inducible mannopine synthase (*mas*) P2 promoter and the caulifl wer mosaic virus (CaMV) 35S tandem promoter. The research of Chong et al. (1997) has opened a way for the expression of human milk protein–casein in transgenic potato plants and thus for the replacement of bovine milk in baby foods for prevention of gastrointestinal diseases in children.

Dai et al. (2000) optimized *Acidothermus cellulolyticus* endoglucanase (E1) gene expression in transgenic potato (*Solanum tuberosum* L.). The E1 coding sequence was transcribed under control of a leaf-specifi promoter (tomato RbvS-3C) or the Mac promoter (a hybrid promoter of mannopine synthase promoter and caulifl wer mosaic virus 35S promoter enhancer region). The E1 gene was expressed in both the leaf and tuber tissues under the control of Mac promoter. They suggested dual-crop applications in which potato plants can serve as enzyme production bioreactors while tubers are preserved for culinary purposes. Mor et al. (2001) have achieved expression of recombinant human acetylcholinesterase in transgenic tomato plants. Prevention and treatment of organophosphate pesticide poisoning depend on the availability of large amounts of cholinesterases, which can be produced from transgenic plants. Active and stable cholinesterase, which retained the kinetic characteristics of human enzymes, were found to possess high levels of specifi activity in leaves (up to 25 nmol min^{-1} mg $protein^{-1}$) and fruits (up to 250 min^{-1} mg $protein^{-1}$).

Plant-based antibodies have potential for medical uses such as passive immunization, disease diagnostics, and targeted drug delivery. However, the use of antibodies in therapeutics suffers from a few constraints such as limited amount available and higher cost of production in pharmaceutical plants. These constraints could be eliminated if these antibodies are produced by transgenic plants in agricultural fields Transgenic plants have been studied for the production of antibodies and other biopharmaceuticals for immunotherapy purposes (Sharma et al. 1999; Daniell et al. 2001). Porceddu et al. (1999) bioengineered tobacco and carrot plants to express human glutamic acid decarboxylase (GAD65), a major autoantigen in human insulin-dependent diabetes. About 0.01% and 0.04% of the total soluble protein in transgenic tobacco and carrot plants was expressed

as human GAD65, respectively. Arakawa et al. (1998) used transgenic potato tubers that produced human insulin up to a level of 0.05% of the total soluble protein. They linked the insulin to the C-teminus of cholera toxin B subunit (CTB) so that plant-synthesized insulin is delivered directly to the gut-associated lymphoid tissues. Artsaenko et al. (1998) have successfully used potato tubers as a biofactory for the production of recombinant antibodies. Among the soluble tuber proteins, recombinant antibodies constituted about 2% of the proteins. Even after one and a half year of cold storage of potato tubers at 4°C, 50% of the antibody activity in tubers was still present.

Zeitlin et al. (1998) used transgenic soybean to produce a humanized monoclonal antibody (mAb) for the development of an inexpensive method of mucosal immunoprotection of vagina and genital herpes. Human α-interferon is another important protein that has been successfully expressed in transgenic plants using lipofectin-mediated transformation (Sawahel 2002). Human papillomavirus (HPV) is known to cause cervical cancer and human papillomavirus-like particles (HPV-VLPs) have shown considerable potential as a parenteral vaccine for the prevention of cervical cancer. Warzecha et al. (2003) have expressed HPV type 11 L1 major capsid protein coding sequence into tobacco and potato. They obtained plant-expressed L1 self-assembles into VLPs with immunological properties comparable to those of native HPV virions and can activate potentially protective humoral immune response. Lindh et al. (2008) have recently introduced the p24 gag gene encoding the nucleocapsid protein from HIV-1 subtype C into the *Arabidopsis thaliana* genome. The transgenic plants showed between 0.2 and 0.5 μg p24 of protein per gram of fresh tissue, with stem containing more than twice that the leaves. When fresh transgenic tissues were fed to mice, antigag IgG appeared in the serum after a booster injection of recombinant p37 Gag.

The demand for therapeutic mAbs required for the diagnosis and treatment of various cancers is growing rapidly and cannot be met by the mammalian tissue culture and transgenic animals. Use of transgenic plants offers an attractive option to meet these increasing requirements. A number of studies have been reported for the production of these mAbs using bioengineered plants (Ko et al. 2003). The light and heavy chains of human antirabies mAb were expressed and assembled in transgenic plants. Brodzik et al. (2006) have expressed heavy and light chains of mAb BR55-2 (IgG2a) in low-alkaloid transgenic tobacco plants and they achieved mAb yield of 30 mg/kg of fresh leaves. The plant-derived BR55-2 mAb efficientl inhibited SW948 tumor growth in xenografted nude mice. Compared with leaves, transgenic *Arabidopsis* seeds have been reported to accumulate higher amounts of recombinant proteins in a relatively small volume (Droogenbroeck et al. 2007). Sack et al. (2007) have expressed the human monoclonal antibody 2F5 in transgenic tobacco By2 suspension of cell cultures, and this mAb showed broadly neutralizing activity against the HIV-1. This plant-based mAb exhibited similar kinetic characteristics as the Chinese hamster ovary cell-derived antibodies and possessed 89% of their binding capacity. The common contention against the plant-derived antibodies is the presence of β1, 2-xylose and core α 1, 3-fucose residues on complex *N*-glycan residues which may induce unwanted side-effects in humans (Jin et al. 2008). For the production of recombinant proteins from transgenic plants for any parenteral human application, they suggested the use of glycol-engineered plants lacking these antigenic *N*-glycans.

Edible Vaccines

The WHO reported that each year more than 30 million children are not vaccinated against many infectious diseases that can otherwise be prevented through the use of vaccines (Clemens and Pressman 2008; Tiwari et al.

2009). The production of recombinant proteins (vaccines) in bioengineered plants has many advantages, such as being more economical than traditional expression system; post-translational modificatio similar to that found in mammalian systems; proteins can be expressed in different plant parts (e.g., seeds, which need no refrigeration) with optimized accumulation; easier scaling up to industrial level; no risk of contamination of finishe product with pathogens, which could occur if done in animals; and the possibility of expression of vaccines in edible parts of plants that can be taken as food or feed, without the use of needles and risk of infection (Kumar et al. 2004).

The idea of producing plant-based vaccines was initiated by Mason et al. (1992) who bioengineered tobacco plant for the expression of Hepatitis B surface antigen. Later on, the research work on the production of plant-based edible vaccines was intensifie (Ma et al. 2003), and a number of recombinant proteins have been expressed in edible parts of plants (Table 4.3).

A number of enteric diseases are the most common causes of child mortality in the world, especially in the developing countries. *Vibrio cholerae* is a pathogenic organism responsible for causing cholera in children and adults. Cholera toxin B subunit protein (CTB) is reported to be functional as an adjuvant for cytoplasmatic proteins if directed to ER, but not to the cytoplasm of the plant cells (Mikschofsky et al. 2009). Yusibov et al. (2002) have tested the effica y of their plant virus-based rabies vaccine in human volunteers and showed clear indication of the possibility of using plant virus-based expression system as supplementary oral booster dose for rabies vaccinations. Rojas-Anaya et al. (2009) expressed rabies virus G protein into carrots (*Daucus carrota*) using pUCpSSrabG vector. Tacket et al. (1998) tested the effectiveness of feeding human volunteers with 150 g of raw, peeled, diced transgenic (expressing Norwalk virus capsid protein, NVCP) potatoes (containing 215–751 μg of NVCP) which marginally increased the serum levels of antibody.

Table 4.3 Production of edible vaccines in bioengineered plants

Disease	Antigen involved	Transgenic plants used	References
Rabies virus	Virus glycoprotein and nucleoprotein fused with AIMV coat protein	Spinach	Yusibov et al. (2002)
	Virus glycoprotein sub cloned into pUCpSSrabG vector	Carrot	Rojas-Anaya et al. (2009)
Escherichia coli	Non-toxic B subunit (recLT-B)	Potato	Lauterslager et al. (2001)
Hepatitis B	Hepatitis B large surface antigen (HBsAg)	Tomato	Lou et al. (2007)
Hepatitis E	HEV-E2 antigen protein	Tomato	Ma et al. (2003)
Cholera	Toxin co-regulated pillus subunit A (TCPA) fused with CTB subunit protein	Tomato	Sharma et al. (2008)
Viral enteric diseases	Norwalk virus capsid protein (NVCP)	Potato	Tacket et al. (2000)
SIV	Simian immunodeficien y virus: CTB linked to SIVmac Gag p27 capsid gene (CTP-Gag)	Potato	Kim et al. (2004)
Measles	B cell epitope (H386-400) of measles virus hemagglutinin protein with T cell epitope (tt830-844)	Carrot	Bouche et al. (2003)
HPV	Human papillomavirus virus type 11 L1 major capsid protein	Potato	Warzecha et al. (2003)
Periodontal disease	*P. gingivalis* fimbria protein, *fim*	Potato	Shin et al. (2009)

Source: Adapted from Dalal et al. (2006).

Bouche et al. (2003) expressed a designer polyepitope combining tandem repeats of a protective loop-forming B cell epitope (H386-400) of the measles virus hemagglutinin protein with a human measles-unrelated T cell epitope (tt830-844) in transgenic carrot. For the gram-negative anaerobic bacterium, *Porphyromonas gingivalis*, which causes periodontal disease in humans, Shin et al. (2009) have cloned the fimbria protein, *fim* with mannopine synthase promoter in plant expressed vector pPCV701 and transferred the plasmid into potato leaf cells by *Agrobacterium tumefaciens* to prevent attachment of this bacterium to human teeth. Attempt has also been made to fin a potato-based vaccine to prevent simian immunodeficien y virus (SIV) infection in African green monkeys and many other primates (Kim et al. 2004).

A number of reviews have appeared recently on edible vaccines for various diseases such as measles, cholera, and hepatitis B. These vaccines may also help to suppress autoimmune disorders such as type 1 diabetes, diarrhea, and rheumatoid arthritis. Readers are directed to these reviews on the production of vaccines in genetically modifie plants (Nicholson et al. 2006; Mishra et al. 2008; Yusibov and Rabindran 2008).

Future Research Needs

From 1994, when the firs GM tomato was commercially sold in the United States, a number of other transgenic crops have been approved for cultivation. Currently, soybean, maize, cotton, and rapeseed (Canola) are the four major bioengineered crops being cultivated commercially in many countries. Among the vegetables, potato, tomato, and sugar beet have been accepted for commercial cultivation (Batista and Oliveira 2009). These transgenic crops have been developed to resist insects, pests, and diseases, and with potentials for better shelf life and nutritional quality. The use of lower amounts of agricultural chemicals for crop protection has not only reduced the residual levels of these contaminants in our food supply but also resulted in savings in energy and machinery used by the farmers, and less contamination of surface water and atmosphere. Genetic engineering has created transgenic plants with improved yield; resistance to insects, pests, crop pathogens; and nutritional, processing, handling, and storage quality (Stier 2007).

There is no doubt that consumers are apprehensive about GM foods and their potential effect on health and environment (Dona and Arvanitoyannis 2009). The consumers' concern will have to be addressed, and more advanced analytical techniques need to be invented for evaluating the safety of these transgenic products. However, genetic engineering has tremendous potential to improve food security and supply for the ever-increasing world population.

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Chapter 5

Nutritional Profile of Vegetables and Its Significance to Human Health

Masood Sadiq Butt and Muhammad Tauseef Sultan

Introduction

In general, the term "vegetable" is define as "plants cultivated for food or as the edible part or parts of such plants" and includes some fruits and possibly legumes too (Rubatzky and Yamaguchi 1997). The Asian Vegetable Research and Development Center (AVRDC 1992) proposed vegetables as "an edible, usually succulent plant or a portion of it eaten with staples as main course or as supplementary food in cooked or raw form." Over 10,000 plant species are eaten as vegetables worldwide, and among these about 50 species are of commercial interest (Decoteau 2000). Although a "fungi," mushrooms are also considered as vegetables.

Vegetables can contribute to our daily requirements for nutrients like minerals, vitamins, dietary fibers proteins, fats, starch, and energy. Vegetables are a major source of vitamin B complex and vitamin C. Owing to the health benefit of vegetables, the USDA's Food Guide Pyramid recommended daily consumption of at least fi e servings of vegetables. Besides providing nutrition, vegetables contribute to color, texture, and fla vor of the fina food product. This chapter provides an overview of nutritional profil of vegetables and its significanc to human health.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

General Composition

Generally, the composition of vegetables is influence by various factors including climatic conditions, variety, cultural practices, maturity, and storage conditions (Maynard et al. 2006). On the basis of high moisture content (>80%), vegetables are considered as "succulent" and impart less energy as compared to cereals. Vegetables contain 3–20% carbohydrates which act as body fuel. Starch occurs as storage polysaccharide, while cellulose, hemicellulose, and pectin contribute firmnes to vegetables. Proteins are in 0.5–3.5% range with the exception of legumes such as peas and beans, which are high in protein content. Lipid content of vegetables is about 0.1–3% (Titchenal and Dobbs 2003).

Vegetables are well known for their mineral and vitamin content. Among vitamins, B-complex and C are more promising along with ample quantity of vitamin K. Vegetables contain appreciable quantities of potassium, iron, sodium, calcium, and magnesium. Most vegetables are equally important for their non-nutritive components like chlorophyll, carotenoids, phenolics, fl vonoids, sulphoraphane, indoles, and anthocyanins; generally these compounds contribute to color, aroma, and fl vor. Vegetables contain enzymes such as oxidoreductases (lipoxygenases, phenoloxidases, peroxidases), hydrolases (proteases, estareses), and transfereses (transaminases).

The nutrients present in vegetables can be categorized as macro- and micronutrients.

Macronutrients

Water, carbohydrates, proteins, fat, and fibe comprise the major macronutrients.

Water

Most vegetables contain more than 80% water; however, some have more than 90%, for example, cucumber, spinach, tomatoes, cabbage, and lettuce. In comparison, starchy vegetables contain less than 80% water. The amount of moisture in the fina produce is dependent upon various factors including water availability in the field temperature, and time of harvest. Therefore, it is desirable to harvest vegetables at maximum freshness with higher moisture content. The role of water in plant physiology is indispensable for maintaining the cell integrity, growth, and transport of nutrients. As is well known, water is critical in human health; it acts as a universal solvent and transports nutrients and metabolic products throughout the body (Franks 2000). Additionally, water participates in metabolic activities of proteins, nucleotides, and carbohydrates, and in chemical reactions including hydrolysis and condensations (Taylor 1987).

Carbohydrates

Carbohydrates are the second most abundant component after water. Carbohydrate biosynthesis in plants is photosynthesis-driven. Carbon dioxide and water from the atmosphere combine to form the simple sugar glucose in the presence of sunlight through photosynthesis. Glucose is relatively unstable as its aldehyde group spontaneously oxidizes to carboxyl group; the excess glucose is usually stored as starch. Some of the simple sugars are also converted to disaccharides like sucrose that act as medium for energy transport within plant tissues.

Vegetables such as peas, beans, potatoes, and sweet potato contain appreciable quantity of starch. Carbohydrates perform a specialized role as structural component of cell wall and membranes. Table 5.1 lists the amount of carbohydrates, protein, fat, and calorie contents in vegetables.

Cellulose is an important polysaccharide that gives firmnes to the cell's structure as it is the main component of cell wall. Along with hemicelluloses, it exists in varying amounts, depending upon the nature of the plant, age, and the parts used. They act as dietary fibe and cannot be digested by humans, though they provide bulk to the food. In addition, they perform as prebiotics for the microorganisms present in the gastrointestinal tract, thus improving human health. Other carbohydrates like lignins, pectins, and oligosaccharides are also important as dietary fibe .

Proteins

Proteins are one of the important macronutrients for proper growth and development. They combine with specifi compounds to form specialized structures like tissues and organs. Vegetables are not among the rich sources of proteins. However, *Amaranthus* contains an appreciable amount of protein (17.5–38.3% of dry matter fraction) rich in lysine; a limiting amino acid in wheat. The protein composition of vegetables (Table 5.1) explicates that peas have the highest protein content. With the exception of sweet corn, Brussels sprouts, and mushrooms, typically, vegetables are poor sources of protein, i.e. $< 3\%$.

Lipids

The fatty acids and glycerol combine in random order to form mono-, di-, and triglycerides. They are nutritionally important components including fats, oils, waxes, and phospholipids. Sometimes they combine with carbohydrates and protein to form glycolipids and lipoproteins, respectively. Most of the

Table 5.1 Macronutrient composition of raw vegetables (per 100 g)

Vegetable	Carbohydrates (g)	Protein (g)	Fat (g)	Calories
Asparagus	3.88	2.20	0.12	20
Bean, green (snap)	7.13	1.82	0.12	31
Beetroot	9.55	1.61	0.17	43
Broccoli	6.64	2.82	0.37	34
Brussels sprouts	8.95	3.38	0.30	43
Cabbage	5.80	1.28	0.10	25
Carrot	9.58	0.93	0.24	41
Caulifl wer	5.30	1.98	0.10	25
Celery	2.97	0.69	0.17	16
Cucumber	3.63	0.65	0.11	15
Leek	14.15	1.50	0.30	61
Lettuce, green	2.97	1.36	0.15	15
Mushroom, white	3.28	3.09	0.34	22
Okra	7.03	2.00	0.10	31
Onion	9.34	1.10	0.10	40
Peas	14.45	5.42	0.40	81
Peppers	4.64	0.86	0.17	20
Potato, white	15.71	1.68	0.10	69
Pumpkin	6.50	1.00	0.10	26
Radish	3.40	0.68	0.10	16
Spinach	3.63	2.86	0.39	23
Sweet corn, yellow	19.02	3.22	1.18	86
Tomatoes	3.92	0.88	0.20	18
Turnip	6.43	0.90	0.10	28
Yam	27.88	1.53	0.17	118

Source: USDA Nutrient Database (http://www.nal.usda.gov).

vegetables contain less than 1% fat, but some such as Brussels sprouts, sweet corn, parsnip, and okra have >1% fat.

Dietary Fiber

It refers to the cell wall components of plants including pectin, β-glucans, hemicelluloses, cellulose, lignin, oligosaccharides, and gums. The amount of dietary fibe would vary due to the type of vegetables, maturity, growing conditions, etc. The composition of dietary fibe determines the physiological effect of a specifi vegetable (Marlett et al. 2002). The components of dietary fibe are water-soluble and insoluble fractions. Dietary fibe can be partly digestible or completely indigestible by the bacteria in the colon. The components that are partly digestible include pectin, hemicelluloses, and cellulose; however, lignin is not digestible by the bacterial enzymes. Lignin also lowers the digestibility of the other fibe components. Dietary fibe has the potential to lower blood cholesterol level, thus reducing the risk of cardiovascular disorders; it is also effective in gastrointestinal problems and weight management.

Vegetables, especially green leafy types, contain dietary fibers Artichoke, sweet potato, and turnip are among the rich sources with 6.5, 4.1, and 4.8 g of dietary fibe per one-half cup portion, respectively. Likewise, half cup of Brussels sprouts has more than 3 g of dietary fibe . Generally, dietary fibe concentrates in the peel portion; therefore, many researchers recommend consuming vegetables with their edible peel or skin portion.

Micronutrients

The micronutrients required in minute quantities are vitamins and minerals. Vitamins are further grouped as water soluble and fat soluble. Vegetables are considered to be a

major source of water-soluble vitamins; fat-soluble vitamins are present in traces, although carotenoids, a precursor of vitamin A, are available in ample amounts in carrots.

Water-soluble Vitamins

Vitamin B complex and vitamin C are water-soluble vitamins and are distributed in the water-fille compartments of vegetables. These vitamins are needed for normal body functions. Some of the water-soluble vitamins remain in the lean tissues for a specifi period and actively exchange materials with body fluid (Wildman and Medeiros 1999).

Vitamin B Complex

The important members of vitamin B complex family with reference to vegetables are briefl discussed.

Thiamin (B_1): It acts as a coenzyme in energy-yielding reactions from carbohydrate, fat, and protein. It is the key component of coenzyme thiamin pyrophosphate (TPP) that participates in decarboxylation of glucose, essential for nucleic acids synthesis. Beans and peas contain 0.28–0.36 mg/100 g and 0.25–0.52 mg/100 g vitamin B_1, respectively. Deficien y of thiamin leads to beriberi disease.

Riboflavi (B_2): Closely associated with thiamin, ribofl vin is lacking when thiamin deficien y prevails and vice versa; however, its deficien y symptoms are not obvious as thiamin. Leafy vegetables are a rich source of vitamin B_2, while serving vegetables with whole-grain or enriched bread and cereal products also enhance its level. Usually, ribofl vin contents range from 0.03 to 0.12 mg/100 g of vegetables with the exceptions of asparagus (0.08–0.30 mg/100 g) and parsley (0.18–0.60 mg/100 g).

Niacin (B_3): Nicotinic acid and nicotinamide (or niacinamide), synonymous terms used for niacin, are the active parts of niacin coenzymes, nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP) that help in oxidation-reduction reactions to provide energy (Kirkland 2004). The essential amino acid, tryptophan is the precursor of niacin (60 mg of tryptophan = 1 mg of niacin equivalent). Among vegetables, sweet potato, potato, and peppers are its rich sources along with peas and beans.

Pyridoxine (B_6): Vitamin B_6 is a group of compounds which contains pyridoxal, pyridoxine, pyridoxamine, and their phosphorylated forms. Green leafy vegetables like broccoli, caulifl wer, and spinach are amongst the rich sources. High processing temperature is detrimental to this vitamin (Dakshinamurti and Dakshinamurti 2004).

Folic acid (B_9): It is important for normal functioning of red blood cells, and its deficien y leads to macrocytic anemia. It is observed that folic acid along with vitamin B_{12} is important for a number of biochemical reactions in the body. Green leafy vegetables like spinach, legumes, as well as asparagus are potential sources of folic acid. Recently, emphasis has been placed on its inclusion in micronutrients fortificatio programs along with iron and zinc as they are effective in reducing the maternal and child mortality.

Vitamin C

Also called as antiscurvy factor, vitamin C occurs in two distinct but interchangeable forms; a reduced form called L-ascorbic acid and an oxidized form called dehydroascorbic acid. Green leafy vegetables, tomatoes, and peppers are among the good sources (Insel et al. 2007; Rickman et al. 2007a, 2007b). The vitamin C content of vegetables is given in Table 5.2. Caulifl wer, pepper, Brussels sprouts and cabbage contain 8–114 mg, 73–342 mg, 35–128 mg and 20–220 mg/100 g ascorbic acid, respectively. Vitamin C is considered the most labile of vitamins. The major routes of vitamin C loss are through thermal destruction, water leaching, and enzymatic oxidation.

Table 5.2 Vitamins and minerals content in selected vegetables (per 100 g)

Vegetable	Ascorbic acid (mg)	Carotenoids (mg)	Thiamine (mg)	Ribofl vin (mg)	Niacin (mg)	Folic acid (μg)	Calcium (mg)	Iron (mg)
Asparagus	13–41*	0.38–0.55	0.1–0.23	0.08–0.3	0.8–1.5	25–156	13–28	0.5–2.0
Beans, green	5–28	0.02–0.6	0.04–0.24	0.05–0.14	0.2–1.14	12–48	30–65	0.5–3.0
Beetroot	Trace–6	Trace–0.1	0.01–0.03	0.01–0.06	0.06–0.4	20	15–32	0.4–2.0
Broccoli	40	2.5	0.06	0.2	0.6	50	160	1.5
Brussels sprouts	35–128	0.18–0.7	0.06–0.13	0.09–0.19	0.4–1.04	14–86	10–53	0.1–2.0
Cabbage	20–220	Trace–4.8	0.03–0.17	0.03–0.21	0.15–1.55	20	30–204	0.5–1.0
Carrot	4–58	6–13.6	0.04–0.07	0.03–0.05	0.2–1.16	10	29–57	0.2–1.0
Caulifl wer	8–114	Trace–0.04	0.04–0.13	0.04–0.1	0.25–0.89	30	13–43	0.2–1.0
Celery	5–15	0–0.8	0.02–0.5	0.02–0.4	0.2–0.4	7	31–53	0.5–9.0
Cucumber	8–19	0–0.04	0.02–0.1	0.02–0.11	0.1–0.6	6	15–23	0.3–0.5
Leek	15–32	0.04–1.46	0.06–0.8	0.06–0.1	0.39–0.5	—	50–85	1.0–2.0
Lettuce, green	3–33	0.15–7.8	0.04–0.14	0.03–0.1	0.2–0.5	20	17–107	0.5–4.0
Onion	6–10	0–0.06	0.02–0.03	0.02–0.04	0.1–0.2	—	24–52	0.2–0.3
Peas	12–35	0.18–0.5	0.25–0.52	0.06–0.14	1.3–3.3	8–46	13–52	1.2–3.0
Pepper, green	73–342	0.15–2.7	0.03–0.1	0.02–0.18	0.3–2.17	—	10–29	0.7–1.0
Pumpkin	4–20	0.17–5.9	0.04–0.05	0.03–0.08	0.4–0.9	—	20–66	0.3–0.5
Potato, white	8–64	Trace–0.03	0.04–0.16	0.02–0.04	0.3–5.1	6	4–13	0.5–1.0
Radish	6–43	Trace–0.04	0–0.04	0.01–0.08	0.2–0.65	10	25–52	0.3–1.0
Spinach	1–59	2.88–7.35	0.05–0.15	0.08–0.24	0.35–0.75	53–129	60–595	0.8–4.0
Squash	3–46	Trace–4.3	0.02–0.1	0.01–0.1	0.2–1.4	8–23	9–40	0.2–2.0
Sweet corn	10	0–0.06	0.15	0.1	1.7	—	9	0.7
Tomato	19–48	0.19–1.45	0.04–0.11	0.02–0.12	0.45–0.91	5	5–14	0.4–1.0
Turnip	17–37	Trace–0.01	0.03–0.07	0.03–0.06	0.4–0.94	4 (raw)	30–65	0.1–0.3

Source: USDA Nutrient Database (http://www.nal.usda.gov).
Data ranges cover content in processed and raw forms.

Fat-Soluble Vitamins

The fat-soluble vitamins A, D, E, and K are mainly concentrated in the lipid part of the food. Most of these vitamins act as antioxidants and protect the body from free radicals damage. Vegetables are not considered a good source of these vitamins.

Carotenoids present in some vegetables transformed into vitamin A and are often referred to as precursors of vitamin A or provitamin A. About 50 carotenoids are recognized as provitamin A, of which β-carotene is the major contributor from plant sources (Harrison 2005). Both α-carotene and β-cryptoxanthin deliver substantial amounts of vitamin A in the diets. The activity of β-carotene and other provitamin A carotenoids is assumed to be 1/6th and 1/12th of retinol, respectively (FAO/WHO 1988). β-Carotene is present in spinach and vegetables such as broccoli and cabbage. Human body absorbs about 75% of the carotenoids, of which 10% are transformed into retinol while the rest are stored in the form of retinyl esters in the liver (Insel et al. 2007).

Vegetables also contain vitamin K; the compounds exhibiting vitamin K activities are often called quinones. Phylloquinone derived from plants is the most active form of this family. Green leafy vegetables such as spinach, turnip greens, and broccoli can be a good source of phylloquinone in our diet.

Minerals

Calcium is one of the important minerals because of its critical role in bone and teeth development. However, its requirements vary with age of the individuals. Its deficien y leads to the onset of rickets in children and osteomalacia and osteoporosis in adults, though reduced intakes of vitamin D and

phosphorous are the major contributory factors. Carrots, onions, cluster beans, okra, turnip, and artichoke are the good sources among vegetables. However, bioavailability of minerals from different vegetables is important while assessing the mineral profil of vegetables, for example, spinach contains an appreciable quantity of calcium but the presence of oxalates hinders its absorption. Phosphorous acts synergistically with calcium in bone development. Moreover, it is important in human metabolism, and nerve and muscle function. Peas, beans, and potatoes are good sources of phosphorous.

Spinach and green leafy vegetables contain ample amounts of magnesium, as it is an integral part of chlorophyll. It plays a role in enzyme activation required for energy-yielding reactions. It is also required by the genetic material and for proper bone development. Green beans, mushrooms, and broccoli contain considerable amount of potassium which helps in maintaining regular flui balance and proper functionality of nerves and muscles.

Beans, spinach, and cabbage enhance body reserves of iron, although sometimes the presence of oxalic acid in some vegetables hinders its absorption. Iron intake is important as it is an integral part of hemoglobin essential for oxygen transport. Zinc enhances the bioavailability of iron from the diet; among vegetables, beans, potatoes, and pumpkin are important sources of zinc. It is important in improving the oxidative defense capacity of the body.

Selenium, copper, manganese, and molybdenum are the other minerals present in vegetables. They are required in very small amounts but are components of various reactions within the body. Selenium interacts with vitamin E to prevent the breakdown of fats and body metabolites.

Phytochemicals

Phytochemicals are the bioactive molecules in plant foods that provide protection against diseases, free radical scavenging, and antimicrobial properties. Vegetables are a rich source of phytochemicals, such as carotenoids, chlorophylls, anthocyanins, and fl vonoids (Andersen and Jordheim 2006). Additionally, these compounds give specifi color to the vegetables; for example, chlorophyll yields green, xanthophylls give yellow, while anthocyanins-containing vegetables are usually red or purple. Likewise, lycopene, a carotenoid, is responsible for the red color of tomatoes and watermelon.

The carotenoids family consists of around 600 compounds; β-carotenes, α-carotene, lutein, lycopene, cryptoxanthin, and zeaxanthin are more prominent. Carotenoids and their sources are important not only as a precursor of vitamin A but also because of their health-promoting properties. Flavonoids like resveratrol, anthocyanins, and quercetins are present in several vegetables. Red-colored vegetables contain resveratrol, considered to be effective in reducing the risk of cardiovascular disorders. Anthocyanins-containing vegetables provide protection against the signs of aging and urinary infections (Rice-Evans et al. 1995; Cook and Sammon 1996). Quercetin, a potential natural antioxidant, is present in onions, kale, broccoli, lettuce, and garlic.

Sulphoraphane and indoles are the class of phytochemicals called isothiocyanates. They are effective in reducing the risk of certain types of cancer including breast and colon cancers (Steinmetz and Potter 1996). Cruciferous vegetables such as broccoli, caulifl wer, kale, Brussels sprouts, cabbage, collard greens, and turnips are the recognized sources of sulphoraphane.

Garlic, onions, chives, leeks, and scallions are rich sources of sulfur-containing compounds, for example, diallyl sulfide allicin (diallyl thiosulphate), δ-glutamyl-S-allyl-L-cysteines, and S-allyl-L-cysteine sulfoxides (alliin) collectively called allium compounds. They are effective in reducing the risk of certain types of cancer as well as in managing

cholesterol and blood pressure (Butt et al. 2009). These vegetable sources also contain quercetin. Corn, water squash, and spinach are rich sources of zeaxanthin.

Health Benefits

Pivotal links have been established between dietary components and human health (Schwager et al. 2008; Ares et al. 2009). There is evidence that consumption of vegetables is important for human health (Tapsell et al. 2006) as they are good sources of dietary fibers antioxidants, carotenoids, sulfur-containing compounds, water-soluble vitamins, and minerals (Steffen 2009). Epidemiological studies conducted in various parts of the world have revealed that consumption of vegetables rich in these functional ingredients is associated with reduced risk of chronic disorders (Visioli and Hagen 2007).

Consumption of antioxidant-rich foods may improve antioxidant defense mechanism and provide protection against oxidative damage caused by the free radicals (Valko et al. 2007). The process of cellular metabolism produces reactive oxygen species like hydrogen peroxide and the superoxide anion free radical. There is consensus that free radical production causes oxidative stress whenever there is an imbalance between antioxidants and oxidants. Different studies have shown that antioxidants can play a key role in delaying ailments and conditions that are associated with aging such as cancer, heart disease, decreased immune function, and visual and cognitive impairment (Tapsell et al. 2006).

Dietary phytoestrogens have been reported to be helpful in reducing the risk of certain hormone-stimulated malignancy such as breast and prostate cancers (Murphy and Hendrich 2002). However, further research is needed to fully elucidate their anticancer properties. Flavonoids found in garlic and onions are being studied for control of cancer-cell proliferation through specifi enzyme inhibition (Table 5.3).

Cardiovascular Diseases

Management of plasma cholesterol continues to be the topmost issue in the prevention of cardiovascular diseases (CVD). Hypercholesterolemia and low-density lipoprotein (LDL) oxidation play a key role in the onset of atherosclerosis characterized by high cholesterol, especially LDL and inflammation Owing to rich phytochemistry with special reference to polyphenols, natural products might be suitable for coronary care and regulation of blood cholesterol (Singh et al. 2007; Matsuura et al. 2008).

Vegetables which are effective in reducing the pathogenesis of cardiovascular disorders are listed in Table 5.3. In one example, garlic and its extracts were shown to reduce the risk of CVD by decreasing cholesterol and LDL, and improving the high-density lipoprotein (HDL) level of the body. Moreover, they are effective in reducing platelet aggregation and lowering arterial calcificatio and homocysteine levels in the body (Butt et al. 2009). Cabbage and broccoli, excellent sources of indoles, dithiolthiones, isothiocyanates, and chlorophyllins, are also effective in minimizing the risk of heart attack (Howard and Kritchevsky 1999). Sweet potato, garlic, and onion are useful in reducing arterial calcifica tion that leads to artery hardening. Cabbage, bitter gourd, spinach, Brussels sprouts, ginger, and garlic are contributors in proper circulation of blood; tomatoes and broccoli are beneficia in reducing blood pressure. Obesity is also a risk factor for cardiovascular disorders, and vegetarians in many surveys have shown less body mass index (BMI) than that of people who consume meat and dairy products (Key and Davey 1996).

Cancer

Cancer is the second leading cause of death in the United States, following heart disease. There are many factors which are involved in the pathogenesis of cancer, for example,

Table 5.3 Phytochemicals and health benefits of selected vegetables

Name	Phytochemicals	Health benefit
Asparagus	Dietary fibe , vitamin, and fl vonoid	Antibiotic, antispasmodic, demulcent, diaphoretic, diuretic, laxative
Broccoli	Sulphoraphane, indoles, β-carotene, lutein, and quercetins	Antioxidant status, anticancer potential, reduce LDL oxidation
Brussels sprouts	Sulphoraphane and indoles	Protects from DNA damage, lowers risk of heart attack, anticancer potential, improves gastrointestinal tract
Cabbage	Sulphoraphane and indoles	Antioxidant, anticancer, improves digestion and skin tone
Carrots	β-Carotene	Effective in diabetes mellitus, lowers cholesterol, reduces colon cancer, improves skin tone
Caulifl wer	Sulphoraphane and indoles	Improves antioxidant capacities and detoxificatio mechanisms
Cucumber	Antioxidants, carotenoids, and vitamins	Antioxidant potential, improves the skin tone
Garlic	Sulfur-containing compound	Antioxidant potential, cardiovascular disorders, and anticancer activities
Lettuce	Quercetins and carotenoids	Antioxidant, anticancer properties, and cardiovascular disorders
Okra	Antioxidants	Prevents constipation, improves heart health
Peas	Proteins and fiber	Lowers cholesterol and improves bone health
Potato	Antioxidants	Antioxidant, effective against diabetes mellitus
Pumpkin	β-Carotene	Antioxidant, anti-inflammator perspectives, inhibits arthritis and prostate cancer, improves skin tone
Radish	Anthocyanins	Reduces weight, respiratory problems, and diabetes mellitus
Spinach	β-Carotene, lutein, and zeaxanthin	Prevents lung, colon, and breast cancer; protects from blindness and memory loss
Squash	α- and β-Carotenes, zea-xanthin	Prevents atherosclerosis, lowers the cholesterol
Sweet potato	β-Carotene	Antioxidant and anti-inflammator properties, lowers cholesterol and LDL, effective in diabetes mellitus
Tomato	Lycopene	Potent antioxidants, lowers cholesterol/glucose, anticancer potential
Turnips	Indoles and sulphoraphane	Cardiovascular disorders, high blood glucose

Source: Butt et al. (2009), Gorbach and Goldin (1992), Howard and Kritchevsky (1999), and Hsing et al. (2002).

genetic mutation, smoking, heavy metal ingestion, and indeed lack of proper diet.

According to the American Institute for Cancer Research, chances of cancers can be prevented up to 30–40% by adopting physical and dietary advice from competent nutritionists. Consumption of vegetables is regarded as the second most important strategy for cancer prevention after giving up on the smoking habit. The effective vegetables in this category are onions, garlic, beans, carrots, corn, and dark leafy vegetables. The diets containing these vegetables provide resistance against mouth, pharyngeal, esophageal, lung, stomach, and colon cancer.

Among vegetables, garlic and onions are more popular for their anticancer properties (Hsing et al. 2002). These vegetables have sulfur-containing compounds and quercetin, which are effective against cancer. Some dietary supplements like aged garlic extract (AGE) and Di-allyl disulfid and ajoene derived from garlic have shown chemopreventive action. Similarly, tomatoes and its lycopene-rich products have potential for minimizing certain forms of cancer.

Isothiocyanates present in spinach and broccoli also prevent cells from becoming cancerous. Similar to carotenoids, high-fibe diet is effective in reducing the risk of colon

cancer. Considering the importance of fibe , the National Cancer Institute (USA) and American Diabetes Association have suggested daily dietary fibe intake of 20–35 g.

Diabetes Mellitus

Diabetes mellitus and its complications are one of the leading causes of deaths in the world. It is estimated that by the end of 2030, approximately 376 million people will be affected worldwide with diabetes (Wild et al. 2004). Drug therapies are obligatory, but in addition to side effects, their effectiveness decreases with the passage of time (Zakir et al. 2008). Proper diet is imperative for the management of diabetes and its accompanying complications including immune dysfunction, degenerative, and cardiovascular disorders.

The diets containing higher amounts of fibe , fruits, and vegetables are considered effective to control this metabolic syndrome. The vegetables that are helpful in management of diabetes mellitus are listed in Table 5.3. There are some components in bitter gourd that possess anti-obesity properties that may be helpful for weight management and glycemic response.

Digestive Health

The gastrointestinal tract is an intricate arrangement of tissues and organs responsible for conversion of carbohydrates, proteins, and lipids into simple sugars, amino acids, and fatty acids, respectively. It plays a key role in the transport of nutrients and phytochemicals into the blood for their delivery to body cells. Consumption of diets high in sugars and fats is often linked with digestive problems. Dietary fiber are needed to maintain gut health and their deficien y can cause gastro-esophageal reflux diverticular, and Crohn's diseases.

Furthermore, dietary factors influenc the frequency and severity of gastrointestinal disorders. The fibrou portion of diets is also helpful for the microorganisms living in the gastrointestinal tract. The activities of these bacteria are of prime significanc as they provide some essential nutrients to humans. Spinach is one such example that can stimulate digestive secretion, thus improving the gut health.

Vegetables should be cooked before their use as their digestibility is improved by heating. The sulfur-containing compounds present in some vegetables are helpful in digestion.

Miscellaneous Health Benefits

There are several other health benefit owing to the consumption of vegetables. Improvement in the immune system and disorders like bronchitis, cataracts, asthma, and other respiratory syndromes is often mentioned.

The concept of immuno-nutrition utilizes the beneficia role of microorganisms residing in the gastrointestinal tract (Gorbach and Goldin 1992; Wu et al. 2001). Many formulations containing probiotics are available in the market. The vegetables which improve the immune functioning include cabbage, caulifl wer, bitter gourd, garlic, onions, carrots, Brussels sprouts, to name a few.

According to a study, eating fruits and vegetables often has a protective effect against cataract (Christen et al. 2005). In different epidemiological studies, it is reported that humans relying on fruits and vegetables have 10–15% lower risk of developing cataract than those who ate less amounts of fruits and vegetables.

Nutrient Losses during Food Processing

Vegetables are perishable commodities and postharvest losses are established to be greater than 20–40% in the tropical and subtropical regions. The main losses occur during harvesting, transportation, storage, and

Table 5.4 Effects of processing on various nutrients

Nutrient	Processing effects
Fat	• Oxidation accelerated by light
Protein	• Denatured by heat (improves digestion)
Amino acids	• Some are sensitive to light. Lysine bio-availability reduced by non-enzymatic browning
Vitamin C (ascorbic acid)	• Decreases during storage, drying, heating, oxidation, cell damage (e.g., chopping or slicing) • Stable to heat under acidic conditions
Vitamin B1 (thiamine)	• Destroyed by high temperatures, neutral and alkaline (e.g., baking soda, baking powder) conditions. • Lost in cooking water
Vitamin B2 (ribofl vin)	• Sensitive to light at neutral and alkaline conditions • Moderately heat stable under neutral conditions • Sensitive to heat under alkaline conditions
Vitamin B3 (niacin, nicotinamide)	• The most stable vitamin • Stable to heat and light • Leaches into cooking water
Folate	• Decreases with storage or prolonged heating • Lost in cooking water • Destroyed by use of copper utensils
Vitamin B6 (pyridoxine, pyridoxal)	• Heat stable in alkaline and acidic conditions • Pyridoxal is heat labile
Vitamin B_{12}	• Destroyed by light and high pH
Carotenes	• Easily destroyed by heat • Oxidize and isomerize when exposed to heat and light
Vitamin A	• Very heat labile—easily destroyed by heat • Easily oxidized
Vitamin D	• Oxidizes when exposed to heat and light
Vitamin E	• Oxidizes readily

Source: Morris et al. (2004).

processing. The harvesting losses can be overcome by adopting appropriate technologies, whereas moisture losses during transportation can be minimized by proper packaging.

Processing of vegetables has the following objectives: (1) improving the shelf life and quality of vegetables, (2) enhancing the palatability and digestibility of vegetables, and (3) inactivation of nutritional inhibitors that increase protein and other nutrients' availability.

The nutritional losses during processing are of significan importance (Somsub et al. 2008) as cooking is necessary in order to improve the palatability and digestibility of vegetables. Cooked vegetables are more digestible as compared to raw, with the exception of cucumber, which is usually consumed fresh. A summary of effects of processing on nutrients is given in Table 5.4.

Thermal processing is the commonly used method in household and industrial food production. However, high processing/cooking temperatures can affect heat labile vitamins and amino acids. In some cases, excessive heating may cause the generation of toxic metabolites. Figure 5.1 shows loss of vitamin C in peas as a result of various preparations, processing, or cooking steps, which ranges from 56 to 65% (Christian and Greger 1988).

Canning

Vegetables such as peas, beans, and green leafy vegetables are canned after preparatory operations like washing, sorting, peeling,

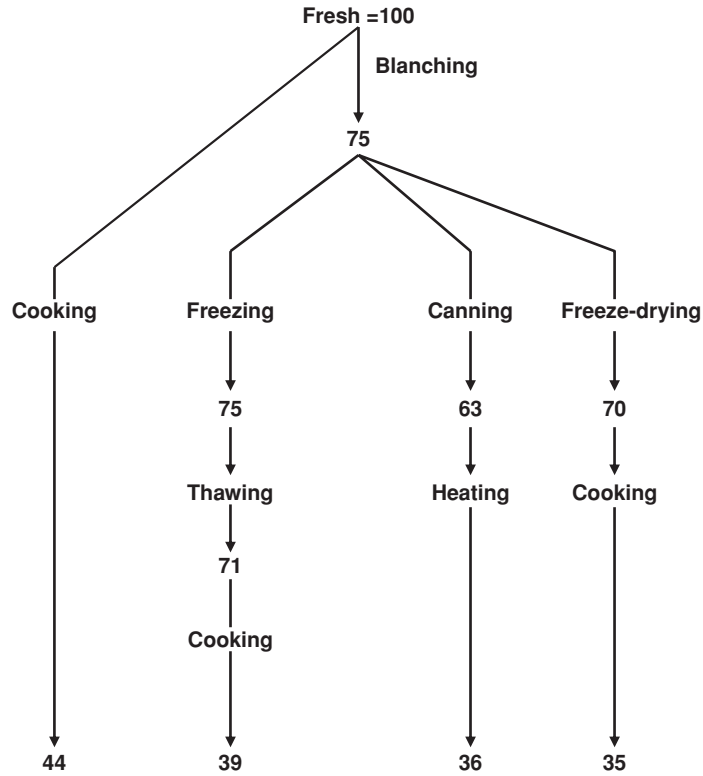

Figure 5.1 Percentage of vitamin C retained in peas by currently used processing and cooking methods (Christian and Greger 1988).

trimming, chopping, filling exhausting, and sealing, following which heat treatment is applied to safeguard the food from the hazardous effects of microorganisms and enzymes.

Heat treatment is also responsible for nutritional and quality losses. There are slight changes in color, fl vor, texture, and overall acceptability of the produce. The water-soluble vitamins and phytochemicals are lost during excessive heating (Figure 5.2). Broadly, thermal degradation and leaching are the two main causes of nutritional losses (Kalt 2005; Martínez and Whitaker 1995). However, it is not possible to generalize the losses during processing as these vary with conditions and method applied. These losses are further dependent on the following factors: improper preparation of foods; temperature of blanching and/or heat treatment; contamination and decomposition during heating; and exposure to air and high temperature for a long time.

During heat treatment, vitamin C losses range from 15 to 40%. Such losses even continue during storage of canned items. Similarly, thiamin tends to decrease by about 50% during processing and further 15–40% after 12 months of storage. Canned vegetables have 12–15% less ribofl vin as compared to fresh produce, and during subsequent storage, the losses may extend up to 50%. However, niacin and other vitamins are heat stable. Like vitamins, losses in carotenoids ranged from 15–50% during heat treatment (Figure 5.3). Blanching of vegetables for a period of

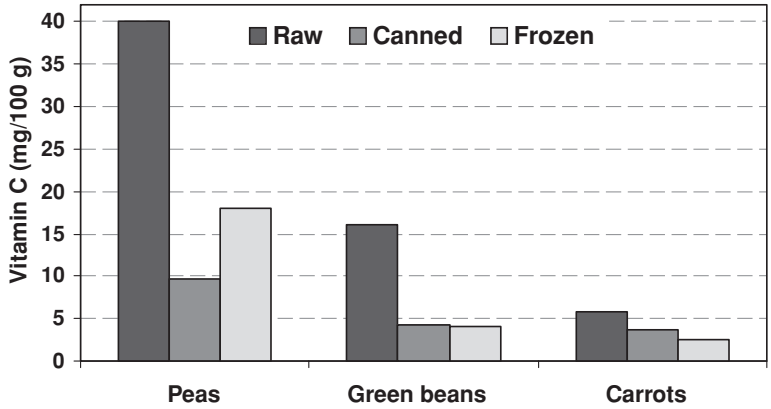

Figure 5.2 Effect of processing on vitamin C content in selected vegetables. (USDA Nutrient Database (USDA 2009).)

1 minute resulted in 12–-26% loss in total phenolics (Ismail et al. 2004). During canning, chlorophyll is converted to pheophytin due to the high temperatures. Loss of amino acids during processing and postcanning storage may influenc the fl vor of canned products. In one such example, heating peas at 120°C for an hour resulted in 6.9% loss of amino acids. In another study, it is observed that losses in amino acids during blanching are relatively high for spinach as compared to peas.

The antioxidant potential of vegetables is also of significan importance (Kaur and Kapoor 2001). Losses in the antioxidant potential of some vegetables have been presented in Figure 5.4. It was reported that the canning process resulted in reduced (18% to 35%) antioxidant activities of garlic, peas, broccoli, and Brussels (Murcia et al. 2009).

The canned products further spoil (fla sour, bacillus spoilage, and hydrogen swell) due to microbes and enzymes. The nutritional losses during canning can be minimized

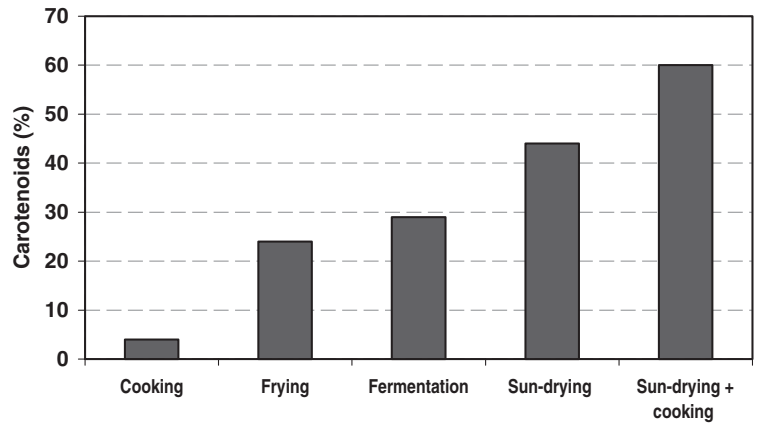

Figure 5.3 Carotenoids losses in green leafy vegetables during processing. (Speek et al. 1988.)

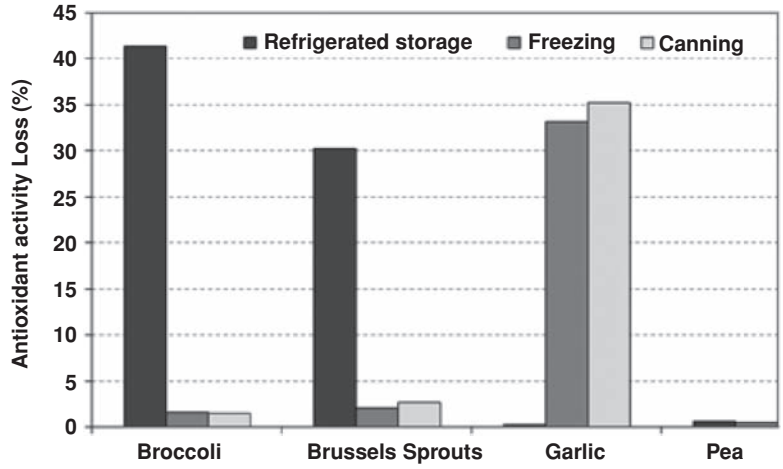

Figure 5.4 Losses in antioxidant activity of some vegetables (Murcia et al. 2009).

by the following guidelines (MacEvilly and Peltola 2003; Titchenal and Dobbs 2003):

- Optimized conditions during canning and storage of vegetables are accomplished, avoiding extremely high or low temperatures and relative humidity.
- Use of tin containers instead of glass should be preferred due to ease of handling and heat exchange abilities.
- Aseptic fillin is more useful for vegetable juices or puree.
- Continuous agitation can reduce the processing time.
- Proper exhausting of the air from the cans reduces the nutrient losses.
- Storage should be done at a suitable temperature.

Drying/Dehydration

Drying is as old as human history, and early man dried the vegetables for their intended use during off-season. The promising drying methods employed are sun drying, still air, forced air, and spray drying.

During the drying/dehydration process, extra heat is applied to evaporate the moisture and in such cases, interaction between amino acids and reducing sugars (Maillard reaction) may occur, resulting in quality and hedonic loss (Martínez and Whitaker 1995). Drying also induces significan losses in water-soluble vitamins and phytochemicals like carotenoids and anthocyanins. Nonetheless, vitamin retention of dehydrated vegetables depends on the nature of the crop and sensitivity of the particular vitamin against heat, oxygen, and light (Chun et al. 2006). These losses may be curtailed by the guidelines given below:

- Sulphiting can be introduced to inhibit enzymatic browning and Maillard reaction.
- Reducing the moisture content below 1–3% retards the process of browning; however, the time/temperature relationship should be properly managed.
- Storing dried products at cool temperature also minimizes the quality deterioration. Modifie atmosphere packaging and controlled atmosphere storage are modern techniques to retard the deteriorative process during storage.

Freezing

Freezing ensures the shelf life of the produce with maximum nutrient retention. Frozen

Table 5.5 Nutrient losses in peas and spinach resulting from blanching

		Losses (%)	
Vegetables	Nutrient	Steam blanching	Water blanching
Peas	Vitamin C	12	26
Peas	Amino acids	13	25
Spinach	Amino acids	60	80

Source: Lund (1975).

foods retain their natural color, fl vor, and texture better than those that are heat processed. The important benefit derived from freezing of vegetables are described as follows:

- Prevents the growth of spoilage organisms and retards the activity of enzymes
- Minimizes the deteriorative changes in nutritive value
- Enhances the shelf life of the produce

The nutritional losses during freezing are mainly due to some preparatory operations, especially blanching prior to freezing. Although there are some benefit of blanching as it inactivates the growth of microorganisms and retards the activities of the enzymes, some nutrient losses, for example, 9–60% in thiamin and up to 20% in ribofl vin, are reported in green peas and beans as a result (Salunkhe et al. 1991). Table 5.5 shows a comparison of losses resulting from steam or water blanching. Blanching vegetables in hot water incurs significantl higher nutrient losses as a result of leaching.

Changes in proteins and amino acids occur in stored processed foods. Freeze-dried mushroom stored at 30°C for 9 months showed decrease in aspartic acid, threonine, asparagines, serine, valine, phenylalanine, ornithine, lysine, and histidine, and increase in glutamic acid, proline, alanine, methionine, and argenine as compared to those at 0°C.

The process of thawing is a contributory factor in nutrient loss. As the temperature of food rises during thawing, growth of spoilage organisms begins. It is advisable to thaw food in slightly warm water with agitation as this process reduces the thawing time. Oxidation of ascorbic acid in frozen vegetables proceeds very slowly at –18°C; however, 25–40% losses in the ascorbic acid content have been reported above this temperature.

The antioxidant activities of vegetables are also affected as a result of refrigeration and freezing. Industrial refrigeration of vegetables for 7 days resulted in reduced antioxidant activities of broccoli, asparagus, garlic, spinach, green beans, Brussels sprouts, and peas. However, industrial freezing of vegetables maintained the antioxidant capacities. On the contrary, antioxidant activities of garlic and onion were reduced as a function of freezing and subsequent storage, while antioxidant potential remained unaffected due to refrigeration (Murcia et al. 2009).

Organic versus Conventional Vegetables

High crop yields are obtained through good agricultural practices, application of fertilizers and pesticides, and use of high-yielding varieties. However, such operations, especially the use of pesticides, create opportunity for harmful chemicals to enter the food chain and cause potential health hazards including heavy metal toxicity, liver damage, cancer, and oxidative stress. As a result, the concept of organic food production aimed at growing crops by following natural farming practices free of chemical fertilizers and pesticides has taken root (Ewa 2007).

Production of organically grown foods is part of a broad movement consisting of a spectrum of attitudes and practices with

social, philosophical, and agronomic implications (Lintas 1992). However, neither an officia definitio nor standard for organically grown foods exists. Scientifi basis has been sought in the recent years to establish the superiority of organic foods over conventional foods. Generally, it is considered that organic foods are safer due to the absence of pesticide and fertilizer residues. Growers are also emphasizing that organic foods contain a better arrangement of nutrients as a result of superior resource management.

Worthington (2001) compared the signifi cance of organic and conventional vegetables and observed that vitamin C contents were 17–52% higher in organic vegetables. Likewise, minerals including iron, phosphorous, and magnesium were also relatively high, i.e., 12–41%, 13–69%, and 13–22%, respectively. In another study, vitamin C, potassium, calcium, and magnesium were significantl high in organic foods as compared to conventional foods (Bourn and Prescott 2002). The most important criterion for the selection of organic foods is the absence of the hazardous effects of excessive pesticide sprays and fertilizer application (Anonymous 2006). The concept of organic food has led to kitchen gardening to get healthy vegetables free from pesticide and fertilizer residues as well as genetically modifie products.

Summary

Vegetables are an important component of human diet due to their diverse nutrient profil and rich phytochemistry. In the recent years, unprecedented growth has been witnessed in the consumption of vegetables. Vegetables are a rich source of essential nutrients, especially carbohydrates, vitamins, and minerals. Moreover, the presence of phytochemicals has enabled this group to perform several therapeutic functions, for example, effectiveness against cardiovascular disorders, cancer, and diabetes mellitus. Substantial quantities of nutrients are lost during processing operations like canning, dehydration, and storage; thus, care should be taken to reduce such losses. Developments in scientifi knowledge have led to consumer awareness for the use of safe foods. The concept of organic food has flourishe with allied benefit over conventionally grown vegetables. Overall, daily four to fi e servings of vegetables are recommended to cope with the requirements of essential nutrients; however, the type and conditions of processing are important in this context.

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Chapter 6

Bioactive Phytochemicals in Vegetables

Fereidoon Shahidi, Anoma Chandrasekara, and Ying Zhong

Introduction

Vegetables are important components of human diet, providing not only a broad range of nutrients such as essential vitamins and minerals but also a rich source of bioactive phytochemicals. Diets rich in protective agents such as those present in fruits, vegetables, and whole grains are believed to have benefi cial effects on our health. International studies suggest that a daily intake of 400–600 g of fruits and vegetables is associated with a 50% reduction in incidence of some aerodigestive tract cancers (World Cancer Research Fund and American Institute for Cancer Research 1997).

Phytochemicals are nonnutrient bioactive compounds found in plant foods, including fruits, vegetables, grains, nuts, and seeds, among others. Many phytochemicals participate in biological processes of the plant and may also affect the color and fl vor of foods (Naczk and Shahidi 2003). Phytochemicals are categorized into different groups according to their chemical structures (e.g., polyphenols, carotenoids, organosulfur compounds, alkaloids, and N-containing compounds). Although a single phytochemical may display one or more bioactivities, the mixture of different components consumed as a whole may act in a complementary or synergistic manner and render health effects that are not found for isolated pure phytochemical supplements (Heber 2004).

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Vegetables are rich in phytochemicals that can reduce platelet aggregation, modulate synthesis and absorption of cholesterol, and reduce blood pressure (Sanchez-Moreno et al. 2000). Some phytochemicals such as many polyphenols are anti-inflammator agents by acting as inhibitors of cyclooxygenase (COX)-2, a proinflammator cytokine that is not detected in most normal tissues but inducible by inflammator and mitogenic stimuli (Heber 2004). Some phytochemicals display anticancer activity. A consistently higher intake of fruits and vegetables is believed to provide protection against cancers of the lung, colon, breast, cervix, esophagus, oral cavity, stomach, bladder, pancreas, prostate, and ovary (Block et al. 1992). The dietary phytochemicals in vegetables such as lycopene in tomatoes, glucosinolates in broccoli, Brussels sprout, and kale, and allyl sulphides in garlic can limit DNA and chromosome damage through antioxidant action, modulation of detoxificatio and immune system, interference with hormone metabolism and regulation of gene expression in proliferation, cell cycle activity, and apoptosis in cancer (Pinto and Rivlin 2001; Singh et al. 2002).

Vegetables, similar to other food sources, show variation in both content and composition of their phytochemicals due to genetic and environmental factors. The climate, season, temperature, and rainfall, as well as cultural practices (e.g., native, uncultivated/semicultivated, and commercially produced), processing techniques (e.g., frying, steaming, and boiling), and storage conditions are

all important factors affecting phytochemical content in vegetables and related food products (Cartea and Velasco 2008; Rodriguez-Amaya et al. 2008). This chapter provides an overview of phytochemicals in vegetables with insight into their distribution, chemical characteristics, bioactivities, and potential health effects.

Bioactive Phytochemicals in Vegetables

In general, vegetables are rich sources of various classes of phenolic compounds, which include phenolic acids and fl vonoids such as fl vones, fl vonols, fl vonones, fl vononols, isofl vones, and fl vans, and amino phenolic compounds.

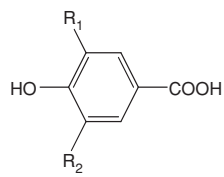
Phenolic Compounds

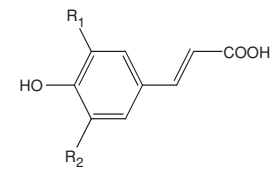
Plant phenolics are a group of secondary metabolites composed of an aromatic ring bearing one or more hydroxyl groups, together with a number of other side groups (Shahidi and Naczk 2004). Phenolic compounds occur most widely in plants as simple phenolics, phenolic acids (Figure 6.1), fl vonoids, coumarins, stilbenes, tannins, lignans, and lignins (Naczk and Shahidi 2006). Flavonols are among the major fl vonoids commonly found in vegetables (Figure 6.2).

Phenolic compounds such as tannins have the ability to bind and precipitate macromolecules such as protein, carbohydrates, and digestive enzymes, thus causing harmful nutritional effects (Lugasi et al. 2003). However, their potency as antioxidants and free radical scavenging can have positive effects on cardiovascular diseases and certain cancers (Duthie et al. 2000; Tapiero et al. 2002).

Two classes of phenolic acids, hydroxybenzoic acids and hydroxycinnamic acids, are found in plants (Shahidi and Naczk 2004, Figure 6.1). The compounds with a phenyl ring (C_6) and a C_3 side chain are known as phenylpropanoids and serve as precursors for the synthesis of other phenolic compounds. The fl vonoids are synthesized via condensation of a phenylpropanoid with three molecules of malonyl coenzyme A, leading to the formation of chalcones. The chalcones are subsequently cyclized under acidic conditions to form fl vonoids (Shahidi and Naczk 2004).

The polyphenol content in plant materials depends on a number of external factors, such as agronomic practices, light, and climatic and postharvest conditions (DuPont et al. 2000; Romani et al. 2002). Phenolic compounds are able to scavenge reactive oxygen species (ROS) due to their electron- and hydrogen-donating properties. Their antioxidant effectiveness depends on the stability of

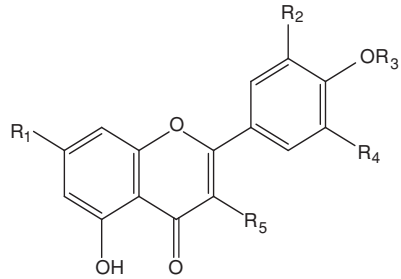




Benzoic acid derivatives	R_1	R_2
p-Hydroxybenzoic acid	H	H
Vanillic acid	OCH_3	H
Syringic acid	OCH_3	OCH_3
Protocatechuic acid	H	OH
Gallic acid	OH	OH

Cinnamic acid derivatives	R_1	R_2
p-Coumaric acid	H	H
Caffeic acid	H	OH
Sinapic acid	OCH_3	OCH_3
Ferulic acid	OCH_3	H

Figure 6.1 Structures of phenolic acids.



Compound R	R_1	$_2$	R_3	R_4	R_5
Kaempferol	OH	H	H	H	OH
Rutin	OH	OH	H	H	*O*-rutinoside
Quercetin	OH	OH	H	H	OH
Quercirtrin	OH	OH	H	H	*O*-rhamnoside
Isoquercirtrin	OH	OH	H	H	*O*-glucoside
Myricetin	OH	OH	H	OH	OH
Isorhamnetin	H	OCH_3	OH	H	OH

Figure 6.2 Structures of some flavonol derivatives.

compounds in different systems, as well as the number and the location of hydroxyl groups in the molecule of interest (Shahidi and Naczk 2004).

Phenolic Compounds in Fruit Vegetables

Fruit vegetables such as peppers, tomatoes, eggplant, bitter melon, and pumpkin are reported to contain a wide array of phenolic compounds. Some of the common free phenolic acids found in sweet pepper (*Capsicum annuum*) include protocatechuic, chlorogenic, coumaric, and ferulic acids (Estrada et al. 2000). The pericarp of sweet peppers (*Capsicum annuum*) constituted of hydroxycinnamic derivatives, *O*-glycosides of quercetin, luteolin, and chrysoeriol, and a number of C-glycosyl fl vones (Marin et al. 2004) (Table 6.1). The total phenolic content in pericarp of sweet pepper decreased during fruit maturation from 20.24 to 2.54 mg/100 g fresh weight (fw). Quercetin-3-*O*-rhamnoside and luteolin 7-*O*-(2-apiosyl-6-malonyl) glucoside were the major phenolic compounds reported in sweet pepper, representing 41% of total fl vonoids. Furthermore, phenolic compounds in sweet pepper were mainly located in the peel (Marin et al. 2004).

In hot pepper, sinapic and ferulic acids constituted 60% of the dry mass while the content of luteolin apiosylglucoside and quercetin rhamnoside was 35% (Howard et al. 2000). Red fruits of four cultivars (Bronowicka Ostra, Cyklon, Tornado, and Tajfun) of hot pepper fruits showed higher antioxidant activity than that of green fruits as determined by β-carotene/linoleic acid model system and the radical scavenging activity by the 1,1-diphenyl-2-picrylhydrazyl (DPPH) assay (Materska and Perucka 2005). Among the several phenolics (Table 6.1) identifie in red hot pepper, sinapoyl and feruloyl glycosides were isolated as the major compounds. However, quercetin-3-*O*-L-rhamnoside was the main compound, which decreased during fruit maturation in green pepper (Materska and Perucka 2005).

Bitter melon (*Momordica charantia*) or bitter gourd is widely used as a vegetable in Asia and has been studied for its hypoglycemic (Ali et al. 1993; Srivastava et al.

Table 6.1 Phenolic compounds in vegetables

Vegetables	Phenolic compounds	References
Sweet pepper	Quercetin 3-*O*-rhamnoside, quercetin-3-*O*-rhamnoside-7-*O*-glucoside, luteolin 7-*O*-(2-apiosyl)-glucoside, luteolin-7-*O*-(2-apiosyl-6-acetyl)glucoside, luteolin-7-*O*-(2-apiosyl-diacetyl)-glucoside, luteolin-7-(2-apiosyl-6-malonyl)glucoside, chrysoeriol-7-*O*-(2-apiosyl-6-acetyl) glucoside, 6,8-di-*C*-hexosyl of luteolin, apigenin, chysoeriol, 6-*C*-pentosyl-8-*C*-hexosyl of luteolin, apigenin, chysoeriol, 6-*C*-hexosyl-8-*C*-pentosyl of luteolin, apigenin, chysoeriol, luteolin 6-*C*-hexosyl-8-*C*-rhamnosyl, luteolin 6-*C*-rhamnosyl-8-*C*-hexosyl, luteolin 6-*C*-(6-malonyl)hexosyl-8-*C*-hexoside, luteolin 6-*C*-(6-malonyl)hexosyl-8-*C*-pentoside	Marin et al. 2004
Hot pepper	*trans*-*p*-Feruloyl-β-D-glucopyranoside, *trans*-*p*-sinapoyl-β-D-glucopyranoside, quercetin 3-*O*-α-L-rhamnopyranoside-7-*O*-β-D-glucopyranoside, *trans*-*p*-ferulyl alcohol-4-*O*-[6-(2-methyl-3-hydroxypropionyl)] glucopyranoside, luteolin 6-C-β-D-glucopyranoside-8-C-α-L-arabinopyranoside, apigenin 6-*C*-β-D-glucopyranoside-8-C-α-L-arabinopyranoside, luteolin 7-*O*-[2-(β-D-apiofuranosyl)-β-D-glucopyranoside], quercetin 3-*O*-α-L-rhamnopyranoside, luteolin 7-*O*-[2-(β-D-apiofuranosyl)-4-(β-D-glucopyranosyl)-6-malonyl]-β-D-glucopyranoside	Materska et al. (2003), Materska and Perucka (2005)
Eggplant	Delphinidin 3-(*p*-coumaroylrutinoside)-5-glucoside (nasunin), delphinidin 3-rutinoside, delphinidin 3-glucoside, petunidin 3-(*p*-coumaroylrutinoside)-5-glucoside, delphinidin 3-caffeoylrutinoside-5-glucoside	Azuma et al. (2008)
Spinach	Patuletin 3-*O*-β-D-glucopyranosyl(1→6)-[β-D-apiofuranosyl(1→2)]-β-D-glucopyranoside, spinacetin 3-*O*-β-D-glucopyranosyl(1→6)-[β-D-apifuranosyl(1→2)]-β-D-glucopyranoside, patuletin 3-*O*-β-D-(2″-feruloylglucopyranosyl)(1→6)-[β-D-apiofuranosyl(1→2)]-β-D-glucopyranoside, spinacetin 3-*O*-β-D-(2″-*p*-coumaroylglucopyranosyl)(1→6)-[β-D-apiofuranosyl(1→2)]-β-D-glucopyranoside, spinacetin 3-*O*-β-D-(2″-feruloylglucopyranosyl)(1→6)-[β-D-apiofuranosyl(1→2)]-β-D-glucopyranoside, spinacetin 3-*O*-β-D-glucopyranosyl)(1→6)-β-D-glucopyranoside, jaceidin 4′-glucuronide, 5,3′,4′-trihydroxy-3-methoxy-6:7-methylenedioxyfl vone 4′-glucuronide, 5,4′-dihydroxy-3,3′-dimethoxy-6:7-methylenedioxyfl vone 4′-glucuron	Howard et al. (2002)
Tronchuda cabbage	3-*p*-Coumaroylquinic acid, kaempferol 3-*O*-glucoside, kaempferol 3-*O*-sophoroside, kaempferol 3-*O*-(sinapoyl)sophoroside, kaempferol 3-*O*-sophoroside-7-*O*-glucoside, kaempferol 3-*O*-(caffeoyl)sophoroside-7-*O*-glucoside, kaempferol 3-*O*-(sinapoyl)sophoroside-7-*O*-glucoside, kaempferol 3-*O*-(feruloyl)sophoroside-7-*O*-glucoside, kaempferol 3-*O*-sophorotrioside-7-*O*-glucoside, kaempferol 3-*O*-sophorotrioside, kaempferol 3-*O*-sophorotrioside-7-*O*-sophoroside, kaempferol 3-*O*-sophoroside-7-*O*-sophoroside, kaempferol 3-*O*-tetraglucoside-7-*O*-sophoroside, kaempferol 3-*O*-(feruloyl)sophorotrioside, 1-sinapoyl-2-feruloylgentiobiose, 1,2′-disinapoyl-2-feruloylgentiobiose, 1,2,2′-trisinapoylgentiobiose	Sousa et al. (2005), Ferreres et al. (2005)

(*Continued*)

Table 6.1 (*Continued*)

Vegetables	Phenolic compounds	References
Broccoli	1,2,2′-trisinapoylgentiobiose, 1,2-diferuloylgentiobiose, 1,2′-disinapoyl-2-feruloylgentiobiose, 3-O-caffeoyl-quinic acid, 1,2-disinapoylgentiobiose , 1-sinapoyl-2-feruloylgentiobiose, 1-sinapoyl-2,2-diferuloylgentiobiose	Vallejo et al. (2003)
Pak Choi	Kaempferol 3-*O*-hydroxyferuloylsophoroside-7-*O*-glucoside, kaempferol 3-*O*-diglucoside-7-*O*-glucoside, kaempferol 3-*O*-hydroxyferuloyldiglucoside-7-*O*-glucoside, kaempferol 3-*O*-caffeoyldiglucoside-7-*O*-glucoside, kaempferol 3-*O*-sinapoyldiglucoside-7-*O*-glucoside, kaempferol 3-*O*-glucoside-7-*O*-glucoside, kaempferol 3-*O*-feruloyldiglucoside-7-*O*-glucoside, kaempferol 3-*O*-coumaroyldiglucoside-7-*O*-glucoside, isorhamnetin-3-*O*-glycoside-7-*O*-glucoside, kaempferoldiglucoside, kaempferolglucoside, coumaroylqunic acids, feruloylquinic acid, caffeoylmalate, hydroxyferuloylmalate, coumaroylmalate, feruloylmalate, sinapoylmalate	Harbaum et al. (2007)
Caulifl wer	Kaempferol 3-diglucoside-7-diglucoside, kaempferol 3-triglucoside-7-diglucoside, kaempferol 3-feruloyldiglucoside-7-diglucoside, kaempferol 3-sinapoyltriglucoside-7-glucoside, kaempferol 3-disinapoyltriglucoside-7-glucoside, kaempferol 3-sinapoyltriglucoside-7-diglucoside, kaempferol 3-disinapoyltriglucoside-7-diglucoside	Llorach et al. (2003)
Carrot	3′-caffeoylquinic acid, 5′-caffeoylquinic acid, 3′-*p*-coumaroylquinic acid, 3′-feruloyquinic acid, 3′,4′-dicaffeoylquinic acid, 5′-feruloyquinic acid, 5′-*p*-coumaroylquinic acid, 4′-feruloylquinic acid, 3′,5′-dicaffeoylquinic acid, 3′,4′-diferuloylquinic acid, 3′, 5′- diferuloylquinic acid	Alasalvar et al. (2001)

1993; Jayasooriya et al. 2000), anticarcinogenic, and hypocholesterolemic (Ganguly et al. 2000; Ahmed et al. 2001) effects. The total phenolic content of bitter melon seed, inner tissues, and the fles ranged from 4.67 to 8.02, 4.64 to 8.94, and 5.36 to 8.90 mg chlorogenic acid equivalents (CAE/g dry weight), respectively (Horax et al. 2005). A number of phenolic acids, gallic, gentisic, and chlorogenic acids as well as fl vans, catechin, and epicatechin were identifie in bitter melon. Of these, chlorogenic acid was reported only in the fles of bitter melon whereas gentisic acid was not recovered from the seeds. Protocatechuic, vanillic, syringic, *p*-coumaric, and benzoic acids were <10 mg/g dry weight (dw) in the fles of bitter melons.

Eggplant (*Solonum melongena*) is a common fruit vegetable consumed throughout the world. Whitaker and Stommel (2003) identifie several phenolic compounds, namely chlorogenic acid (5-*O*-caffeoylquinic acid), its 3-*O*-, 4-*O*-, and 5-*O*-*cis* isomers, 3,5- and 4,5-dicaffeoylquinic acid isomers, four amide conjugates, two unknown caffeic acid conjugates, and 3-*O*-acetyl esters of 5-*O*- and 4-*O*-caffeoylquinic acids in eggplant fruits. Chlorogenic acid was the most abundant phenolic acid present in eggplant, accounting for >75% of the total phenolic acids present (Luthria and Mukhopadhyay 2006). The purple pigments in eggplant peels are anthocyanins; the major acylated anthocyanin in eggplant is identifie as nasunin (Kuroda and Wada 1933, 1935; Sakamura et al. 1963). Azuma et al. (2008) identifie fi e anthocyanins from eggplant varieties (Table 6.1). Delphinidin 3-caffeoylrutinoside-5-glucoside showed the highest radical-scavenging activities toward both DPPH and

linoleic acid radicals, followed by nasunin and petunidin 3-(*p*-coumaroylrutinoside)-5-glucoside.

According to Chun et al. (2005), the total phenolic and fl vonoid contents of pumpkin were 15.9 mg gallic acid equivalents (GAE) and 0.8 mg catechin equivalents/100 g fw, respectively. Chlorogenic and syringic acids were the major phenolic acids in the raw puree of different pumpkin cultivars. Caffeic and *p*-coumaric acids were also reported in varying quantities (Dragovic-Uzelac et al. 2005). Whole hull-less seed, skin and oil cake meal, dehulled kernel, and hull of pumpkin (*Cucurbita pepo*) were reported to serve as rich sources of protocatechuic, *p*-hydroxybenzoic, vanillic, *trans-p*-coumaric, ferulic, *trans*-sinapic acids, and *p*-hydroxybenzaldehyde (Pericin et al. 2009). Caffeic acid was present in all samples except the hulls, whereas syringic acid was not detectable in the skin and the oil cake meal.

Tomoato is an important component of our diet, consumed either as raw or as processed tomato products (juice, tomato paste, tomato sauces, etc.). The tomato pericarp contains hydroxycinnamic acids, namely *p*-coumaric, caffeic, ferulic, sinapic, and chlorogenic acids (Anterola and Lewis 2002). The fl vonoids in tomato are rutin, kaempferol-3-*O*-rutinoside, and naringenin chalcone (Crozier et al. 1997; Muir et al. 2001; Long et al. 2006).

Pasteurization at high temperatures (98°C) even for a short time (40 seconds) decreased total phenolic content of tomato puree (Pérez-Conesa et al. 2009). However, an earlier study reported that the tomato phenolics increased by 23–34% following blanching at 100°C for 30 minutes (Shen et al. 2007). *In vivo* studies further demonstrated that total antioxidant capacity and phenolic contents in plasma increased after administration of fresh tomato and tomato juice which also synergistically promoted the antioxidant activity (81–100%) of tomato carotenoids in human subjects (Shen et al. 2007). In this study, the administration of fresh tomato and tomato juice showed a decrease in triacylglycerol and low-density lipoprotein (LDL) cholesterol but increase in high-density lipoprotein (HDL) cholesterol.

Phenolics in Allium Vegetables

Quercetin is the predominant compound representing ≥95% of their total fl vonoids in onions. Total phenolic in the onion bulbs ranged between 25.2 and 75.9 mg gallic acid equivalents (GAE)/100 g fw (Galdon et al. 2008). Several fl vonoids, namely quercetin diglucoside, two quercetin monoglucosides, quercetin, isoquercetin, and kaempferol were reported in onions (Galdon et al. 2008). Hydroxycinamic acids found in onions were caffeic, ferulic, and *p*-coumaric acids (Pineda Alonso et al. 1999), whereas myricetin was reported among the fl vonoids (Sellappan and Akoh 2002).

In green onions, Xiao and Parkin (2006) identifie several phenolic compounds, namely ferulic acid, *p*-hydroxyphenethyl *trans*-ferulate, and *N-trans*-feruloyl 3-*O*-methyldopamine. Furthermore, in another study they identifie several other compounds, namely 5-hydroxy-3-methyl-4-propyl sulfanyl-5H-furan-2-one, 5-(hydroxymethyl) furfural, acetovanillone, methyl 4-hydroxyl cinnamate and methylferulate which were active in inducing quinone reductase in murine hepatoma cells (Xiao and Parkin 2007).

Total phenolic and fl vonoid contents of onions differ depending on the variety. Shallots contained the highest total phenolics (114.7 mg GAE/100 g fw) among the varieties tested (Figure 6.3). Western Yellow onion exhibited the highest total fl vonoid content (69.2 mg catechin equivalents/100 g fw) (Yang et al. 2004). All varieties examined showed a strong correlation between total phenolic as well as fl vonoid contents and total antioxidant activity.

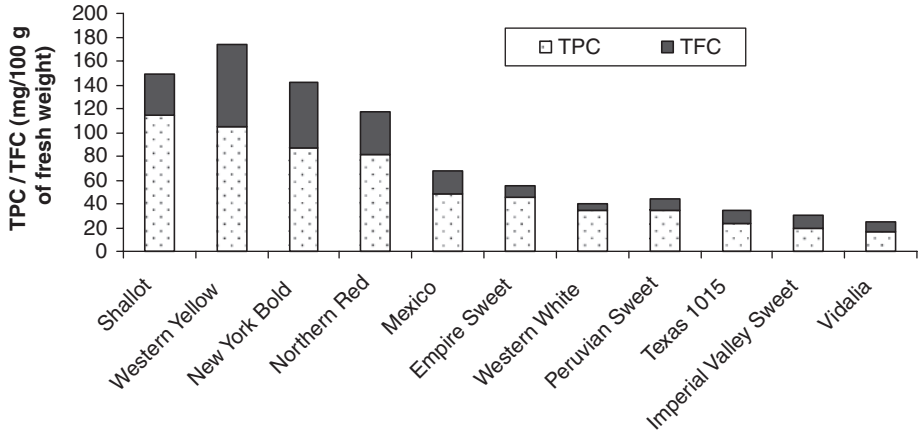


Figure 6.3 Total phenolic (TPC) and total flavonoid contents (TFC) of different onion varieties. TPC in gallic acid equivalents; TFC in catechin equivalents. (Data adapted from Yang et al. 2004.)

The edible bulb of red onions generally has higher total fl vonoid content than the bulbs of white or sweet yellow onions due to the presence of anthocyanins (Rhodes and Price 1996). Anthocyanins reported in red onions include peonidin 3-glucoside, cyanidin 3-glucoside, and cyaniding 3-arabinoside; their malonylated derivatives, cyanidin 3-laminariobioside, delphinidin, and petunidin derivatives (Donner et al. 1997). However, yellow onions have been reported to contain higher levels of quercetin than red onions, with pink and white onions having the lowest concentration (Patil et al. 1995).

Phenolics in Root and Tuber Vegetables

The root (carrots, beets) and tuber (sweet potatoes, potatoes) vegetables are sources of different phenolic compounds. The chapters on carrot, potato, and sweet potato have described the phenolics and antioxidant aspects of these root vegetables and will not be discussed here.

The major group of phenolics in beet is betalains consisting of betacyanins, which are red violet, and betaxanthins, which are yellow (Figure 6.4). The major betalain reported in red beets is a betacyanin, betanin (betanidin 5-*O*-β-glucoside) containing a phenolic and a cyclic amine group, demonstrating potent electron donor activity, and acting as an antioxidant (Kanner et al. 1996). The concentration of betanin in beetroot was 300–600 mg/kg, whereas isobetanin, betanidin, and betaxanthins were present at lower concentrations (Kanner et al. 2001).

A relatively low concentration of betanin was found to inhibit lipid peroxidation of membranes or linoleate emulsion catalyzed by the "free iron" redox cycle, H_2O_2-activated metmyoglobin, or lipoxygenase (Kanner et al. 2001). Betanin and betanidin at very low concentrations inhibited lipid peroxidation and haeme decomposition. The phenolic compounds were distributed mostly in outer parts of the red beetroot (*Beta vulgaris*) (Kujala et al. 2000). The total phenolic content of peel, crown, and fles was 15.5, 11.4, and 4.2 mg GAE/g dw, respectively. Detectable levels of isobetanin were found in the crown and the peel, but not in the flesh Yellow beet consisted of several betaxanthins, the yellow-orange water-soluble pigments and vulgaxanthin I being the major compound among others, and betacyanins were completely

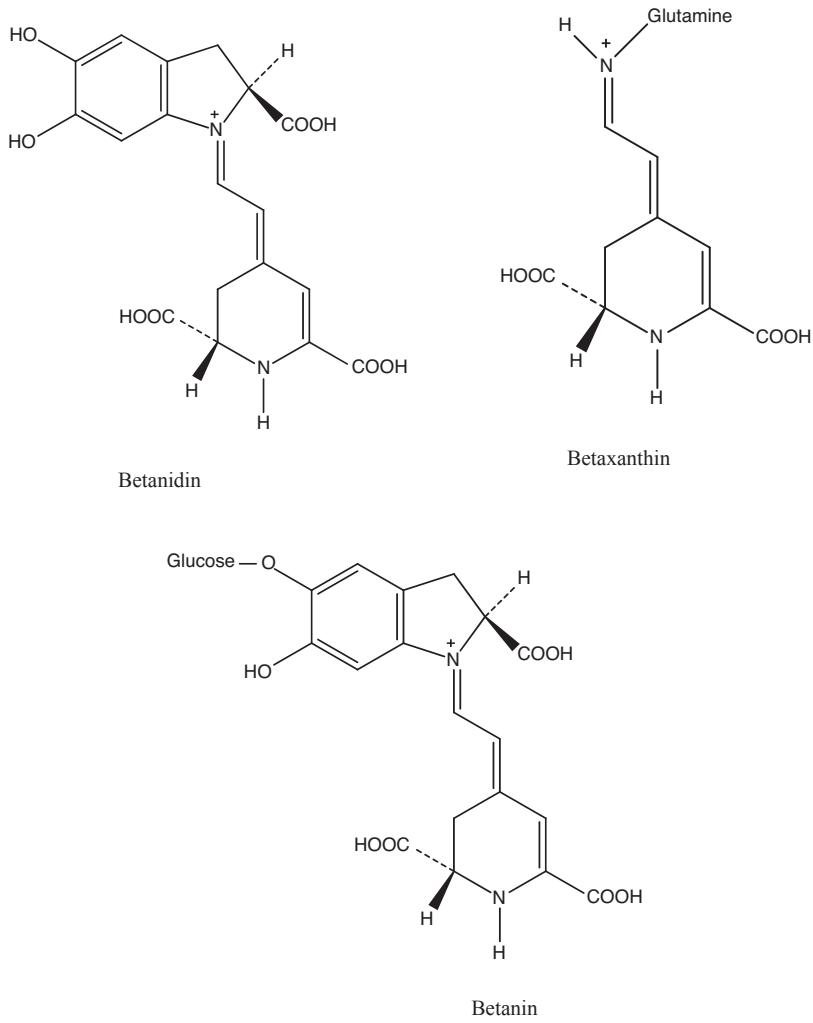


Figure 6.4 Structures of betalains in beet and Swiss chard.

absent in the extracts from the fles of yellow beet (Stintzing et al. 2002).

Phenolics in Leafy Vegetables

The total phenolic content of different lettuce cultivars as measured by high-performance liquid chromatography (HPLC) varied from 0.9 to 2.4 mg/g fw (Heimler et al. 2007). The main phenolic acids isolated were caffeoyl derivatives and fl vonoids, quercetin, kaempferol, luteolin, apigenin, and crysoeriol derivatives (Heimler et al. 2007). The total content of phenolic acids and fl vonoids in both green and red tissues was maintained throughout the storage, whereas the anthocyanin concentration decreased (Ferreres et al. 1997).

Phenolic metabolites are important in lettuce as they cause tissue browning during processing. Once the lettuce tissue is wounded, an increase in the concentration of soluble phenolic compounds is observed in the midribs of iceberg lettuce (Ke and

Saltveit 1989), butter leaf and romaine lettuce (Tomas-Barberan et al. 1997a), and in lettuce stem disks (Tomas-Barberan et al. 1997b). Changes in the external environment such as wounding and preharvest exogenous treatments with secondary metabolites such as methyl jasmonate increase the synthesis and accumulation of phenolic compounds in lettuce (Tomas-Barberan et al. 1997b; Kim et al. 2007). Wounding increased the antioxidant capacity of lettuce (Kang and Saltveit 2002). Kim et al. (2007) showed that preharvest exogenous treatments with methyl jasmonate significantl increased total phenolic content and antioxidant capacity of romaine lettuce. This was attributed to the induction of phenylalanine ammonia-lyase (PAL) activity by methyl jasmonate treatment. There was a 35% increase in the total phenolic content.

The total fl vonoid content of spinach (*Spinacia oleracea*) is reported to be about 1,000 mg/kg (Gil et al. 1999). Spinach fl vonols demonstrated antioxidant (Gil et al. 1999), anti-inflammator (Lomnitski et al. 2000a, 2000b), antimutagenic (Edenharder et al. 2001), and anticarcinogenic (Nyska et al. 2001) properties. The major fl vonoids in spinach included glucuronides and acylated di- and triglycosides of methylated and methylenedioxy derivatives of 6-oxygenated fl vonols (Aritomi and Kawasaki 1984; Aritomi et al. 1986; Ferreres et al. 1997; Gil et al. 1999).

Kale is known to contain polyphenols and phenolic acids (Kurilich et al. 1999; Podsedek 2007). Olsen et al. (2009) reported 32 phenolic compounds including glycosides of quercetin and kaempferol and derivatives of *p*-coumaric, ferulic, sinapic, and caffeic acids in curly kale. The total fl vonol and hydroxycinnamic acid contents in curly kale determined as rutin equivalents (RE) were 646 and 204 mg of RE/100 g fw, respectively. The contents of individual fl vonoids ranged from 2 to 159 mg of RE/100 g fw, with the main compounds being kaempferol-3-sinapoyl-diglucoside-7-diglucoside (18.7%) and quercetin-3-sinapoyl-diglucoside-7-diglucoside (16.5%). After acid hydrolysis, two fl vonol aglycones, namely quercetin and kaempferol, with total contents of 44 and 58 mg/100 g fw, respectively, were identifie in curly kale. The total fl vonol content quantifie by HPLC and the total phenolic content measured by the Folin-Ciocalteu assay were 661 mg/100 g dw and 1,667 GAE/100 g dw, respectively, in curly kale at the commercial harvest time (Hagen et al. 2009).

Vegetables in the Brassica family are reported to possess cancer-preventive properties (Beecher 1994) attributed to their glucosinolates (Stoewsand 1995) and phenolic compounds (Le Marchand 2002; Galati and O'Brien 2004). Ferreres et al. (2005) identifie several fl vonoids, mainly glycosylated kaempferol derivatives, from the external leaves of tronchuda cabbage (*Brassica oleracea* L. var. costata) (Table 6.1). Different cabbage genotypes showed considerable variations in the concentration of phenolic compounds and their antioxidant capacity. Total phenolic content ranged from 110.2 to 153.3 mg GAE/100 g. Total antioxidant capacity varied from 108.4 to 176.1 mg vitamin C equivalents/100 g, and fl vonoids from nondetectable to 2.61 mg quercetin/100 g and from 1.30 to 7.03 mg kaempferol/100 g. Phenolic compounds were mainly responsible for free radical scavenging activity of red cabbage (Podsedek et al. 2008). Harbaum et al. (2007) identifie 28 polyphenols, 11 fl vonoid derivatives, and 17 hydroxycinnamic acid derivatives in different cultivars of the Chinese cabbage pak choi (*Brassica campestris* L. ssp. *chinensis*var. *communis*).

The betalain pattern of differently colored Swiss chard (*Beta vulgaris* L. ssp. cicla [L.] cultivar Bright Lights) was studied and 19 betaxanthins and 9 betacyanins were identifie (Kulger et al. 2004). The cultivar Bright Lights of Swiss chard (*Beta vulgaris* L. ssp. cicla [L.] is a mixed cultivar that produces differently colored plants with purple,

red-purple, yellow-orange, and yellow petioles. The purple petioles contained the highest betalain concentrations (75.4 mg/kg fw), followed by red-purple (50.6 mg/kg fw) and yellow stems (49.7 mg/kg fw), with lowest amounts in yellow-orange Swiss chard petioles (33.6 mg/kg fw).

Phenolics in Flower Vegetables

Flavonoids, caffeic acid derivatives, and sinapic acid derivatives were reported in methanolic extracts of broccoli cultivars (*Brassica oleracea* L. var italica) (Vallejo et al. 2002). The occurrence of two main fl vonol glycosides, namely quercetin 3-*O*-sophoroside and kaempferol 3-*O*-sophoro side, in broccoli floret has been reported (Price et al. 1998).

Chlorogenic and neochlorogenic acids were identifie along with hydroxycinnamoyl derivatives in broccoli floret (Vallejo et al. 2003) (Table 6.1).

Several active polyphenolic compounds, namely 1-caffeoylquinic acid, chlorogenic acid, luteolin rutinoside, cynaroside, narirutin, apigenin-7-rutinoside, and cynarin were purifie from artichoke (*Cynara scolymus*) (Wang et al. 2003). Apigenin-7-rutinoside and narirutin were reported to be unique to artichoke heads. Total phenolic content of immature heads of different artichoke varieties varied from 2.6% to 3.1% of dw, whereas that of artichoke leaves was 6.8–9.8% of dw (expressed as chlorogenic acid equivalents) (Wang et al. 2003). Artichoke leaf extracts had significan antimicrobial activities against bacteria, yeasts, and molds (Zhu et al. 2004). Furthermore, four caffeoylquinic acid derivatives and four fl vonoids were isolated from artichoke leaf extracts and identified They showed inhibitory activity against most of the tested bacteria, yeast, and mold species. Among them, chlorogenic acid, cynarin, luteolin-7-rutinoside, and cynaroside exhibited relatively higher activity than other compounds and they were more effective against fungi than bacteria (Zhu et al. 2004).

Studies showed that artichoke extracts were effective in the treatment of hepatobiliary disfunction and digestive complaints (Adzet et al. 1987; Kirchhoff et al. 1994; Kraft 1997; Speroni et al. 2003), in preventing the oxidative modificatio of blood lipoproteins, and in reducing blood cholesterol levels (Kirchhoff et al. 1994; Gebhardt 1998, 2002; Zapolska-Downar et al. 2002; Shimoda et al. 2003). Furthermore, leaf extracts displayed antioxidative and protective properties against hydroperoxide-induced oxidative stress in cultured rat hepatocytes (Gebhardt 1998; Miccadei et al. 2004). Several studies reported that artichoke-based dietary supplements and byproducts were also rich sources of phenolic compounds and possessed free radical scavenging activity and capacity to inhibit lipid peroxidation (Llorach et al. 2002; Schutz et al. 2006). The phenolic compounds from cooked edible artichoke were bioavailable (Azzini et al. 2007).

Phenolics in Stem Vegetables

High amounts of ferulic acid and its derivatives were detected in walls from the lower parts of asparagus (Rodriguez-Arcos et al. 2002). In fresh asparagus, >60% of the total ferulic acid was in the form of diferulic acids, and this increased with storage time. The main ferulic acid dehydrodimers were 8-8-, 8-*O*-4-, and 8-5-diferulates. Asparagus contained phenolic compounds, mainly rutin and other fl vonoids, such as quercetin and kaempferol glycosides which possessed strong antioxidant properties (Makris and Rossiter 2001). The extracts had a rutin content of 274.1–286.5 mg/kg fw.

Carotenoids

Carotenoids are among the most widespread natural pigments occurring in plants, animals, and microorganisms. They are synthesized

de novo in the photosynthetic apparatus of all higher plants and algae, and are responsible for the yellow, orange, or red colors of many fl wers, fruits, and vegetables. The presence of carotenoids in some photosynthetic tissues, however, is masked by the green color of chlorophyll, as in many green leafy vegetables. Carotenoids in animals are believed to originate from plant sources through the diet. Carotenoids including carotenes and xanthophylls are a group of fat-soluble substances, unless conjugated to some strong polar groups. The majority of carotenoids are unsaturated tetraterpenes with the same basic C40 isoprenoid skeleton resulting from the joining of eight isoprene units in a head-to-tail manner, with the exception of the tail-to-tail connection at the center. The carotenes are hydrocarbons soluble in nonpolar solvents such as hexane and petroleum ether, whereas xanthophylls, the oxygenated derivatives of carotenes, dissolve better in polar solvents such as alcohols (Gross 1991). About 750 naturally occurring carotenoids have been reported as of 2004 (Britton et al. 2004), among which the largest structural variety is encountered in marine carotenoids (Liaaen-Jensen 1991).

Carotenoids are of biological importance in living organisms. In photosynthetic systems of higher plants, algae, and phototrophic bacteria, carotenoids participate in a variety of photochemical reactions including singlet–singlet and triplet–triplet energy transfer, oxidation, reduction, and isomerization (Frank and Cogdell 1993). In nonphotosynthetic organisms, carotenoids perform a protective function against photooxidative damage caused by singlet or triplet oxygen (Shahidi et al. 1998). Carotenoids, either isolated from natural sources or chemically synthesized, have been widely utilized, due to their distinctive coloring properties, as natural nontoxic colorants in manufactured foods, drinks, and cosmetics. Carotenoids possess numerous bioactivities and play important roles in human health and nutrition, including provitamin A activity, antioxidant activity, regulation of gene expression, and induction of cell-to-cell communication (Paiva and Russell 1999). The structurally diverse carotenoids exhibit varied stability and *in vivo* bioavailability. Blanquet-Diot et al. (2009) reported that zeaxanthin and lutein were stable throughout artificia digestion, but β-carotene and all-*trans* lycopene degraded (about 30% and 20% loss, respectively) in the jejunal and ileal compartments, and the stability of 5-*cis* lycopene was superior to all-*trans* and 9-*cis* lycopene.

An updated Brazilian database on food carotenoids reported important vegetable-derived carotenoids, including α-carotene, β-carotene, β-cryptoxanthin, lycopene, lutein, and zeaxanthin (Figure 6.5), and factors affecting carotenoid composition in vegetables (Rodriguez-Amaya et al. 2008). Carotenoids appear to be less affected by processing and storage of vegetables compared with other micronutrients such as vitamin C. In general, processing of vegetables is believed to improve the bioavailability of carotenoids, as it helps release carotenoids from the plant cells by breaking down the cellulose structure of the cell wall (Van het Hof et al. 2000). Moreover, processing of tomato products into sauces, soups, and juices increases the bioavailability of lycopene by increasing the percentage of its *cis*-isomers (Garner et al. 1997). However, certain carotenoids were thought to be potentially more available from fruits than vegetables for gastrointestinal absorption (O'Connell et al. 2007).

The total carotenoid content was reported for some major vegetable sources, including kale (34.8 mg/100 g), red hot pepper (27.4 mg/100 g), parsley (25.7 mg/100 g), spinach (17.3 mg/100 g), lamb's lettuce (16.0 mg/100 g), carrot (15.8 mg/100 g), and tomato (12.7 mg/100 g) (Müller 1997). Each vegetable has its unique carotenoid profile Tomato and its products, for example, are the richest sources of lycopene, especially in a typical American diet, accounting for

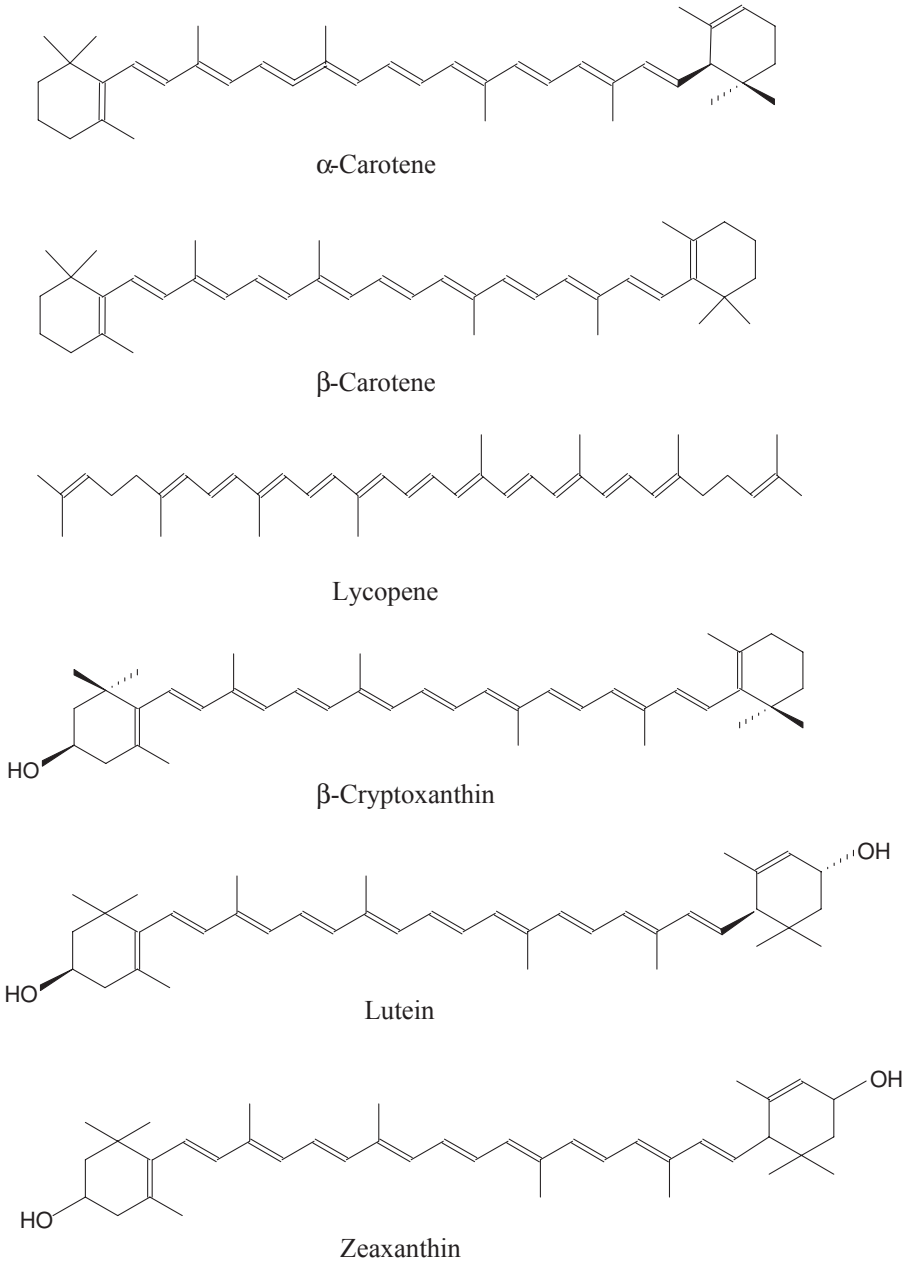


Figure 6.5 Chemical structures of α- and β-carotene, lycopene, β-cryptoxanthin, lutein, and zeaxanthin.

85% of lycopene found in the diet and more than three-fourths of the total lycopene intake of Americans (Minorsky 2002; Canene-Adams et al. 2005). In addition to lycopene, other carotenoids in tomato and its products include α-, β-, γ-, and ζ-carotene, lutein, zeaxanthin, α- and β-cryptoxanthin, violaxanthin, neoxanthin, neurosporene, phytoene,

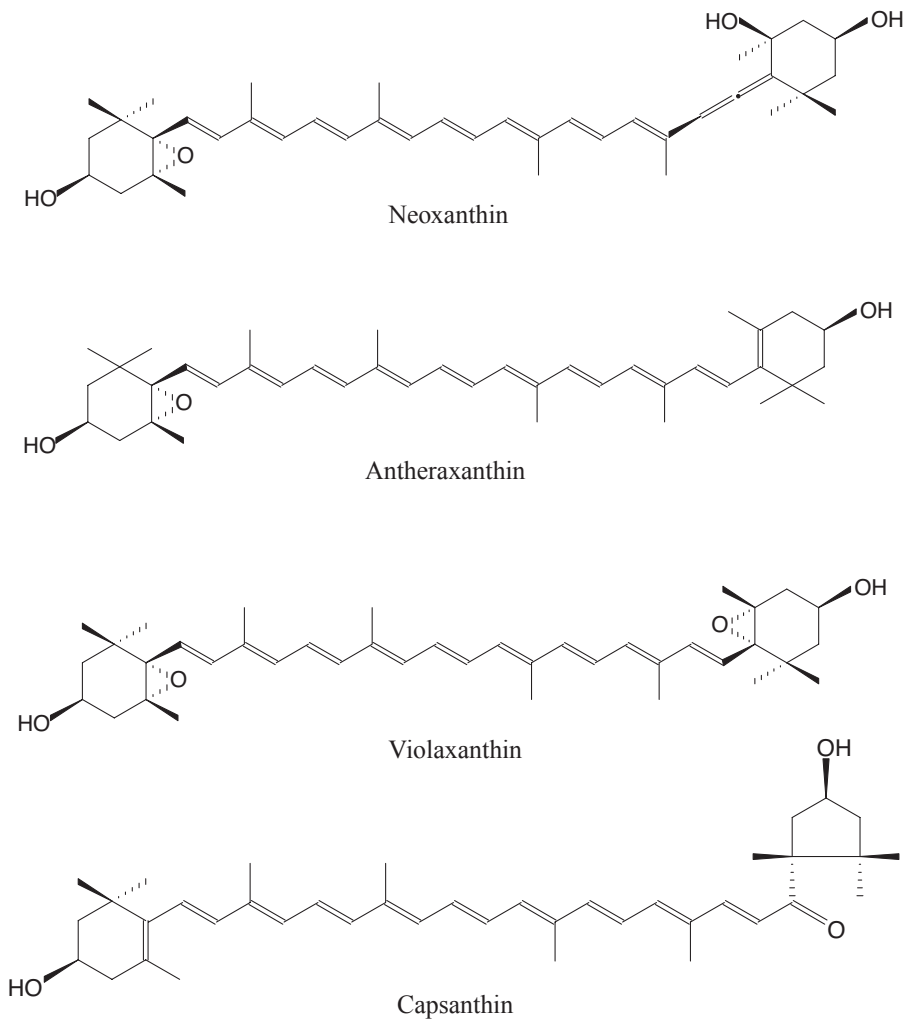


Figure 6.6 Chemical structures of neoxanthin, antheraxanthin, violaxanthin, and capsanthin.

phytofluene cyclolycopene, and β-carotene 5,6-epoxide (Heinonen et al. 1989; Fraser et al. 1994; Khachik et al. 2002; Burns et al. 2003). It has been reported that lycopene content increased in tomato exposed to UV-C or red light but sunlight decreased β-carotene (Liu et al. 2009a). Pepper is also rich in β-carotene, lycopene, and predominantly its characteristic carotenoid capsanthin (Figure 6.6). Ripe sweet peppers *Capsicum Annuum* cv. Raruku and Sarara had a high capsanthin content of 63 and 59% of the total carotenoids, respectively (Suzuki et al. 2007). Suzuki et al. (2007) investigated carotenoids in 13 types of sweet peppers at full maturity and found a consistent ratio of β-carotene to capsanthin of 1:10 by weight. Other major carotenoids present in peppers (*Capsicum Annuum cultivars*) include capsolutein, capsorubin, violaxanthin, zeaxanthin, β-carotene, β-cryptoxanthin, and cryptocapsin (Topuz and Ozdemir 2007). Cultural practices appear to have an effect on carotenoid content in peppers. Total carotenoids were 3,231, 2,493, and

1,829 mg/kg for organic, integrated, and conventional sweet peppers, respectively, suggesting that organic farming may result in a higher yield of carotenoids in peppers (Perez-Lopez et al. 2007). Pepper and its products need to be properly stored to avoid loss of carotenoid caused by fungal infection. A substantial loss of total carotenoids (88.55%) was observed for powdered red hot pepper upon *in vitro* infection of *Aspergillus flavu* (Tripathi and Mishra 2009).

Pumpkin is another excellent source of carotenoids. The total carotenoid content in fresh pumpkin normally ranges from 2 to 10 mg/100 g (Nawirska et al. 2009). Seo et al. (2005) demonstrated that the carotenoid extract from pumpkin *Cucurbita moschata* by liquid–liquid and supercritical flui extraction contained >80% of β-carotene and lesser amounts of lutein, lycopene, α-carotene, and *cis*- β-carotene. However, different compositions were reported by Murkovic et al. (2002) for three pumpkin species, *C. pepo*, *C. maxima*, and *C. moschata*, which contained 0–17 mg/100 g of lutein, 0.06–7.4 mg/100 g of β-carotene, and 0–7.5 mg/100 g of α-carotene. The variation may be caused by difference in pumpkin species and/or extraction methods. For instance, degradation and isomerization of carotenoids may occur during saponification a pretreatment procedure in carotenoid extraction (Seo et al. 2005). Other vegetables such as bitter melon and squash have also been shown to contain considerable amounts of carotenoids, in particular lycopene in bitter melon, and β-carotene and lutein in squash (Yen et al. 1981; Perry et al. 2009).

Green leafy vegetables are rich in carotenoids, although the red pigments are often masked by the green chlorophylls present. Total carotenoids content in three common vegetables, namely lettuce (*Lactuca scariola* var. *sativa*), cabbage (*Brassica oleracea* var. *capitata*), and leaf mustard (*B. Juncea*) was reported as 10.2, 17.3, and 21.8 mg/100 g fw, respectively (Takagi 1985). Amaranth green contained 37.72 mg/100 g dw of carotenoids (Mosha et al. 1997). Green leafy vegetables are the major contributors of dietary lutein (Perry et al. 2009) and contain substantial amounts of β-carotene, Antheraxanthin, violaxanthin, and neoxanthin (Figure 6.6) (Mueller 1996). Lutein and β-carotene have been identifie as the predominant carotenoids in white, red, and savoy cabbage (Singh et al. 2006), as well as other *Brassica oleracea* vegetables. The latter includes Chinese kale, Brussels sprout, and some other Chinese leafy vegetables such as Chinese chives, spinach, cabbage, and water cress (Singh et al. 2007; Chen et al. 2009). Aizawa and Inakuma (2007) studied 70 vegetables and found that all leafy vegetables had relatively high levels of lutein and β-carotene, among which kale (*Brassica oleracea L.* var. *acephala*) ranked highest for lutein and β-carotene content (Kopsell et al. 2004), which varied during leaf development (Lefsrud et al. 2007). Parsley, dill, and spinach also contained high levels of lutein (≥4.4 mg/100 g, and may also contain some zeaxanthin) and β-carotene (1.0–7.6 mg/100 g) (Heinonen et al. 1989). Despite the abundance of carotenoids in green leafy vegetables, it is believed that carotenoids from yellow and orange fruits and vegetables are better absorbed by the body (Ribaya-Mecardo 2002; Benadi 2003).

Root (carrot), tuber (potato), fl wer (broccoli, caulifl wer), stem (asparagus, celery), and bulb (garlic, onion) vegetables also contain carotenoids. Carrot, containing 95.1 mg/100 g total carotenoids, is exclusively rich in β- and α-carotenes (Melo et al. 2006; Aizawa and Inakuma 2007). Potatoes are known for their β- and α-carotenes as well as zeaxanthin (Andre et al. 2007; Liu et al. 2009b). The major carotenoids in fl wer vegetables such as broccoli and caulifl wer are lutein and β-carotene, similar to that of green leafy vegetables (Singh et al. 2007). Asparagus exhibits a higher carotenoid content in the cooked form than in the raw. Cooking increased the content of β-carotene and lutein plus zeaxanthin in asparagus by 24 and 25%, respectively, possibly due to the denaturation

Table 6.2 Major carotenoids in selected vegetables

Vegetables	Carotenoids identifie	References
Tomato	Lycopene, α-, β-, γ- and ζ-carotene, lutein, zeaxanthin, α- and β-cryptoxanthin, violaxanthin, neoxanthin, neurosporene, phytoene, phytofluene cyclolycopene, β-carotene 5,6-epoxide	Müller (1997), Khachik et al. (2002), Burns et al. (2003), Fraser et al. (1994)
Pepper	Capsanthin, capsolutein, capsorubin, violaxanthin, zeaxanthin, lutein, β-carotene, lycopene, β-cryptoxanthin, neoxanthin, neolutein, cryptocapsin	Perez-Lopez et al. (2007), Topuz and Ozdemir (2007), Perry et al. (2009), and Larsen and Christensen (2005)
Pumpkin	β-Carotene, lutein, lycopene, α-carotene, *cis*-β-carotene, cryptoxanthin, zeaxanthin	Murkovic et al. (2002), Mosha et al. (1997), Seo et al. (2005), Parry et al. (2006)
Squash	Lutein, α- and β-carotene, cryptoxanthin, violaxanthin	Perry et al. (2009), Müller (1997)
Amaranth green	α- and β-carotene	Mosha et al. (1997)
Lettuce	Lutein, zeaxanthin, cryptoxanthin, β-carotene, neoxanthin, violaxanthin, neolutein	Perry et al. (2009), Larsen and Christensen (2005), Müller (1997)
Chinese cabbage	β-Carotene, zeaxanthin, lutein, neoxanthin, violaxanthin, luteoxanthin	Wills and Rangga (1996)
Cabbage	β-Carotene, lutein, neoxanthin, cryptoxanthin, zeaxanthin, violaxanthin, antheraxanthin	Heinonen et al. (1989), Singh et al. (2006), Singh et al. (2007), Khachik et al. (1986), Müller (1997)
Kale	α- and β-carotene, lutein, violaxanthin, zeaxanthin, neoxanthin, neolutein, cryptoxanthin, antheraxanthin	Perry et al. (2009), Mercadante and Rodriguez-Amaya (1991), Khachik et al. (1986), Müller (1997)
Brussels sprout	β-Carotene, lutein, cryptoxanthin, neoxanthin, violaxanthin, neolutein	Heinonen et al. (1989), Perry et al. (2009), Khachik et al. (1986), Müller (1997)
Spinach	β-Carotene, lutein, neoxanthin, violaxanthin, neolutein, zeaxanthin, antheraxanthin	Heinonen et al. (1989), Perry et al. (2009), Khachik et al. (1986), Larsen and Christensen (2005), Müller (1997)
Parsley	α- and β-carotene, lutein, zeaxanthin, cryptoxanthin, neoxanthin, violaxanthin, neolutein, antheraxanthin	Heinonen et al. (1989), Perry et al. (2009), Parry et al. (2006), Larsen and Christensen (2005), Müller (1997)
Water cress	β-Carotene, zeaxanthin, lutein, neoxanthin, violaxanthin, auroxanthin, luteoxanthin	Wills and Rangga (1996)
Broccoli	β-Carotene, lutein, neoxanthin, violaxanthin, neolutein, cryptoxanthin	Perry et al. (2009), Heinonen et al. (1989), Khachik et al. (1986), Larsen and Christensen (2005)
Caulifl wer	β-Carotene, lutein, cryptoxanthin, violaxanthin, antheraxanthin	Heinonen et al. (1989), Müller (1997)
Carrot	α- and β-carotene, lutein, lycopene, cryptoxanthin, violaxanthin, neoxanthin, antheraxanthin	Heinonen et al. (1989), Grassmann et al. (2007), Müller (1997)
Sweet potato	α- and β-carotene,	Mosha et al. (1997)
Asparagus	Lutein, zeaxanthin, cryptoxanthin, β-carotene	Perry et al. (2009), Fanasca et al. (2009)
Celery	β-Carotene, lutein	Heinonen et al. (1989)
Onion	β-Carotene, lutein, zeaxanthin, cryptoxanthin, violaxanthin, antheraxanthin	Heinonen et al. (1989), Parry et al. (2006), and Müller (1997)

of carotenoid–protein complex and stability against degradation (Fanasca et al. 2009). The major carotenoids found in commonly consumed vegetables are summarized in Table 6.2.

Carotenoids possess a number of essential functional and physiological properties and may serve as important nutraceuticals. As discussed in the composition and nutritional chapter of this book, the most important physiological function of carotenoids in humans is pro-vitamin A activity. Some carotenoids, particularly carotenes containing at least one terminal β-ionone ring (e.g., β-, α-, and γ-carotene, cryptoxanthin), can yield vitamin A by splitting the middle of

their chains, and can be used to supply this essential vitamin. Carotenoids are also effective antioxidants against lipid oxidation and other destructive processes mediated by free radicals both in *in vitro* and *in vivo* systems. Carotenoids are capable of quenching reactive oxygen species (ROS), particularly singlet oxygen, which helps explain the skin protection effica y of carotenoids, such as β-carotene and lycopene, in light-sensitive (erythropoietic protoporhyria, EPP) individuals (Mathews-Roth 1993). The xanthophylls lutein and zeaxanthin selectively accumulate in the macular region of retina, where they function as singlet oxygen quenchers and blue light filter and protect against the development of age-related macular degeneration (AMD) (Seddon et al. 1994). Carotenoids are also UV-light protectants and are important for eye and skin health.

Lycopene and EPA (eicosapentaenoic acid) at low concentrations could synergistically inhibit the proliferation of colon cancer cells and suppress cancer cell survival by upregulation of apoptotic protein expression (Yang et al. 2009). It has recently been suggested that the metabolites or oxidation products of lycopene (e.g., lycopene 5,6-epoxide) rather than lycopene itself are responsible for its disease-prevention ability (Zaripheh et al. 2006; Lindshield et al. 2007). The health benefit of carotenoids are also attributed to their synergistic effect with other phytochemicals (e.g., other carotenoids, phenolics, and vitamins C and E) in vegetables (Das et al. 2005; Boileau et al. 2009), and therefore consumption of whole vegetables rather than carotenoid supplements is recommended.

Organosulfur Compounds

Glucosinolates in Brassica Vegetables

The consumption of cruciferous vegetables such as broccoli, caulifl wer, cabbage, kale, Brussels sprouts, and turnip green has been linked to a reduced risk of cancers of the lung, stomach, colon, and rectum, among others (Heber 2004). As also discussed in the chapter on asparagus, broccoli, and caulifl wer, the health-promoting properties of these vegetables have been attributed to their high glucosinolate contents. Glucosinolates are a group of sulfur-containing glycosides found abundantly in cruciferous plants, with the Brassica vegetable family being their major dietary source for humans (Fenwick et al. 1983). They are mainly amino acid-derived secondary metabolites responsible for the characteristic fl vor and odor of these vegetables and are believed to have biological effects on humans. Glucosinolates are normally conjugated to a sugar moiety and are stable within the plant tissues, but upon hydrolysis by endogenous myrosinase (thioglucoside glucohydrolase), which is activated by disruption of the plant cells during cutting, crushing, or chewing, they release a variety of bioactive and volatile breakdown products such as isothiocyanates, indoles, nitriles, thiocynates, oxazolidinethiones, and organic cyanides, among others (Figure 6.7) (Verkerk et al. 1998). Isothiocyanates derived from their glucosinolate precursors produce a specifi pungent, bitter, or herbaceous fl vor in injured plant tissues, contributing synergistically to the positive and negative sensory properties of Brassica products. They are bioactive compounds playing important roles such as anticarcinogenic and antimutagenic agents. Various degradation products are formed from enzymatic hydrolysis of glucosinolates, and their occurrence depends on a number of factors such as the glucosinolate substrates, pH, ferrous ion concentration, the level and activity of specifi protein factors and coenzymes, and the treatment of plant material before hydrolysis. For instance, isothiocyanates are the major products at physiological pH, whereas nitriles are formed in more acidic environments (Halkier and Du 1997). Nitriles are also formed in larger amounts in fresh tissues than in thermally treated plants (Stoewsand 1995).

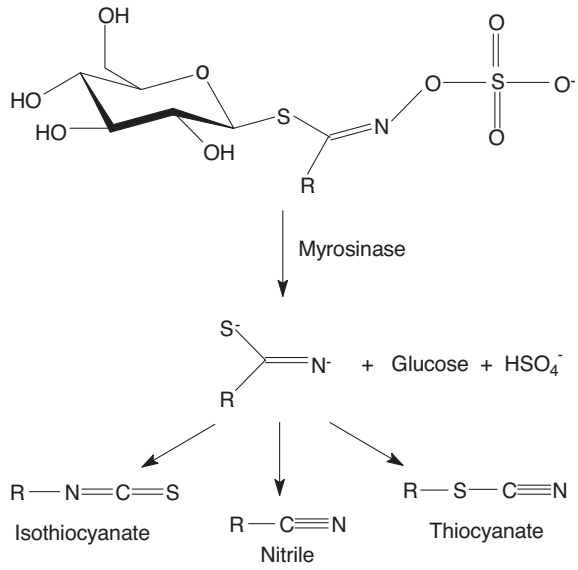
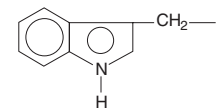
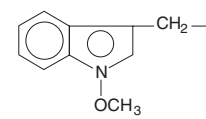
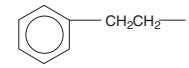


Figure 6.7 Decomposition of glucosinolate by myrosinase.

According to their amino acid precursors, glucosinolates are classifie as aliphatic (methionine), indole (tryptophan), and aromatic (tyrosine or phenylalanine), as summarized in Table 6.3 (Giamoustaris and Mithen 1996). There are approximately 120 glucosinolate structures identifie in plants but only about 16 are common in plant foods consumed by humans (Fahey et al. 2001). The total amounts and profile of glucosinolates vary among the Brassica crops and are influence by growing conditions, stage of plant development, and postharvest processing and storage conditions. Therefore, glucosinolates have been proposed as chemical markers in chemotaxonomy of Brassica vegetables.

Among all Brassica vegetables, Brussels sprouts have the highest level of total glucosinolates (0.6–3.9 mg/g) (Heaney and Fenwick 1980a), with the predominant components being sinigrin, gluconapin, progoitrin, glucotropaedin, glucobrassicin, and glucoerucin (Heaney and Fenwick 1980b; Kushad et al. 1999). The isothiocyanates from sinigrin and progoitrin contribute to the bitterness of Brussels sprouts (van Doorn et al. 1998). Broccoli is a rich source of glucoraphanin (>50%), sinigrin, progoitrin, gluconapin, and the indole glucosinolates glucobrassicin and neoglucobrassicin (Kushad

Table 6.3 Glucosinolates commonly found in Brassica vegetables

Glucosinolates	R-group
Aliphatic glucosinolates	
Sinigrin	CH_2=CH–CH_2–
Gluconapin	CH_2=CH–CH–CH_2
Glucoraphanin	CH_3–SO–CH_2–CH_2–CH_2–CH_2
Glucoiberin	CH_3–SO–CH_2–CH_2–CH_2–
Glucoiberverin	CH_3–S–CH_2–CH_2–CH_2–
Glucoerucin	CH_3–S–CH_2–CH_2–CH_2–CH_2–
Progoitrin	CH_2=CH–CH(OH)–CH_2–
Indole glucosinolates	
Glucobrassicin	
Neobrassicin	
Aromatic glucosinolates	
Gluconasturtiin	

et al. 1999). Isothiocyanates have been reported to comprise approximately 40% of total phytochemicals in fresh broccoli extract (methylene chloride extract) (Sok et al. 2003). Hydrolysis of the primary glucosinolate, glucoraphanin, in broccoli yields the aglucone sulforaphane, an isothiocyanate with antioxidant and chemopreventive potentials (Yeh and Yen 2009). Developing broccoli products with high glucosinolate content is encouraged, and two products Broccosprouts (broccoli sprouts obtained from glucosinolate-rich genotypes) and Superbroccoli (high glucosinolates broccoli breeding) have been introduced to the US and the European markets, respectively (D'Antuono et al. 2009). Major glucosinolates in caulifl wer are glucobrassicin, sinigrin, progoitrin, glucoiberverin, and glucoiberin (Nilsson et al. 2006; Volden et al. 2009). The bitter taste of cooked caulifl wer is thought to be due to the presence of sinigrin and neoglucobrassicin (Engel et al. 2002). Sinigrin, glucobrassicin, and glucoiberin are identifie as the predominant glucosinolates in cabbage and kale (Nilsson et al. 2006; Cartea et al. 2008). Cabbage also contains progoitrin and gluconasturtiin, whose breakdown products (isothiocyanates) are responsible for the pungent and bitter taste of cabbage (Rosa et al. 1997). *Brassica rapa* vegetables show relatively little variation in their glucosinolates compared to *Brassica oleracea*. Alkenyl glucosinolates such as gluconapin and glucobrassicanapin, and their hydroxylated forms progoitrin and gluconapoleiferin predominate in Chinese cabbage (*B. rapa* subspp. *nipposinica* and *chinensis*) (Cartea and Velasco 2008). Gluconapin and glucobrassicanapin are also found as fl vor compounds in turnip greens (*B. rapa* var. *rapa*) (Cartea and Velasco 2008). The roots of turnip contain mainly progitrin and the aromatic glucosinolate, gluconasturtiin, which is also present at high levels (44–47%) in the leaves of Asian turnip (*B. rapa* subspp. *rapa*) (Krumbein et al. 2005). Gluconasturtiin and its hydrolysis product phenethyl isothiocyanate are found in high levels in some minor vegetables such as water cress and radish, accounting for the "hot" sensation of these vegetables (Heaney and Fenwick 1980b). Mustard as a rich source of glucosinolates predominantly contains sinigrin, as reported in black mustard (*B. nigra*) seeds and mustard greens (*B. juncea*) (Krumbein et al. 2005; Cartea and Velasco 2008). Major glucosinolates in selected Brassica vegetables are given in Table 6.4. Other than Brassica vegetables for human consumption, glucosinolates are present abundantly in some seed meals fed to livestock (Stoewsand 1995).

Cooking methods such as boiling, steaming, blanching, and microwaving can lead to approximately 30–60% loss of glucosinolates. Blanching of caulifl wer reduced the total aliphatic and indole glucosinolates by 31 and 37%, respectively (Volden et al. 2009). Heat treatment also caused a substantial degradation of indole glucosinolates, releasing thiocyanates and indoleacetonitriles (Slominski and Campbell 1989). Although cooking at high temperatures normally denatures myrosinase in the vegetables, the residual glucosinolates can be decomposed by myrosinase and its isoenzymes in microflor of human alimentary tract, yielding secondary compounds for human nutrition and health improvement (Shapiro et al. 2001; Volden et al. 2009). Glucosinolates themselves are not bioactive until they are enzymatically hydrolyzed, upon cellular disruption, into glucose, bisulphate, and a mixture of volatile compounds including isothiocyanates and organic nitriles, among others (Heaney and Fenwick 1980b). Indole isothiocyanates, the degradation products from indole glusosinolates, are unstable and are further degraded into indole-3-carbinol. This compound may condense under acidic conditions of the stomach to form potential toxic compounds (Cartea and Velasco 2008). However, it has also shown chemopreventive effects against many types of cancers (Stoewsand 1995).

Table 6.4 Major glucosinolates in selected Brassica vegetables

Vegetables	Major glucosinolates identifie	References
Brussels sprout	Sinigrin, progoitrin, gluconapin, glucotropaeolin, glucoerucin, neoglucobrassicin, glucobrassicin	Heaney and Fenwick (1980a, 1980b), Kushad et al. (1999)
Caulifl wer	Progoitrin, glucoraphanin, glucoiberin, sinigrin, glucoerucin, glucobrassicin, neoglucobrassicin, glucoiberverin, 4-hydroxy-glucobrassicin, 4-methoxy-glucobrassicin	Nilsson et al. (2006), Volden et al. (2009)
Kale	Glucobrassicin, glucoiberin, sinigrin, progoitrin, gluconapin, neoglucobrassicin, 4-hydroxy-glucobrassicin, 4-methoxy-glucobrassicin	Nilsson et al. (2006)
Cabbage	Sinigrin, glucobrassicin, glucoiberin, progoitrin, gluconapin, glucobrassicanapin, glucoiberverin, neoglucobrassicin, glucoraphanin, 4-hydroxy-glucobrassicin, 4-methoxy-glucobrassicin, gluconasturtiin	Nilsson et al. (2006), Cartea and Velasco (2008), Rosa et al. (1997)
Broccoli	Glucoraphanin, glucoiberin, progoitrin, sinigrin, glucoalysiin, gluconapin, glucobrassicanapin, glucoerucin, gluconapoleiferin, glucobrassicin, neoglucobrassicin, gluconasturtiin, 4-hydroxy-glucobrassicin, 4-methoxy-glucobrassicin	Kushad et al. (1999), Cartea and Velasco (2008)
Turnip greens	Gluconapin and glucobrassicanapin	Cartea and Velasco (2008)
Chinese cabbage	Gluconapin, glucobrassicanapin, progoitrin, gluconapoleiferin	Cartea and Velasco (2008)

Glucosinolates in Brassica vegetables confer defense functions to the plants and provide a source of bioactive compounds that are important to human nutrition and health. Brassica vegetables are therefore of great interest for their potential use in disease risk reduction and are considered as functional foods (Cartea and Velasco 2008). The health-promoting effects of Brassica vegetables have been attributed to the physiological properties of glucosinolate breakdown products, mainly isothiocyanates and indoles. These compounds have been reported to act as anticarcinogens during many stages of cancer development through multiple mechanisms, including activation of detoxificatio enzymes (phase II enzymes), inhibition of carcinogen activation enzymes (phase I enzymes), antiproliferation, blocking cell cycle, and promoting apoptosis, among others (Hayes et al. 2008). The most potent phase II enzyme-inducing isothiocyanates include sulforaphane (from glucoraphanin), iberin (from glucoiberin), and erucin (from glucoerucin) (Thornalley 2002). The aliphatic isothiocyanate sulforaphane is known as a powerful inducer of phase II enzymes implicated in carcinogen detoxifica tion, such as glutathione-S-transferase, which help neutralize potential carcinogens by turning them into water-soluble compounds and excreting through urine (Cartea and Velasco 2008). Sulforaphane is able to inhibit phase I enzymes such as cytochrome P450, which is involved in metabolic activation of most carcinogens in humans (Henderson et al. 2000). Sulforaphane and other aliphalic and phenethyl isothiocyanates as well as indole products from glucosinolates have also been found effective in causing cell cycle arrest and inducing apoptosis of cancer cells, suggesting their use in chemopreventive treatment of cancers (Yeh and Yen 2009). Nevertheless, these health-promoting components are also responsible for the low acceptance of Brassica vegetables as food due to their unpleasant sulfur taste or odor (D'Antuono et al. 2009). In order to enhance the intake of these health-beneficia phytochemicals, breeding vegetable cultivars with moderate glucosinolate content and high consumer acceptance has been proposed. On the other hand, antinutritional effects of glucosinolates have also been reported. Some hydrolysis products of glucosinolates (isothiocyanates,

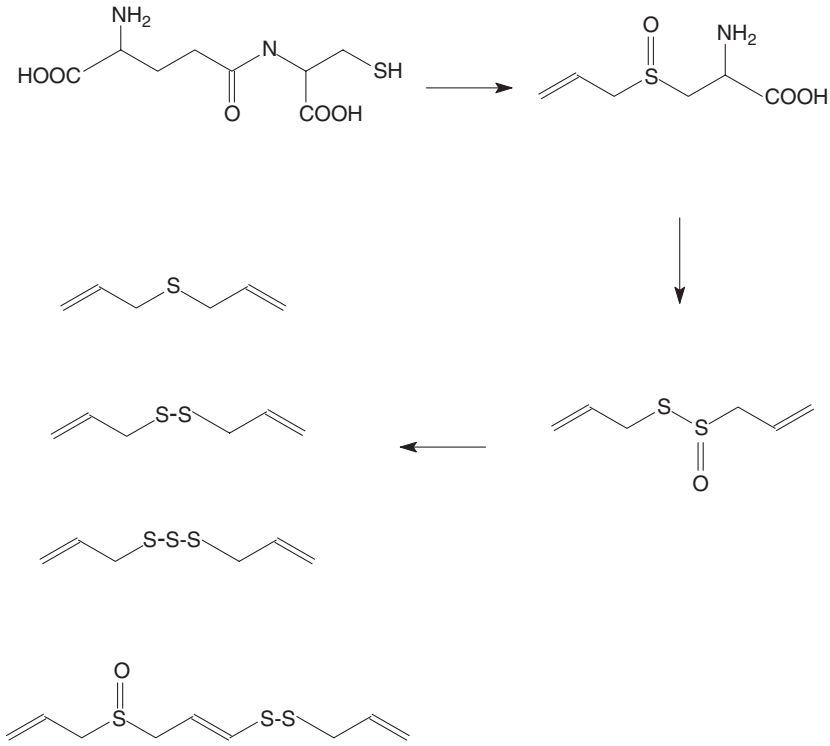


Figure 6.8 Organosulfur compounds in Allium vegetables.

thiocyanates, and oxazolindine-thione), especially those in oilseeds such as rapeseed, mustard, and crambe seeds, have been demonstrated to be goitrogenic and cause impaired/retarded growth and liver damage *in vitro* and in animals; however, evidence of these harmful effects is lacking (Paxman and Hill 1974; Heaney and Fenwick 1980a; Stoewsand 1995; Mithen et al. 2000; Mithen 2001).

Other Organosulfur Compounds

In addition to glucosinolates, another group of amino acid-derived sulfur-containing compounds has been identifie in vegetables, such as allicin and its derivatives in allium vegetables. As also discussed in the chapter on onion and garlic, a number of organosulfur compounds have been found in allium vegetables, including ajoene, diallyl sulphides, S-allylcysteine, and allicin. The primary sulfur compounds in intact allium vegetables are γ-glutamyl-S-alk(en)yl-cysteines (Figure 6.8), which are hydrolyzed and oxidized into S-alk(en)yl-cysteine sulphoxide (alliin) upon disruption of the clove's membrane during cutting, chopping, or crushing of the plant tissue. Alliin is transformed enzymatically by alliinase into allicin, alkyl alkane-thiosulphinates, and other organosulfur compounds (Powolny and Singh 2008). Allicin is responsible for the characteristic odor of garlic. It is unstable and decomposes readily into mono-, di-, and trisulphides, and other organosulfur compounds such as ajoene, dithiins, S-propenylcysteine sulphoxide, S-propylcysteine, and S-methylcysteine sulphoxide (Bianchini and Vainio 2001; Powolny and Singh 2008). It has been

reported that 1 g of freshly blended garlic can provide up to 2.5 mg of allicin, 0.9–1.1 mg of diallyl trisulphides, and 0.53–0.61 mg of diallyl disulphides (Lawson and Gardner 2005; Shukla and Kalra 2007). Thioallyl moiety is common in garlic derivatives, while onions generally contain thiopropyl group in their organosulfur compounds. Ramp or wild leek (Allium tricoccum Ait) contains thiosulphinates and cepaenes (α-sulphinyl disulphides) in their supercritical CO_2 extracts (Calvey et al. 1998).

Organosulfur compounds in allium vegetables have been studied for their bioactivities and potential health effects. They are found to be effective in inhibiting phase I enzymes and enhancing expression of phase II enzymes (Herman-Antosiewicz et al. 2007; Shukla and Kalra 2007). Findings in experimental carcinogenesis, epidemiological studies, and intervention trials have indicated that organosulfur compounds in allium vegetables act as effective cancer-preventing agents (Wargovich 1987; Li et al. 2004; Arunkumar et al. 2006). The mechanism of their chemopreventive effect includes inhibition of mutagenesis, modulation of enzyme activities, inhibition of DNA adduct formation, antioxidant and antiproliferation activities, among others (Bianchini and Vainio 2001). In addition, some organosulfur compounds such as ajoene, diallyl sulphide, and S-allylcysteine have lipid- and cholesterol-lowering effects and are able to inhibit platelet aggregation and protect against cardiovascular disease (Kim and Chun 1999). Ajoene and allicin also showed antimicrobial activity and S-allylcysteine-alleviated senescence-related symptoms (e.g., failing memory) (Kim and Chun 1999).

Vitamin C

Vitamin C or ascorbic acid (Figure 6.9), a water-soluble vitamin, is among the micronutrients most readily associated with vegetables. As this vitamin is covered in other chapters of this book, it will not be discussed in detail here. It is an important antioxidant with multiple functions including quenching various forms of oxygen, reduction of free radicals, and regeneration of primary antioxidants. In biological systems, it protects compounds in the water-soluble portions of cells and tissues and regenerates tocopherols (vitamin E) at the cellular membranes, hence playing a preventive role in a number of human diseases. In addition to its antioxidant and vitamin C activities, ascorbic acid can also act as a fl vorant, an acidulant, and a colorfixin and a reducing agent in food products (Shahidi and Wanasundara 2003).

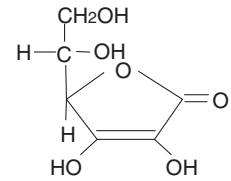
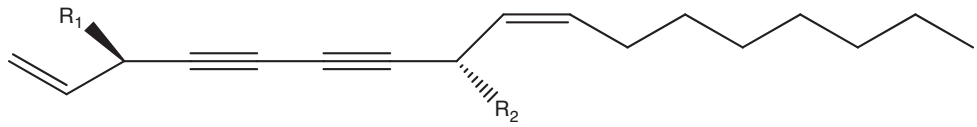


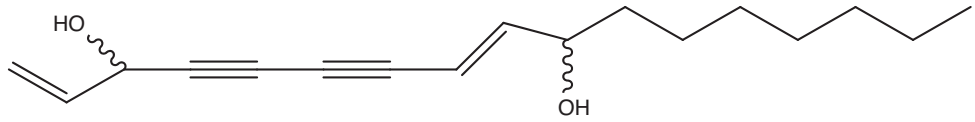
Figure 6.9 Chemical structure of ascorbic acid (vitamin C).

Polyacetylenes

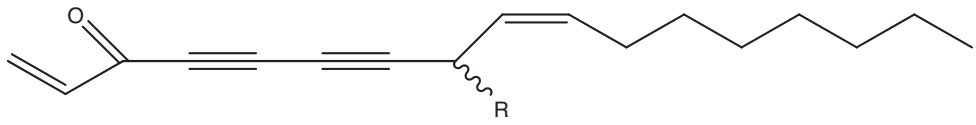
Polyacetylenes are a group of bioactive compounds consisting of carbon–carbon triple bond or alkynyl functional group (Minto and Blacklock 2008). Aliphatic C_{17}-polyacetylenes of the falcarinol type such as falcarinol and falcarindiol are widely distributed in the Apiaceae and Araliaceae families (Figure 6.10) (Hansen and Boll 1986; Minto and Blacklock 2008). Polyacetylenes of the falcarinol type are formed from oleic acid by dehydrogenation that leads to the formation of C_{18}-acetylenes crepenynic acid and dehydrocrepenynic acid, which are then transformed to C_{17}-acetylenes by β-oxidation. Further oxidation and dehydrogenation lead to falcarinol and related C_{17}-acetylenes of the falcarinol type (Hansen and Boll 1986; Minto and Blacklock 2008). Commonly found Apiaceae vegetables such as carrot, celery, celeriac, parsnip, and parsley are known sources



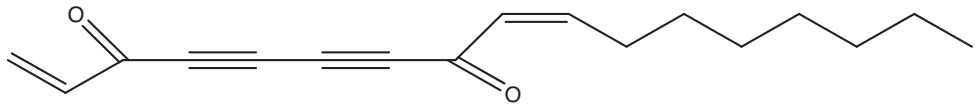
R_1 = OH, R_2 = H; falcarinol
R_1 = R_2 = OH; falcarindiol
R_1 = $OCOCH_3$, R_2 = OH; falcarindiol 3-acetate
R_1 = OH, R_2 = OCH_3; falcarindiol 8-methyl ether



Panaxydiol



R = H; falcarinone
R = OH; falcarinolone



Falcarindione

Figure 6.10 Aliphatic polyacetylenes from Apiaceae vegetables.

of polyacetylenes of the falcarinol type. The C_{17}-polyacetylenes of the falcarinol type have anti-inflammator (Liu et al. 1994; Alanko et al. 1994), anti-platelet-aggregatory (Teng et al. 1989), and immune-stimulating effects (Hansen et al. 1986). Polyacetylenes are phytoalexines that are synthesized by the plants in response to different stresses.

Previous studies have demonstrated that water stress (Lund and White 1990), storage time (Lund and Bruemmer 1991; Kidmose et al. 2004), and genotype (Kidmose et al. 2004) have significan effects on the total polyacetylene content and the contribution of each polyacetylene compound in the polyacetylene profil of carrots. contain three

major polyacetylenes, namely (*Z*)-heptadeca-1,9-diene-4,6-diyne-3-ol (falcarinol), (*Z*)-heptadeca-1,9-diene-4,6-diyne-3,8-diol (falcarindiol), and (*Z*)-3-acetoxyheptadeca-1,9-diene-4,6-diyne-8-ol (falcarindiol 3-acetate) (Czepa and Hofmann 2003, 2004; Zidorn et al. 2005), with contents in carrot root extracts of 43.4, 18.8, and 17.4 μg/g fw, respectively (Christensen and Kreutzmann 2007).

Polyacetylenes have been identifie as the leading cause of carrot's bitter taste (Czepa and Hofmann 2003, 2004). However, polyacetylenes isolated from carrots demonstrated beneficia effects on human health (Hansen et al. 2003; Brandt et al. 2004; Kidmose et al. 2004; Kobæk-Larsen et al. 2005; Zidorn et al. 2005). Falcarinol was reported as the most bioactive polyacetylene present in carrot, showing a significan cytotoxic activity against human tumor cells (Hansen et al. 2003, Brandt et al. 2004, Zidorn et al. 2005). Falcarinol in low concentrations (35 μg/g of freeze-dried extract) showed an inhibitory effect on the development of azoxymethane-induced tumors and aberrant crypt foci in the rat colon (Kobæk-Larsen et al. 2005). Later, bioavailability of falcarinol was demonstrated in human subjects. Ingestion of carrot juice containing 13 μg falcarinol/mL resulted in a plasma concentration of falcarinol of 2 ng/mL for several hours (Hansen-Møller et al. 2002). This is within the range in which inhibitory effects were observed in the *in vitro* studies (Hansen et al. 2003). However, Young et al. (2007) demonstrated a dose dependent biphasic effect of falcarinol on CaCo-2 cells, inducing proliferative and apoptotic characteristics at low and high concentrations of falcarinol, respectively.

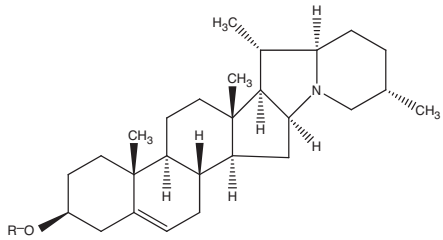
Several polyacetalene compounds, namely falcarinol, falcarindiol, 8-*O*-methylfalcarindiol, and panaxydiol (1,8-heptadecadiene-4,6-diyne-3,10-diol) were elucidated in celery (*Apium graveolens*) (Zidorn et al. 2005). All these polyacetylenes demonstrated medium-level cytotoxicity against leukemia, lymphoma, and myeloma cell lines with IC_{50} values of approximately 30 μM. The contents of falcarinol and facarindiol in fennel (*Foeniculum vulgare*) were 0.04 and 0.24 mg/g of freeze-dried extract, respectively, whereas in parsnip (*Pastinaca sati*va) the contents were 1.60 and 5.77 mg/g of freeze-dried extract, respectively. Parsley contained facarindiol as the major polyacetalene along with 8-*O*-methyl falcarindiol and panaxydiol, but falcarinol was not detected (Zidorn et al. 2005).

Alkaloids

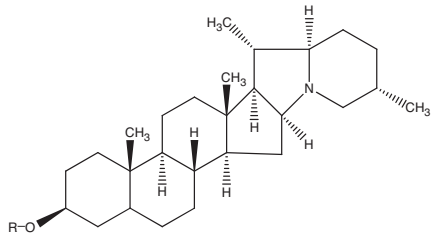
Alkaloids are potentially toxic nitrogen-containing secondary metabolites found mainly in several higher plants as well as some microorganisms and animals (Geissman and Crout 1969; Friedman 1992; Raver et al. 1999). The skeleton of most alkaloids is derived from amino acids although moieties from other pathways, such as those originating from terpenoids, are often possible (Dey et al. 1997). Alkaloids function primarily in plants as chemical defenses, acting as phytotoxins, antibactricides, insecticides, fungicides, and as feeding deterrents to insects, herbivorous mammals, and mollusks (Craik et al. 2002). They are commonly found in the Solanaceae family which includes vegetables such as tomato, potato, eggplant, pepper, and capsicum (Iwai et al. 1979; Aubert et al. 1989; Friedman and Dao 1992; Friedman and Levin 1995).

The types of steroidal glycoalkaloids produced by solanaceous plants differ depending on the species. The differences may arise due to the presence or absence of a C–C double bond, variety of functional groups such as hydroxyl, acetyl, and sugar groups (Chen and Miller 2001).

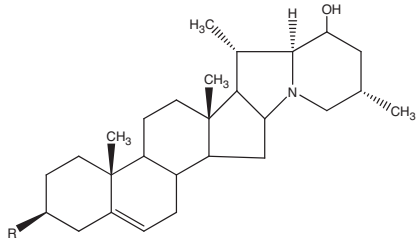
Two major glycoalkaloids in commercial potatoes are α-chaconine and α-solanine which are glycosylated derivatives of the aglycone solonidine (Figures 6.11 and 6.12). Wild potatoes (*Solanum chacoense*) and



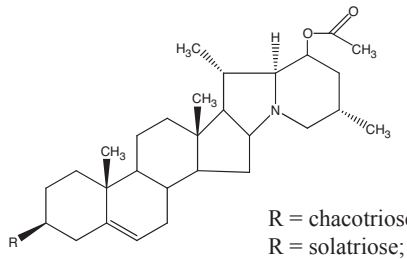
R = solatriose; α-solanine
R = chacotriose; α-chaconine
R = commertetraose; dehydrocommersonine



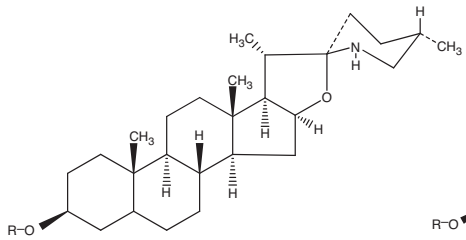
R = commertetraose; commersonine
R = lycotetraose; demissine



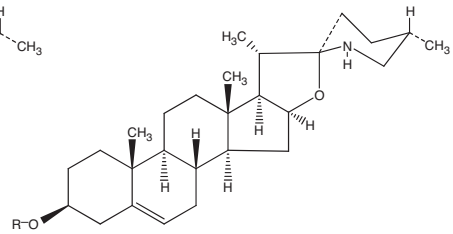
R = chacotrise; leptinine I
R = solatriose; leptinine II



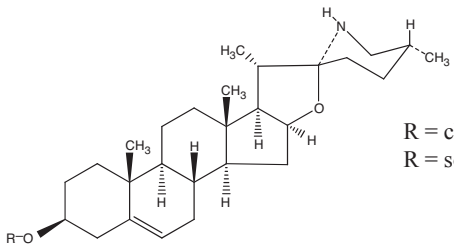
R = chacotriose; leptine I
R = solatriose; leptine II



α-Tomatine



Dehydrotomatine



R = chacotriose; solamargine
R = solatriose; solasonine

Figure 6.11 Structures of potato, tomato, and eggplant glycoalkaloids.

eggplants contain the glycoalkaloid solasonine. The major glycoalkaloid reported in tomatoes is α-tomatine, which is a glycosylated derivative of aglycone tomatidine.

Glycoalkaloids may be toxic at the appropriate levels to microorganisms, animals, and humans. The reported toxicity of glycoalkaloids may be due to several adverse

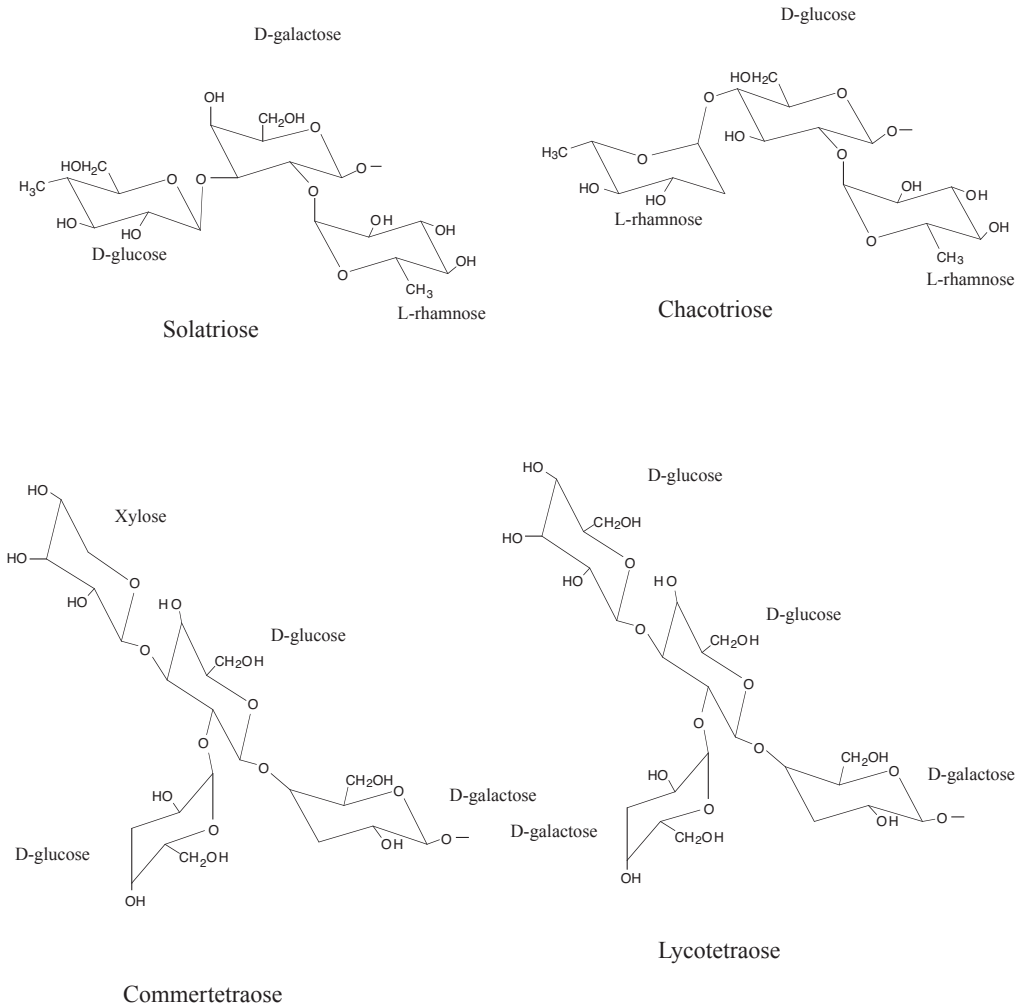


Figure 6.12 Carbohydrate side chains attached in glycoalkaloids.

effects such as anticholinesterase effects on the central nervous system (Roddick 1979), induction of hepatic ornithine decarboxylase, a cell proliferation marker enzyme (Caldwell et al. 1991), and disruption of cell membranes affecting the digestive system (Blankemeyer et al. 1992; Roddick et al. 1992, 1995).

The most prevalent glycoalkaloids in potatoes are α-solanine and α-chaconine, forming as high as 95% of the total glycoalkaloids. Depending on the variety, the concentration ratios of potato glycoalkaloids α-chaconine and α-solanine differed from 74:26 to 40:60 (α-chaconine:α-solanine) (Friedman and Dao 1992; Sharma and Salunkhe 1989). The other glycoalkaloids present were β- and γ-solanines and chaconines, α- and β-solamarines and aglycones demissidine, and 5-β-solanidan-3-a-ol.

Potato glycoalkaloids are cholinesterase inhibitors and cause poisoning, leading to the accumulation of acetylcholine in nerve tissues. Glycoalkaloids are present at high

levels in the leaves, stems, and sprouts of the potato plant and are normally at very low levels in potato tubers (Olsson 1996). However, exposure of potato tubers to light will produce elevated levels of glycoalkaloids, with the highest levels being in the sprouts. Potatoes will also produce high levels of glycoalkaloids in response to mechanical damages as well as to rotting caused by fungi or bacteria.

Potato and tomato glycoalkaloids exhibited several bioactive effects such as inactivation of the herpes simplex virus (Thorne et al. 1985), antibacterial effects (Gubarev et al. 1998), enhancement of general anesthetics that inhibit cholinesterase (Mcgehee et al. 2000), potentiation of a malaria vaccine (Heal et al. 2001), lowering of plasma cholesterol in hamsters (Friedman et al. 2000), and inhibition of growth of human colon and liver cancer cells (Lee et al. 2004). The common glycoalkaloid in tomatoes, tomatine, consists of a mixture of two glycoalkaloids, α-tomatine and dehydrotomatine (tomatidenol-3β-lycotetraose) (Friedman et al. 1994). The content of tomatine in green tomatoes was up to 500 mg/kg fw, and with maturity its level decreased to 1% of the amount found in the immature green fruit (Friedman and Levin 1995).

Tomatine showed a strong affinit for cholesterol *in vitro* (Roddick 1979; Micich 1993) and *in vivo* (Friedman et al. 1997).

Steroidal glycoalkaloids in eggplant reported were solanine, chaconine, solasonine, solamargine, and their aglycones, solasodine, and solanidine (Eanes et al. 2008).

The main components of the capsaicinoid fraction of hot peppers are capsaicin and dihydrocapsaicin (Materska and Perucka 2005). Capsaicin was reported to possess many bioactivities such as anti-inflammator , antinociceptive, and antimicrobial effects (Szolcsányi 1982; Suzuki and Iwai 1984; Buck and Burks 1986; Molina-Torres et al. 1999). Their medicinal value has been evaluated in the treatment of painful conditions such as rheumatic diseases, cluster headache, painful diabetic neuropathy, and postherpetic neuralgia.

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Chapter 7

Microbiology of Fresh and Processed Vegetables

Annemarie L. Buchholz, Gordon R. Davidson, and Elliot T. Ryser

Introduction

An increasing number of foodborne outbreaks traced to fresh fruits and vegetables are partially attributed to production, processing, and consumption patterns. In the United States, the progression from locally grown produce to centralized production has led to numerous multistate and nationwide outbreaks of foodborne illnesses. In many cases, fruits and vegetables are grown on centralized large-scale farms in locations that specialize in a specifi product. A few examples from the United States include the production of baby spinach in California and Arizona, tomatoes in Florida and New Jersey, blueberries in Michigan and New Jersey, and mushrooms in Pennsylvania. Under these conditions, one contamination incident at a large centralized grower or processor could quickly lead to a multistate outbreak with near catastrophic consequences for the industry, as was seen in several recent outbreaks involving baby spinach and tomatoes. By definition fresh fruits and vegetables do not typically undergo any treatment other than washing for the reduction and/or elimination of potentially hazardous microorganisms. Unfortunately, most commercial sanitizers used for washing fresh produce can only reduce the microbial levels by 99% to 99.9% at best, which still makes these products potential vehicles for the transmission of such microbial pathogens as *Salmonella*, *Escherichia coli* O157:H7, *Cryptosporidium*, Hepatitis A, and Norovirus.

Recent advances in modifie atmosphere packaging have enabled producers to develop convenience products such as triple-washed, fresh-cut, ready-to-eat leafy green salad mixes with longer refrigerated shelf lives that are now popular among many consumers. However, these advancements in packaging technology can also allow microbial contaminants to proliferate in the product during extended home storage; particularly if the product is held at 8ºC or higher. Hence, any potential growth of such pathogens as *Salmonella* and *E. coli* O157:H7 in the product becomes an even greater food safety concern due to their potentially low infectious dose. In this chapter we review the microbiology and safety of fresh produce.

Microflora of Fresh Produce

Fresh produce is typically home to a highly diverse group of microorganisms including bacteria, yeasts, molds, parasites, and viruses as well as insects and other plant pests that may exist on plants as harmless commensals, plant pathogens, or potential spoilage organisms. As part of this diverse microbial community, fresh produce may also harbor potential human foodborne pathogens such as *Salmonella*, *E. coli* O157:H7, *Cryptosporidium*, and enteric virus, all of which are

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indicators of fecal contamination. Plants contain numerous sites for colonization and potential entry of microorganisms, ranging from the stems, leaves, and fruiting bodies above ground to the root system below ground. Hence, a brief discussion of these initial microbial interactions with living plant material is the firs step toward a better understanding of the microbiology of fresh produce.

Rhizosphere

The rhizosphere—define as the soil environment surrounding the plant root system—is a highly complex ecosystem where soil, roots, and microbes interact (Brimecombe et al. 2007). This environment which may be laden with fecal material from animals and manure used as fertilizer is a food safety concern due to the potential for human foodborne pathogens to contaminate the plant surface and potentially be taken up into the plant through the root system (Sturz et al. 2000). By their very nature, plant pathogens invade plants and become internalized, much to the detriment of the plant. Given the increasing number of outbreaks associated with consumption of fresh produce, concerns have also been raised regarding the potential for human foodborne pathogens to become internalized within plant tissue. Much of the internalization research has focused on leafy greens, a product category that has received considerable attention following the spinach outbreak of 2006 (Ryser et al. 2009). Studies focusing on the potential internalization of *E. coli* O157:H7 through the root system into spinach plants growing in soil have found little to no evidence for infiltratio (Warriner et al. 2003; Hora et al. 2005). Ryser et al. (2009) hypothesized that the lack of internalization may be attributed to competitive microflor existing in the rhizosphere. Several recent studies also suggest that the internalization of *E. coli* O157:H7 and *Salmonella* from soil into plant tissue through the roots is unlikely, given the low levels of these two pathogens that would be expected to occur in the soil (Ryser et al. 2009; Sharma et al. 2009).

Phyllosphere

The phyllosphere—define as the portion of the plant above the soil line—is host to a diverse community of organisms including a wide variety of bacteria, yeasts, and fungi, some of which may be plant pathogens or human foodborne pathogens, as well as a wide range of insects and pests. Most organisms on the plant surface are harmless commensals that neither help nor harm the plant.

However, some human foodborne pathogens found in the phyllosphere, including *E. coli* O157:H7 and *Salmonella*, may attach, persist, and potentially become internalized through the stomata or enter the plant vascular system when a product such as head lettuce is cut near the soil line at the time of harvest (Taormina et al. 2009). Once internalized, any microorganisms would be unaffected by the commercial sanitizers used during subsequent washing steps (Takeuchi and Frank 2000).

Biofilms

Biofilms define as "an assemblage of microorganisms adherent to each other and/or to a surface and embedded in a matrix of exopolymers" (Costerton et al. 1999), represent another food safety concern in regard to fresh produce as they can also lead to the persistence of human foodborne pathogens that may be present on edible portions of fresh fruits and vegetables. Annous et al. (2005) demonstrated that two clinical isolates of *Salmonella enterica* associated with cantaloupe outbreaks formed biofilm on the surface of cantaloupes. Hence, this pathogen could have been transferred to the edible portion of the cantaloupe during cutting prior to consumption. A further concern is the inability of the commonly used commercial produce sanitizers to inactivate these pathogens and potential spoilage

organisms in biofilm on the plant phyllosphere (Ukuku and Sapers 2001). An area of current research for preharvest contamination prevention is the addition of competitive inhibitors to the exterior of the plant that may help reduce colonization by pathogens.

Foodborne Pathogens

Foodborne pathogens can contaminate produce at the preharvest stage as just summarized, with *E. coli* O157:H7 and *Salmonella* spp. arguably being the two most important public health concerns. While initially used as an indicator of fecal contamination in water, fecal coliform bacteria and *E. coli* can both be used as indicators of fecal contamination for fresh produce (Doyle and Erickson 2006), which in turn may suggest the possible presence of *Salmonella* and/or *E. coli* O157:H7.

Produce-Associated Outbreaks in the United States

As the United States population attempts to move toward healthier eating habits, fresh produce-associated outbreaks are becoming more frequent. Between 1990 and 2006, consumption of fresh fruits and vegetables led to 768 outbreaks that included 35,060 cases of illness (Center for Science in the Public Interest (CSPI) 2008b), with these numbers expected to increase. Furthermore, from 1998 to 2006, the average produce outbreak was responsible for 40.1 cases of illness, which is far greater than that seen for beef (23.4), poultry (24.5), and seafood (8.9) (CSPI 2008a). During the 15-year period from 1990 to 2005, *E. coli* O157:H7 and *Salmonella* were respectively responsible for 6% and 23% of these outbreaks (CSPI 2008b).

Based on the data in Figure 7.1 collected by the Center for Science in the Public Interest for specifi types of fresh produce, lettuce was most frequently associated with outbreaks of illness, followed by potatoes, tomatoes, melons, sprouts, berries, mushrooms, and peppers (CSPI 2008a). Among the broader categories, salads, which would include leafy greens, were responsible for over one-third of all produce-related outbreaks. All of these fresh fruits and vegetables are susceptible to microbial contamination from farm-to-fork with some of the sources for bacterial pathogens including irrigation water, domestic livestock, wild animals, fiel workers, processing equipment, consumer cutting boards, and home refrigerators (Beuchat 2006).

Leafy Greens

Thus far, 363 outbreaks and 13,568 reported cases of illness in the United States have been associated with the consumption of leafy greens, which comprise a wide range of salad and other greens including iceberg lettuce, romaine lettuce, green leaf lettuce, red leaf lettuce, butter lettuce, baby leaf lettuce (i.e., immature lettuce or leafy greens), escarole, endive, spring mix, spinach, cabbage, kale, arugula, and chard. The majority of these outbreaks have been traced to *E. coli* O157:H7-contaminated lettuce and spinach grown in the Salinas Valley of California, with the number of outbreaks having increased dramatically since 2004 (CSPI 2008b). In September 2006, contaminated prebagged baby spinach triggered an *E. coli* O157:H7 outbreak in 26 states and Canada, resulting in fi e deaths and 205 illnesses. This outbreak strain was eventually traced to numerous free-roaming feral swine that were spotted on a cattle ranch roughly a mile away from the implicated spinach fiel (cattle are the primary reservoir of *E. coli* O157). These pigs also had access to the spinach field themselves and their droppings could thereby contaminate the crops. Two genetically based strain-specifi typing methods—multilocus variable number tandem repeat analysis (MLVA) and pulsed-fiel gel electrophoresis (PFGE)—confirme that the clinical and pig isolates of *E. coli* O157:H7 were identical. This observation

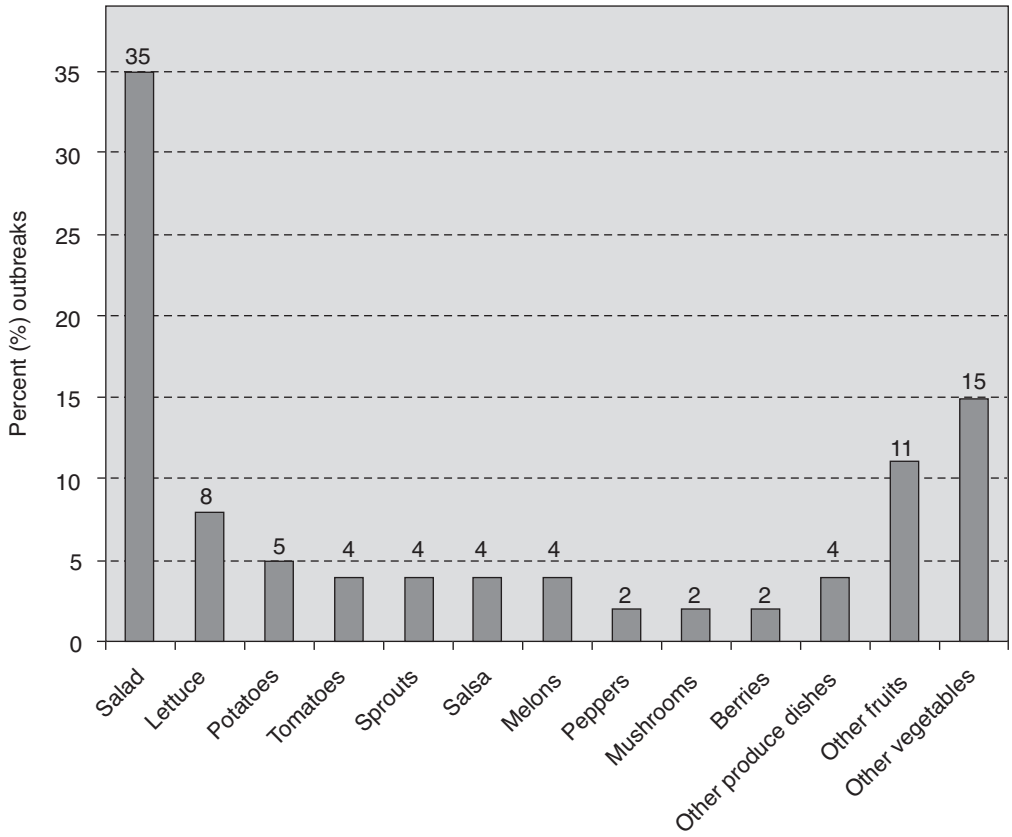

Figure 7.1 Produce-linked outbreak vehicles between 1998 and 2006 (CSPI 2008a).

was further supported by the discovery of pig tracks, rooting activity, and pig feces in the spinach fiel and adjacent vineyards (Jay et al. 2007).

During November and December of 2006, two additional *E. coli* O157:H7 outbreaks were traced to California-grown iceberg lettuce that was shredded and then purchased by two fast-food Mexican restaurant chains in the Midwest and Northeast (FDA 2006, 2007). These two outbreaks sickened a combined total of over 150 individuals (CSPI 2008b). In one of the outbreaks, state health official in Minnesota, Iowa, and Wisconsin ultimately matched the strain of *E. coli* O157:H7 to two environmental samples that were collected from dairy farms near the field where the lettuce was grown (FDA 2007). The source of the other outbreak strain, however, could not be confirme (FDA 2006).

Sprouts

Since 1995, at least 31 sprout-related outbreaks involving 2,022 cases of illness have been documented in the United States (CSPI 2009). Alfalfa sprouts were firs associated with foodborne illness in 1995 when sprouted alfalfa seeds were linked to a large salmonellosis outbreak in the United States. In this outbreak involving 242 cases of illness in 17 US states and Finland, seeds originating from a Dutch company were infected with *Salmonella* serotype Stanley. Subsequently, the clinical and alfalfa sprout isolates yielded similar PFGE patterns, thus confirmin the

source of the outbreak (Mahon et al. 1997). As reported by Taormina et al. (1999), many other serotypes of *Salmonella* including Saintpaul, Goldcoast, Bovismorbificans Newport, Montevideo, Meleagridis, Infantis, Anatum, Senftenberg, Havana, Cubana, and Tennessee were responsible for similar outbreaks between 1995 and 1998, with *Bacillus cereus* and *E. coli* O157:H7 also identifie as causes of sprout-related illnesses during this same period. All of these sprout outbreaks, most of which involved alfalfa sprouts, originated from contaminated seed. One of the most recent sprout-related outbreaks in the United States occurred in February 2009 and involved 235 persons from 14 states. These individuals once again became infected with *Salmonella* Saintpaul after consuming alfalfa sprouts that were grown from contaminated seed (Centers for Disease Control and Prevention (CDC) 2009).

In response to these outbreaks, the United States Food and Drug Administration (FDA) has made sprout safety a priority and approved the immersion of seeds in an aqueous solution of 20,000 ppm (2%) calcium hypochlorite in an attempt to inactivate *E. coli* O157:H7 prior to sprouting. However, *E. coli* O157:H7 is typically resistant to this treatment when internalized in the seed (National Advisory Committee on Microbiological Criteria for Food/The U.S. Food and Drug Administration (FDA) 1999; Weissinger and Beuchat 2000).

Tomatoes

An increasing number of salmonellosis outbreaks have been traced to tomatoes. Between July 2005 and October 2006, three different serotypes of *Salmonella* were implicated in multistate outbreaks involving over 450 individuals. One of these outbreaks involved raw, large, red, round tomatoes that were consumed at various restaurants. The contaminated tomatoes were later traced to two farms on the eastern shore of Virginia where the outbreak strain of *Salmonella* Newport was isolated from an irrigation pond near the tomato fields Shortly thereafter, another group of restaurant customers became ill after consuming raw, prediced Roma tomatoes that were contaminated with *Salmonella* Braenderup. Although investigators subsequently isolated various *Salmonella* serovars from samples of drainage ditch water and animal feces collected at the tomato farm, the outbreak strain of *Salmonella* Braenderup was never recovered.

The inability to pinpoint the exact source of contamination in produce-related outbreaks is not uncommon, as was true for two other tomato-related outbreaks in 2005 and 2006 (CDC 2007a). The food vehicle responsible for a particular outbreak also sometimes remains elusive. This was the case for a widely publicized outbreak of *Salmonella* Saintpaul that spanned 43 states, the District of Columbia, and Canada. This outbreak began in May 2008 and eventually resulted in 1,442 cases of illness, including 286 hospitalizations and two fatalities. An initial case-control study showed a significan association between consumption of raw tomatoes and illness. However, later results implicated jalapeño and serrano peppers that were grown and packed in Mexico. The outbreak strain was found on two types of peppers originating from two farms, suggesting that cross-contamination with other produce items (including tomatoes) during growing, processing, or distribution was also possible. This jalapeño or serrano pepper outbreak, which is the firs of its kind in the United States, highlights some of the present concerns surrounding the safety of fresh produce imported from less developed countries, which may be grown and harvested under less hygienic conditions (CDC 2008).

Cantaloupes

Another imported commodity, cantaloupes, has frequently been implicated in *Salmonella* outbreaks. During the summer of 1991, at least 400 individuals in 23 states and Canada

became infected with *Salmonella* Poona (CDC 1991)—a serotype seldom associated with human illness. Ten years after this outbreak, three additional multistate outbreaks involving *Salmonella* Poona were traced to consumption of cantaloupe imported from Mexico during 2000 to 2002. Subsequent FDA investigations of the farms in Mexico where the implicated cantaloupes originated showed that appropriate measures had not been taken to minimize microbial contamination during the growing, harvesting, packaging, and cooling phases of production. The likely sources of contamination included irrigation water contaminated with sewage, *Salmonella*-contaminated water used during processing (cleaning and cooling), unacceptable hygienic practices among the fiel and factory workers, pests in the packing facility, and improper cleaning/sanitization of the processing equipment (CDC 2002).

Mexican fruits and vegetables are by no means responsible for all of the outbreaks in the United States that have been traced to imported produce. In 2008, *Salmonella* Litchfield-contaminate cantaloupes that originated from a Honduran grower and packer sickened 51 people in the United States and Canada (FDA 2009).

When grown in the field cantaloupes, like other melons, are in direct contact with the soil and potentially animal excrement, which in turn may allow *Salmonella* to contaminate the surface. These bacteria can then be transferred via a knife blade from the rind to the fles of the fruit during cutting, slicing, and dicing. Some of the larger packing houses have chosen to submerge their melons in a chemical sanitizer to reduce surface contaminants (CDC 1991; Ukuku et al. 2001). However, special care must be taken to avoid potential internalization of microorganisms through the vulnerable stem-end of the melon (Beuchat and Scouten 2004; Richards and Beuchat 2004). Temperature abuse during storage can also potentially enhance the growth of the *Salmonella* and other foodborne pathogens inside melons and increase the likelihood of illness (CDC 1991).

Preharvest and Harvest

Sources of Contamination

The increasing frequency of these aforementioned foodborne outbreaks associated with fresh fruits and vegetables is a major concern in the United States. These outbreaks have become the driving force behind the produce industry's efforts to make significan improvements in the way their products are grown, harvested, and processed, because contamination of produce can occur anywhere in its passage from the farm to the fork.

Numerous routes for preharvest contamination of fresh fruits and vegetables have been documented, as shown in Figure 7.2. However, the microbiological quality of the soil, composted manure, and irrigation water, along with fecal contamination from domestic and wild animals, and water runoff from livestock operations continue to receive the most attention. In the *E. coli* O157:H7 outbreak of 2006 that was attributed to baby spinach, fecal contamination from wild pigs or water runoff from a livestock operation was presumed to be the most probable source of contamination.

Soil

The soil environment, which includes the rhizosphere, is an important component when considering the safety of fresh produce. Human pathogens interact with native microflor in the soil, affecting the survival, persistence, and potential contamination of fresh produce. Soil characteristics such as the degree of water permeability, water content, nutrient content, and levels/types of native microflor will affect survivability and persistence of pathogens. Gagliardi and Karns (2000) correlated *E. coli* O157:H7 levels with nitrogen levels in fiel leachate. This correlation demonstrates that fertilization of field should

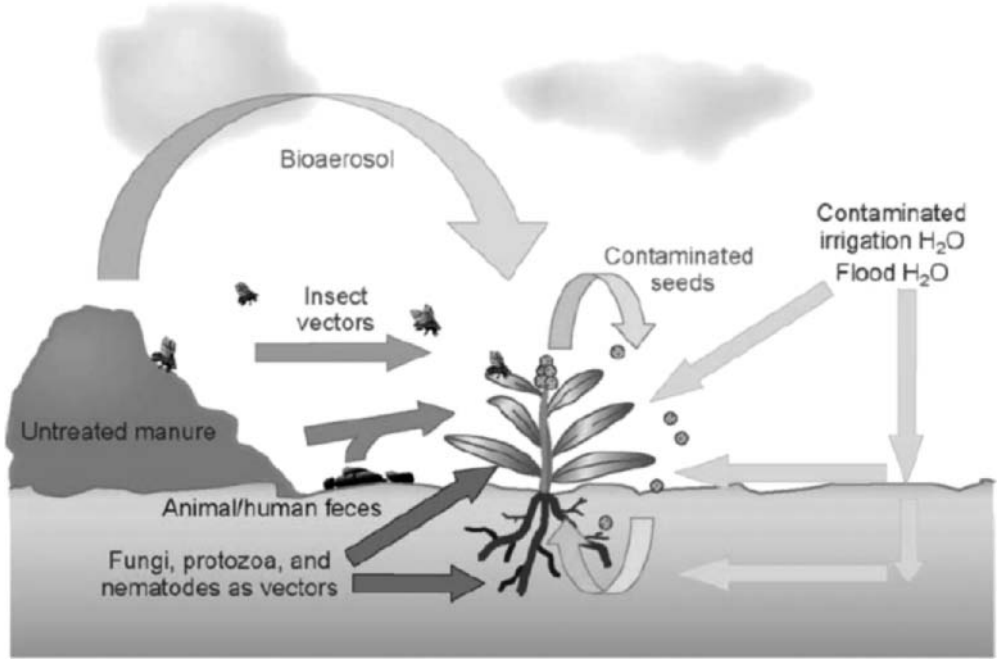

Figure 7.2 Sources of pre-harvest contamination (Brandl 2006).

be limited to the amount that will be used by the crop since additional nitrogen will prolong the persistence of pathogens. Gagliardi and Karns (2002) compared persistence of *E. coli* O157:H7 in soil with and without manure and found that manure did not seem to affect its persistence. Research by Islam et al. (2004) found that *E. coli* O157:H7 could survive for up to 7 months in a vegetable fiel when manure-amended soil was exposed to southern fall-winter conditions. Such find ings demonstrate the need for proper manure composting before application to the field as a fertilizer.

Manure

Manure, the most commonly used type of fertilizer for crops, has been implicated as the source of contamination in numerous outbreaks. Before application to fields all raw manure should be composted until the internal temperature reaches 50°C to inactivate *E. coli* O157:H7, *Salmonella*, and other pathogens of fecal origin that may be present (Beuchat 2006). The climate, covering material, frequency of watering and turning, and the amount and source of the manure are all factors that determine composting time.

Coté et al. (2006) found that 15–26 days of composting was needed to inactivate 90% of the *E. coli* population in liquid hog manure with 54–114 days required to reduce the *E. coli* population to undetectable levels. These finding emphasize the importance of composting until the recommended minimum temperature of 50°C is attained. Controlling pathogen populations in animal wastes destined to be used as fertilizer is crucial to reduce the risk of pathogens contaminating fresh fruits and vegetables that will enter the human food chain.

Kim et al. (2009) identifie the native microflor present in manure as the major suppression factor influencin regrowth of *E. coli* O157:H7 in compost. This findin indicates

that monitoring and maintaining a high population of background microorganisms in compost is important to prevent the potential regrowth of pathogens. Research by Jiang et al. (2002) indicated that indigenous microorganisms along with soil temperature, and manure-to-soil ratio may all be contributory factors in the survival of pathogens in manure-amended soil.

Irrigation Water

Irrigation water is another key source for microbial contaminants including *E. coli* O157:H7 and *Salmonella* as well as protozoan parasites such as *Giardia*, *Cryptosporidium*, and *Cyclospora* (Izumi et al. 2008; Thurston-Enriquez et al. 2002) with the microbiological quality of irrigation water coming from streams, ponds, recreational sources, return fl ws during floo irrigation, or storm drains being highly variable. Persistence of microorganisms in the water is dependent on a number of factors including soluble organic matter, particulate matter, sunlight, and temperature (Gerba 2009). Finally, the method of irrigation used—drip irrigation, which treats the rhizosphere, and overhead irrigation, which treats both the rhizosphere and phyllosphere—will further impact microbiological safety at harvest (Gerba 2009).

Livestock and Wild Animals

In addition to manure and water being carriers of fecal contaminants, domestic livestock including cattle, swine, sheep, and poultry are well-known fecal carriers of pathogens (Chapman et al. 1997) with these animals able to asymptomatically shed *E. coli* O157:H7, *Salmonella*, and *Campylobacter* in their feces. Wild animals including birds and deer can similarly carry pathogens (Sargent et al. 1999; Hernandez et al. 2003). Sela et al. (2005) proposed the Mediterranean fruit fl as a potential vector of bacterial pathogens since in their work a fl contaminated with *E. coli* could harbor the organism for up to 7 days. Wild-caught flie were also shown to be carriers of coliform bacteria.

Internalization

Another area of concern and current debate is the potential internalization of pathogens such as *E. coli* and *Salmonella* into fresh fruits and vegetables via various routes along with their ability to internally persist and survive the commercial washing and sanitizing treatments used during subsequent processing (Ryser et al. 2009). Portals for pathogen entry into fruits and vegetables include the roots and rootlets; stomata of the leaves; stem scar tissue; cut, diseased, or decaying surfaces; and various wounds caused by both insect infestation and improper harvesting/processing practices. Solomon et al. (2002) demonstrated the uptake of a green fluorescen protein-expressing strain of *E. coli* O157:H7 from water and cow manure into lettuce via the plant vascular system. More recently, Kroupitski et al. (2009) showed that *Salmonella enterica* could enter lettuce plants through the stomata of the leaves with internalization of this pathogen enhanced in the presence of light and nutrients produced by photosynthetically active plant cells (Figure 7.3). In contrast, Zhang et al. (2009) were unable to demonstrate internalization of *E. coli* O157:H7 into lettuce leaves when the plants were grown in soil containing 6 log CFU/g of *E. coli* O157:H7. Internalization of foodborne pathogens may also be inhibited by bacterial endophytes that exist as harmless commensals within the plant tissue (Sturz et al. 2000).

Internalization of bacterial pathogens and other microorganisms into fresh produce is a far greater and very real concern during the processing steps of flumin and washing since the weight of a warm product will naturally increase when immersed in cold water due to water uptake, as occurs during the crisping of leafy greens.

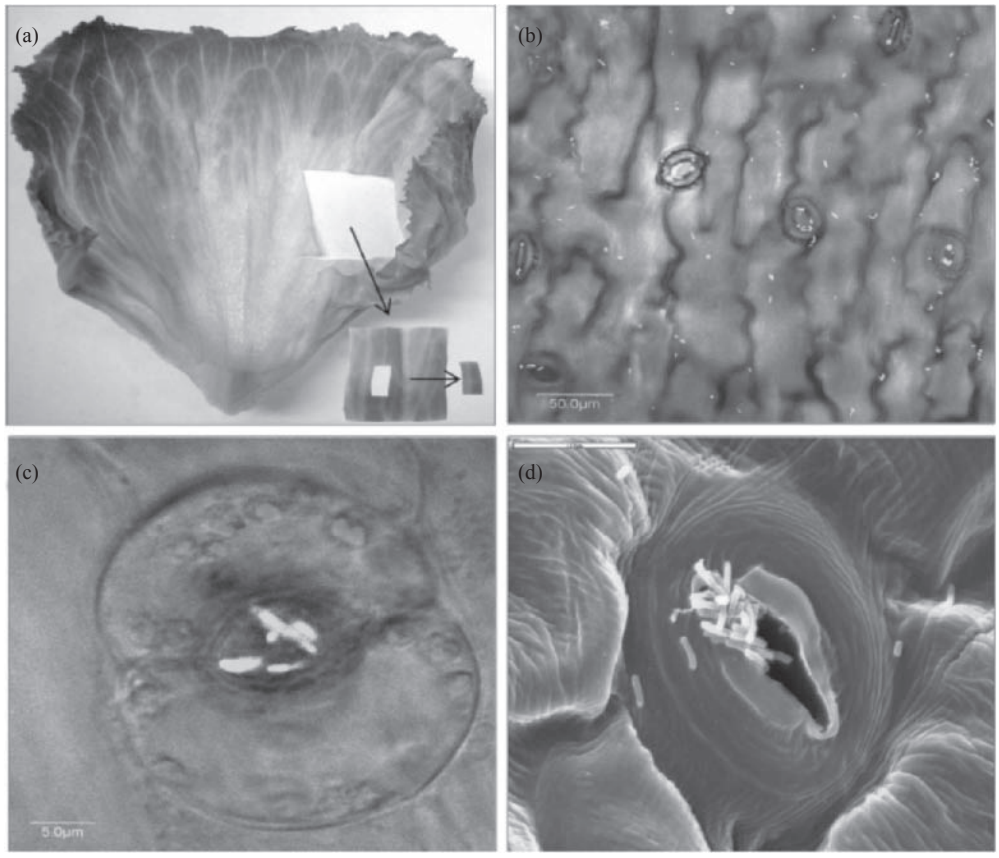

Figure 7.3 Interaction of *Salmonella* Typhimurium cells with lettuce leaves (Kroupitski et al. 2009). Images of lettuce stoma taken under confocal microscopy (b, c, and d). *S. enterica* serovar Typhimurium cells are fluorescing green in b and c. Image d shows multiple cells, probably *Salmonella*, residing in a stoma.

Biological Controls

Some nonpathogenic naturally occurring microorganisms isolated from both soil and fresh produce have been proposed as potential biocontrols to compete against *E. coli* O157:H7, *Salmonella*, and other human foodborne pathogens (Whipps 2001). In one study, Schuenzel and Harrison (2002) were able to inhibit the growth of *E. coli* O157:H7, *Salmonella* Montevideo, *L. monocytogenes*, and *Staphylococcus aureus* using a variety of bacterial isolates from ready-to-eat salad vegetables. However, identifying the correct microflor to inhibit specifi human pathogens presents a far more formidable challenge. Such a control strategy may meet with better acceptance from consumers who are in favor of organically grown produce and opposed to the use of chemical sanitizers during flumin and washing.

Harvesting Methods

Harvesting practices for fresh fruits and vegetables are highly variable and product specifi with countless types of hand tools, mechanical harvesting equipment, containers, and even the workers themselves being possible carriers of human pathogens that could contaminate the product. Good Agriculture Practices (GAPs) as discussed elsewhere

should be followed to minimize the potential spread of microbial pathogens during harvest.

Equipment

Various types of hand tools and harvesting equipment have been implicated as sources of contamination in produce-related outbreaks. Harvesting equipment is product specifi and designed for the specifi location of the product being harvested. Apples are frequently hand picked to avoid mechanical damage and bruising. In contrast, baby spinach is commercially harvested using lawn mower-type machines that can introduce microorganisms, including foodborne pathogens, into the product through contact with soil and manure. Lettuce destined for commercial shredding is often hand-cored in the field Taormina et al. (2009) found that *E. coli* O157:H7 could be transferred to ten consecutive heads of lettuce after the coring device contacted soil containing 2.72 CFU/g of the pathogen.

Workers

Many produce-related outbreaks presumably result from fecal contamination of fresh fruits and vegetables. In one outbreak from 1995, a worker was implicated in the contamination of melons with *Vibrio cholerae* during slicing (Ackers et al. 1997). Clearly, worker health, hygiene, and training are essential in controlling potential hazards and maintaining a safe supply of fresh produce (FDA 1998).

Given that fiel workers typically come from diverse cultural backgrounds, inferior personal hygiene practices may allow for the propagation of human pathogens (Brackett 1998). The ability of workers to recognize the signs and dangers of infectious diseases, such as skin lesions or diarrhea, is a critical firs step to reducing produce contamination. Proper use of lavatory facilities and additional training in regard to proper hand-washing techniques are both critically important.

Processing and Preservation

After harvesting, microbial contamination can come from many different sources such as the water used for cooling and washing, equipment surfaces, and workers. Table 7.1 shows sources of contamination. Microbial contaminants can spread to multiple batches of product during processing

Table 7.1 Sources of contamination during processing

Stage	Contamination sources	
Postharvest processing	Cooling	Water Ice Vacuum cooling
	Transport	Shipping vehicle contamination Storage containers Human handling
Fresh-cut and value-added processing	Debris removal	Human handling Processing equipment: sifters, rollers, destemmers, deleafers, etc.
	Conveyer	Conveyer belt
	Washing	Water
	Value-added processing	Processing equipment: shredder, dicer, core removal, pitter, etc.
	Drying	Processing equipment: centrifugal dryer, rollers, blow dryers, etc.
	Packaging	Human handling Materials Equipment

(e.g., washing, peeling, shredding, slicing, drying, and sorting) which can lead to a potential outbreak of illness if the contaminant is a human foodborne pathogen. Consequently, a wide range of product-specifi microbial reduction strategies aimed at cooling the product and reducing the microbial load through the addition of various chemical sanitizers to the wash water have been developed for fresh produce. The choice of what specifi processing methods are to be used is consumer driven with widespread consumer acceptance of the fina product being the ultimate goal.

Cooling

After harvest, the most immediate concern is reducing the temperature to preserve product quality. Rapidly cooling many types of fresh fruits and vegetables to refrigeration temperatures will decrease water loss and reduce both the rate of respiration and the rate of ethylene production which will, in turn, slow the ripening process with these lower temperatures also minimizing the growth of both spoilage and pathogenic bacteria. Commonly used commercial cooling methods which vary for different types of fruits and vegetables include refrigerated storage rooms with appropriate air circulation (e.g., tomatoes, apples, berries), forced air cooling (e.g., tomatoes, berries , peppers), vacuum cooling (e.g., leafy greens, peppers), hydrocooling (e.g., leafy greens, cantaloupes, peppers, carrots, asparagus), and packing in ice (e.g., asparagus, broccoli) (USDA/ARS 2004). However, both spoilage and pathogenic bacteria can still be transmitted via air, condensate, and water droplets.

Vacuum cooling, which is based on evaporative cooling of a product under low pressure, can be used to rapidly decrease the fiel temperature of many fruits and vegetables and is now the method of choice for leafy greens. However, this cooling method may lead to the internalization of both spoilage and pathogenic bacteria . In one recent study, vacuum cooling significantl increased the infiltratio of *E. coli* O157:H7 (considering both cell numbers and the depth of penetration) into lettuce tissue by more than 90% when compared with the nonvacuum cooled product with these internalized cells protected during quadruple washing of the product in a produce sanitizer (Li et al. 2008).

Water-based cooling methods carry a much greater risk of contamination with the microbial populations for water-cooled produce based on the initial numbers of microorganisms in the water and the numbers of microorganisms transferred between the product and the water. Potable water, define as water that has a coliform count of less than 1 CFU/ml, an aerobic plate count of less than 100 CFU/ml, and is free of *Cryptosporidium, Giardia lamblia, Legionella*, and enteric viruses (U.S. Environmental Protection Agency (EPA) 2009), should be used in all cases, including when making ice. Various chemical sanitizers can be added as appropriate to reduce microbial populations in the water (Rangaranjan et al. 2000). However, the sanitizer concentration must always be maintained at an effective level and be carefully monitored to ensure that the organic load does not decrease the effica y of the sanitizer. Internalization of both spoilage and pathogenic bacteria during water cooling of fresh produce continues to be a major concern, particularly when the temperature of the produce exceeds that of the water by 10°F or more (Rangaranjan et al. 2000).

In an extreme example, one study looked at the extent to which a colored food dye and *Salmonella* Enteritidis were internalized when a commercial heat disinfestation method was used to inactivate tephritid fl larvae in immature and ripened mangoes. After immersion in water at 47°C for 90 minutes, followed by immersion in dyed 21°C water containing *Salmonella*, 67% of the mangos took up the dye. In addition, internalized salmonellae were recovered from 80% and 87% of the immature and ripened fruit with

greater internalization seen at the stem-end as compared with the mid-side or blossom-end (Penteado et al. 2004).

Both strawberries and tomatoes will gain weight during hydrocooling, with this gain in water weight enhanced by the presence of wounds and abrasions on the fruit (Ferreira et al. 1996; Vigneault et al. 2000). When mold spores of *Botrytis cinerea* or *Rhizopus stolonifer* were added to hydrocooling water for strawberries, Ferreira et al. (1996) reported that nearly all of the berries developed decay during storage. Vigneault et al. (2000) reported similar weight gains when tomatoes were hydrocooled using both a shower system and a flume with upward orientation of the stem scars leading to significantly greater weight gains in the shower system. After these tomatoes were processed in chlorine-free hydrocooling water that contained *Erwinia carotovora* subsp. *carotovora* or *Rhizopus stolonifer*, 50% to 100% of the fruit became diseased, validating the need for adding chlorine-based or other appropriate sanitizers to the wash water.

Transport

Fresh fruits and vegetables are prone to temperature abuse and cross-contamination during all stages of transport from the field to the consumer's plate.

Wooden or plastic totes, crates, and other types of storage containers that inevitably come in contact with soil or other debris in the field at the time of harvest are an important source of microbial contamination when transported to processing facilities. Many produce growers are now using plastic instead of wooden containers for transport and storage due to the increased ease of cleaning and sanitizing.

The time–temperature history of fresh produce throughout the entire field-to-fork continuum plays a pivotal role in both the microbial safety and shelf life of the final product. In one example, microbial populations increased 1 to 2 logs on newly harvested blueberries that were stored on pallets for ~12 hours at 15°C before processing, with these increased microbial counts also reflected in the fully processed berries that were subsequently frozen (Popa 2005). Hence, extra attention must be given to proper temperature control when highly perishable fruits and vegetables are transported over long distances for processing. In this regard, radio-frequency identification chips are now being used to continuously monitor both the temperature and relative humidity in trucks during all stages of transport from the farm through retail distribution.

Processing

Human foodborne pathogens, including *E. coli* O157:H7, *Salmonella*, *Listeria*, and *Cryptosporidium*, that may inadvertently contaminate fresh fruits and vegetables in the field or at harvest, can be readily transferred to much larger quantities during subsequent product handling and further processing, raising even greater food safety concerns. In a survey of Japanese ready-to-eat fresh vegetable processors, populations of mesophilic aerobic bacteria exceeded 5.0 log CFU/cm^2 or ml in many samples collected from product contact surfaces of the washing, slicing, dehydrating, and blending equipment, surfaces of the slicer/shredder blades, and the processing room floor, all of which were obtained at the end of processing (Kaneko et al. 1999).

Understanding this ability of foodborne pathogens to attach to stainless steel or other types of equipment surfaces and form biofilms is essential for the development of effective cleaning and sanitizing protocols, since such bacteria are more difficult to remove and more resistant to commonly used sanitizers in flume washing systems. Moore et al. (2003) demonstrated the ability of *Campylobacter jejuni* and *Salmonella enterica* serovar Typhimurium to transfer from stainless steel surfaces to both wet and dry lettuce via direct

contact with 66% of the *Salmonella* population transferring from a dry stainless steel surface to a dry product after 60 minutes of direct contact. In contrast, 23% to 31% of the *Salmonella* population transferred from dry stainless steel to wet lettuce after 120 minutes of direct contact. Transfer of *C. jejuni* ranged from 16% to 38% for dry lettuce and 15% to 27% for wet lettuce after 80 minutes of contact. These results show the ability for *C. jejuni* and *Salmonella* Typhimurium to persist on surfaces and maintain the ability to transfer to food surfaces hours after they become contaminated.

Field-harvested fruits and vegetables will inevitably contain sticks, stones, stems, leaves, and other unwanted material that needs to be removed during initial stages of processing. Product-specifi equipment used to remove such material includes riffl boards and flotatio washers to separate stones, sieves, or screens in combination with air blowers to remove lightweight material, and various types of rollers to remove stems with any accompanying microorganisms easily contaminating the equipment surfaces.

Conveyers

Fruit and vegetable processing typically involves the use of various types of conveyor belt systems manufactured from different belting materials including high-density polyethylene, polypropylene, and acetyl. Two main conveyor belt designs—interlocking (a series of interlocking pieces that contain many microbial harborage sites) and smooth (a continuous belt with a single seam)—can be found in the produce industry with the belting material and design tailored to the specifi product and application. Regardless of the belt type or material, all conveyor belts are prone to microbial buildup and the subsequent transfer of microorganisms to the incoming product over time. The newer smooth continuous belts, which can be more easily cleaned and sanitized, are now generally preferred over the older interlocking belts that must be disassembled and then manually cleaned and sanitized.

Flume Washing

Fruits and vegetables destined for the fresh-cut ready-to-eat market are commercially washed up to three times in various types of flum tanks to remove soil and decrease the levels of microorganisms. In general, washing fresh produce in water alone will only decrease the microbial populations by 90% to 99% (Sapers 2001). In one recent study using *E. coli* O157:H7-inoculated lettuce and baby spinach, 83–97% of the inoculum was transferred to the wash water that recirculated during pilot-scale flum washing (Buchholz 2009a) with any subsequently processed product being immediately inoculated with *E. coli* O157:H7 via direct contact with the contaminated water.

Flume and wash water are ideal vehicles for the spread of microorganisms throughout an entire batch of product. Unfortunately, when added to flum and wash water, the commonly used chlorine-based sanitizers as well as most others including peroxyacetic acid chlorine dioxide and ozone have been shown to be only marginally effective (Davidson et al. 2010; Gil et al. 2009; Sapers 2006). Most industrially used sanitizers are best suited for reducing microbial populations in the wash water rather than those on the product being washed. During continued processing, the level of soil and debris, referred to as the organic load, in this recirculating wash water will increase as additional product is processed. Since chlorine will react with any organic material, most chlorinated sanitizers exhibit decreased antimicrobial activity as the organic load in the water increases, with the potential survival of bacterial pathogens and other microorganisms in the wash water becoming a concern. Popular alternatives to chlorine include peroxyacetic acid, chlorine dioxide, and ozone (Table 7.2).

Table 7.2 Efficacy of common sanitizers used in washing of produce

Sanitizer	Positive attributes	Negative attributes
Chlorine- and chlorine-based compounds	Availability, ease of use, cost effective, wide range of use, effective against vegetative bacteria	Activity is pH dependent, only reduces microbial populations by 1-2 logs, significantl affected by the organic load, corrosive to metals, irritating to the workers
Chlorine dioxide	fewer chlorine by-products formed, residual antimicrobial effectiveness, less corrosive, effective against biofilm	Reduces only microbial populations only 1-2 logs, explosive at higher concentrations, must be made on-site, more expensive than chlorine based compounds, irritating to the workers
Ozone	Activity pH independent, only no hazardous by-products formed, more effective than chorine	Activity pH independent, only reduces microbial populations only 1-2 logs, must be made on-site, a well ventilated work environment is required, corrosive to metals, more expensive than chlorine based compounds or chlorine dioxide
Peroxyacetic acid	Activity pH independent, effective at higher organic loads, no hazardous by-products formed, effective against biofilm	Reduces microbial populations only 1-2 logs, high cost, strong oxidizer, concentrated solutions may be hazardous

When apples, tomatoes, and lettuce were sprayed with an aqueous solution containing 200 or 2,000 ppm chlorine, populations of *Salmonella, E. coli* O157:H7, *L. monocytogenes,* yeasts and molds, and mesophilic aerobic bacteria on the three products decreased only 0.35 and 2.30 log CFU/cm^2 (Beuchat et al. 1998). In an earlier study, exposure to an aqueous 100 ppm chlorine solution was also ineffective against *Salmonella* on tomatoes (Wei et al. 1995). However, using 200 ppm chlorine, Sapers et al. (1999) was able to achieve a 2 log reduction of *E. coli* on Golden Delicious apples intended for cider. After a 10-minute exposure to an aqueous solution of 200 ppm chlorine at 4°C and 22°C, *L. monocytogenes* populations decreased only 1.3 and 1.7 log CFU/g on lettuce and 0.9 and 1.2 log CFU/g on cabbage, respectively (Zhang and Farber 1996). In addition, exposing blueberries to ~10–200 ppm chlorine for less than 1 minute, which is common during commercial processing, reportedly decreased the microbial populations on the berries by less than 1 log (Popa 2005).

Chlorine dioxide (ClO_2) and peracetic acid are generally equally or more effective than chlorine due to their greater oxidation capacity and tolerance to higher organic loads in the wash water. When Zhang and Farber (1996) inoculated *L. monocytogenes* onto shredded lettuce, a 30-second exposure to 5 ppm ClO_2 decreased the levels of this pathogen by more than 1 log. Using 1% acetic acid with 90 ppm peracetic acid, *Listeria* populations decreased up to 1.4 logs on lettuce following 5 minutes of exposure, with the numbers of mesophilic and coliform bacteria decreasing 2 logs. Similarly, Wisniewsky et al. (2000) reported that 80 ppm chlorine and 80 ppm peracetic acid dioxide respectively decreased *E. coli* O157:H7 populations on apples by 4 and 3 logs after contact times of 10 and 5 minutes.

Ozone can also be added to flum and wash water to decrease the microbial load. When 3 and 5 ppm chlorine dioxide, chlorinated trisodium phosphate (100 and 200 ppm chlorine), and 80 ppm peroxyacetic acid were compared, 3 ppm ozone and chlorine dioxide were most effective at reducing the numbers of *E. coli* O157:H7 and *L. monocytogenes* on produce (~5.6 log reduction) with peroxyacetic acid being the least effective (~4.4 log reduction) (Rodgers et al. 2004). These reductions are among the greatest reported in terms of sanitizer effica y.

Further Processing

Despite extensive investigations, the root cause of most produce-related outbreaks is never found, with the fina outcome generally being a series of hypotheses that point to one or more potential sources of preharvest contamination such as irrigation water, manure, or improper worker hygiene practices in the field However, foodborne pathogens can also contaminate the product during processing. In one outbreak of salmonellosis traced to shredded lettuce, Stafford et al. (2002) recovered *Salmonella* Bovismorbifican phage type 32 from the cutting wheel of a mechanical shredder during an environmental audit, with insufficien cleaning and sanitizing of the shredder cited as a key factor in this outbreak. More recently, *E. coli* O157:H7 was shown to transfer from inoculated lettuce to a small-scale commercial processing line with greatest transfer seen to the shredder and conveyor, followed by the flum tank and shaker table (Buchholz et al. 2009a). These find ings again point to the shredder as an important source of contamination. In addition to product-to-equipment transfer, uncontaminated products can also pick up pathogens from contact with equipment surfaces, with such transfer recently confirme by Buchholz et al. (2009b). In their work, when 9 kg of *E. coli* O157:H7-inoculated radicchio was shredded and processed, followed by 900 kg of uninoculated iceberg lettuce, the entire batch of iceberg lettuce was contaminated, with shreds of inoculated radicchio present throughout the batch and also on the shredder, conveyor, and other equipment surfaces after processing. Hence, small amounts of contaminated lettuce or other products coming from the fiel could potentially contaminate an entire day's production.

Drying

After flumin and washing, excess water must be removed before packing through the use of shaker tables, blowers, or centrifugal dryers or by other means to maintain product quality and an acceptable shelf life. Based on recent work, approximately 30% of the microbial population, including any foodborne pathogens, present on leafy greens will likely be shed in the water during centrifugal drying, with this centrifugation water now being targeted for microbial testing to better ensure end-product safety (Buchholz 2009a).

All drying methods are product dependent with the end goal being the preservation of both product quality and shelf life. Whereas iceberg and romaine lettuce can withstand the forces associated with centrifugal drying, other products such as baby spinach, parsley, tomatoes, and blueberries would be severely damaged and must therefore be dried by other means. As one example, tomatoes are dried using sponge rollers and blow driers to avoid skin damage since any open wounds could allow microorganisms, including foodborne pathogens, to become internalized (Suslow 2004).

Preservation Methods

The application of heat, ranging from mild blanching treatments to pasteurization and severe heating as occurs during canning, has long been proven effective for the inactivation of native enzymes found in fresh produce as well as the many microorganisms including spore-forming bacteria that may be present. However, many types of fruits and vegetables lose their fresh-like characteristics after heating, with the usefulness of thermal processing for fruits and vegetables clearly being product dependent. Some of the most important nonthermal processing methods to maintain product quality include dehydration, freezing, and irradiation.

Blanching

Although originally intended to preserve the color and overall keeping quality of fresh produce through the inactivation of

native enzymes, steam and hot water blanching will also reduce the microbial load on the surface of fruits and vegetables. In one study, *Salmonella* populations on inoculated carrots decreased 3.2–3.3 log CFU/g immediately after steam or water blanching (DiPersio et al. 2005b) with this same pathogen also decreasing 4.5–4.8 CFU/g and 5.4 log CFU/g immediately after steam and water blanching of sliced White Russet potatoes, respectively (DiPersio et al. 2005a).

Pasteurization of Juices

Several widely publicized US outbreaks involving *E. coli* O157:H7, *Salmonella*, and *Cryptosporidium* have been linked to consumption of raw apple cider prepared from dropped apples (CDC 1997). In response to these outbreaks and others involving *Salmonella*-contaminated orange juice (Cook et al. 1998; Khan et al. 2007), the FDA now requires that all fresh juices sold at retail be pasteurized using either heat or ultraviolet light to ensure product safety. In addition, any containers of unpasteurized juice purchased by consumers directly from the manufacturer must carry a warning stating that the product has not been pasteurized and may therefore constitute a public health risk (Lima et al. 2009). Thermal pasteurization is most commonly used to eliminate pathogens from the product with 14 seconds of heating at 68.1°C ensuring at least a 5 log reduction of *E. coli* O157:H7, *Salmonella* spp., and *L. monocytogenes* in apple cider. Interestingly, *L. monocytogenes* survived this same treatment but died in the cider within 24 hours at 4°C, implying that a combination of treatments may be better suited to ensure safety (Uljas and Ingham 1999; Mak et al. 2001).

Thermal pasteurization is commonly used by most large commercial juice processors to achieve the required 5 log reduction in pathogens. However, the same end result can also be obtained using ultraviolet light, with this latter pasteurization process serving as a viable low-cost alternative for small seasonal producers (Donahue et al. 2004).

Canning

Canning preserves products in airtight containers for months or years through the application of heat. Low-acid foods having a pH of 4.6 or greater, including many canned vegetables, must undergo a high-temperature sterilization process to reduce the number of *Clostridium botulinum* spores by 12 logs in order to ensure safety of the fina product. Due to the presence of *C. botulinum* spores on many fruits and vegetables and the severity of foodborne botulism, strict government-enforced regulations are in place for canning. Commercially, the canning industry has maintained an almost perfect record with such foods very rarely responsible for outbreaks of botulism. The greater concern remains home-canned low-acid foods such as tomatoes which are still responsible for isolated cases of botulism (CDC 2007b).

Dehydration

One of the oldest means of food preservation, dehydration is based on the removal of water needed for microbial growth. Over time, most bacteria will decrease to nondetectable numbers in dried products. However, one report from New Zealand indicated that *Bacillus cereus* spores were able to survive in potato fla es and then germinate and grow in the rehydrated product, which in turn led to an outbreak of illness (Turner et al. 2006).

Nonthermal Processing

Many fresh fruits and vegetables such as leafy greens and berries cannot be thermally processed without losing their fresh characteristics, with commercial washing of these products in various sanitizer solutions remaining one of the few means to decrease the number of microbial contaminants. However,

as mentioned earlier, even multiple washing steps cannot fully ensure end-product safety. Among the nonthermal processing methods used in the produce industry, freezing is by far the most common, with high-pressure processing and irradiation also gaining increasing support in the United States as the result of several major outbreaks involving fresh-cut salad greens.

Freezing

Freezing, like canning, is widely used in the fruit and vegetable industry with various types of freezers including plate, belt, air-blast, tunnel, spiral, and individually quick frozen systems having been developed to preserve end-product quality. Quick freezing is most desirable due to the more rapid retardation of microbial growth and the formation of smaller ice crystals that have less of a deleterious affect on product quality compared with the much larger ice crystals that are formed during slow freezing. Unlike the other processing methods previously discussed, freezing is generally not considered to be a good microbial reduction strategy with microbial populations in most products decreasing only slightly during extended frozen storage, as evidenced by a large outbreak of hepatitis A among school-aged children that was traced to consumption of frozen strawberries (Hutin et al. 1999).

Irradiation

Food preservation by irradiation is based on the generation of ionizing radiation from gamma rays (requiring a radioactive source) or x-rays, or alternatively electrons produced by an electron beam machine (E-beam) that in turn generates free radicals that are highly destructive to microorganisms. In the produce industry, irradiation doses of <1 kGy have long been used to inhibit sprouting (e.g., potatoes), delay maturation, and control insect/parasite infestations (e.g., wheat, mangoes, strawberries). Mangoes and other tropical imported fruits have been irradiated for many years as an accepted quarantine method by the USDA to ensure the elimination of seed weevils and fruit flies Disinfestation of these products is essential in preventing such pests from entering the United States (Follett 2001). In terms of food safety and shelf-life extension, doses of 1–10 kGy are sufficien to inactivate both foodborne pathogens and spoilage organisms, whereas doses above 10 kGy can be used for sterilization (e.g., dry spices).

In response to the aforementioned *E. coli* O157:H7 outbreaks involving leafy greens, the FDA now allows the irradiation of baby spinach and iceberg lettuce at doses up to 4 kGy for the elimination of bacterial pathogens. Unlike sodium hypochlorite and other commercially available chemical sanitizers for produce, ionizing radiation also has the ability to inactivate any bacterial cells that may have become internalized in fruits and vegetables (Niemira 2007).

High-Pressure Processing

In high-pressure processing (HPP), also known as high hydrostatic pressure processing (HHP) or ultra high-pressure processing (UHP), foods are uniformly subjected to a pressure of about 85,000 pounds per square inch (6,000 atmospheres) in a sealed vessel with or without the addition of heat. In this process, vegetative bacteria and yeast cells are ruptured and thereby inactivated during rapid decompression. HPP retains both product quality and freshness and also extends the product's shelf life.

Regarding produce applications, HPP processing has been successfully used to decrease the microbial populations in orange (Parish 1998) and pineapple juice (Aleman et al. 1996), as well as Guacamole (Palou et al. 2000), salsa (Raghubeer et al. 2000), and fresh-cut pineapple (Aleman et al. 1994) with all of these HPP-treated products exhibiting

a longer shelf life. In one Australian study, *Salmonella* populations decreased at least 7 logs in orange juice that was treated at 600 MPa, 20°C for 60 seconds. Although the numbers of background microorganisms decreased to nondetectable levels after HPP, the remaining survivors eventually grew in the juice during storage. Nonetheless, the shelf life of the HPP-treated samples was signifi cantly longer compared with nontreated samples (Bull et al. 2004).

Packaging

Modified Atmosphere Packaging (MAP)

Modifie atmosphere packaging is designed to enhance the shelf life of fresh fruits and vegetables by decreasing the respiration rate of the product. In this packaging method, the amount of oxygen in the package is typically decreased from 20% to 5% or less to suppress the growth of aerobic spoilage organisms with a portion of the removed oxygen replaced by carbon dioxide, which can further inhibit the growth of bacteria, or by nitrogen, which is inert. Fresh produce will continue to respire in the package, changing the gas composition over time. However, if the O_2 and CO_2 permeability of the packaging fil matches the respiration of the product, an equilibrium modifie atmosphere will be established that will extend the shelf life of the product in combination with low storage temperatures (Hotchkiss 1988; Phillips 1996).

MAP is especially useful for a wide range of produce (e.g., fresh-cut salad greens, potatoes, asparagus, onions, broccoli, cucumbers, beans, peppers) since these products remain metabolically active long after harvest. Berrang et al. (1990) showed that microbial levels significantl decreased on broccoli during 21 days of controlled atmosphere storage at refrigeration temperatures. However, *L. monocytogenes* can grow in some MAP products such as shredded lettuce and cabbage with the extended shelf life from suppression of normal spoilage microflor increasing the public health risk associated with the consumption of these products (Philips 1996). These limitations of MAP suggest that other types of packaging may be required for some products.

Active Packaging

An emerging new concept**,** active packaging focuses on the development of packaging materials that interact with the product to improve its quality, safety, and shelf life. The active portion of the package is typically a packaging fil or wrapper that is impregnated or coated with the active components. Some of these packaging materials have been designed to release various antimicrobial agents (e.g., chlorine dioxide) and carbon dioxide or trap oxygen and ethylene at a controlled rate over time (Suppakul et al. 2003). Alternatively, specially made pouches or sachets can be placed inside the package to release these same active components. In one recent example, methyl cellulose packaging film containing chitosan and vanillin as antimicrobial agents were able to reduce the populations of *E. coli* and yeast on fresh-cut cantaloupe and pineapple (Sangsuwan et al. 2008).

Distribution Chain

Minimizing the temperature abuse of fresh fruits and vegetables that inevitably occurs during transport and distribution in refrigerated trucks is critically important to maximizing product shelf-life, with subsequent transfer of both spoilage organisms and potential pathogens from consumers' hands when selecting individual unpackaged items such as pepper, cucumbers, apples, and tomatoes impacting the shelf life and safety of the entire retail display. Beuchat and Brackett (1990) reported significan growth of *L. monocytogenes* in shredded lettuce after just 3 days of storage at 10°C with some growth of this psychrotrophic foodborne pathogen also observed in samples stored at

5°C. In another study, populations of *E. coli* O157:H7 increased on inoculated iceberg lettuce, sliced cucumbers, and shredded carrots during 14 days of storage at 12°C or higher. However, no growth was observed at 5°C (Abdul-Raouf et al. 1993). In the United States, some types of highly perishable products that are grown locally will arrive at their retail destination within a day or two of harvest, with other products such as leafy greens and tomatoes being transported over longer distances. Finally, imported products such as blueberries from Chile and mangoes from India may encounter considerable temperature abuse during transport by air, sea, and land. Consequently, proper temperature control is essential to inhibit the growth of both spoilage and pathogenic microorganisms at all points in the food chain, including shipping containers, warehouses, retail stores, and home refrigerators.

Working in Japan, Koseki and Isobe (2005) modeled the growth of *E. coli* O157:H7, *Salmonella* spp., and *L. monocytogenes* on iceberg lettuce at 5°C to 25°C and at fluctuat ing temperatures that the product encountered from fiel harvest to retail sale as measured using radio frequency identificatio (RFID) sensors. As expected, only *L. monocytogenes* grew at temperatures of less than 10°C. A similar project led by California Polytechnic State University is using RFID sensor technology to assess the impact of temperature abuse on both the shelf life and safety of leafy greens during transport and cold-chain distribution, with these RFID sensors able to alert retailers to specifi trucks delivering temperature-abused products.

Conclusion

Microbial contamination of fresh produce can occur at any point throughout the farm-to-fork continuum. In the field spoilage and pathogenic microorganisms that adversely impact product safety and shelf life can come from many sources including the soil, manure, irrigation water, and both domestic livestock and wild animals. In this regard, all growers should follow good agriculture practices. After harvest, microbiological quality of the product typically decreases as a result of microbial growth during periods of temperature abuse during shipment. During processing, the microbial load often increases as a result of direct contact with contaminated equipment surfaces (e.g., conveyor belts, slicers, dicers). Typical commercial sanitizers used in wash tanks will decrease the microbial populations on fresh fruits and vegetables no more than 2 logs, with some products becoming recontaminated during subsequent sorting, handling, drying, and packing. In addition to washing, other intervention steps including thermal and nonthermal processing, modifie atmosphere packaging, and the use of antimicrobial packaging materials also play an important role in minimizing the growth of bacterial pathogens and spoilage organisms during periods of temperature abuse that may be encountered during distribution.

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Part II

Postharvest Technology and Storage Systems

Chapter 8

Postharvest Handling Systems and Storage of Vegetables

P. S. Raju, O. P. Chauhan, and A. S. Bawa

Introduction

Production of vegetables is spread out in all regions of the world. Alongside fresh vegetables, which are the mainstay of the developing economies, there is also demand and need to diversify and develop postharvest storage, transport, marketing, and processing infrastructure to extend the use of vegetables beyond their growing seasons and regions. Many Western countries have developed vegetables suitable for cold climates, including potatoes and tomatoes. Among the tropical regions, China, India, Brazil, Pan American countries, and countries of Africa, South-East Asia, and Central Asia have climate and resources suitable for the growth of many types of vegetables. Recent efforts in these countries have emphasized improving the agronomic practices and development of high-yielding good-quality vegetables for domestic and export markets. This chapter discusses the postharvest handling systems and practices for commercial production and marketing of vegetables.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Vegetable Production and Priorities for Pre- and Postharvest Handling

World Vegetable Production

According to the FAO data, the total production of vegetables in the world in 2007 was estimated to be 908.8 million metric tons (MMT) (Figure 8.1). China alone produced about 50% (451.6 MMT) of these vegetables, followed by India (77.2 MMT), United States (38.8 MMT), Turkey (25.7 MMT), and the Russian Federation (16.6 MMT). The top ten vegetable-producing countries (Table 8.1) contributed about 75% of the vegetables produced in the world. Obviously, there is a lot of scope for increasing vegetable production in all parts of the world.

Pre- and Postharvest Handling Priorities

The commercial viability of vegetables depends on improved agricultural inputs and harvest and postharvest practices including, storage, transport, and processing infrastructure. Some of the pre- and postharvest priorities to boost the economy of scale and minimize harvest losses are as follows:

1. Develop/identify suitable varieties of vegetables for table use and processing.
2. Identify key vegetables and regions with market potentials.

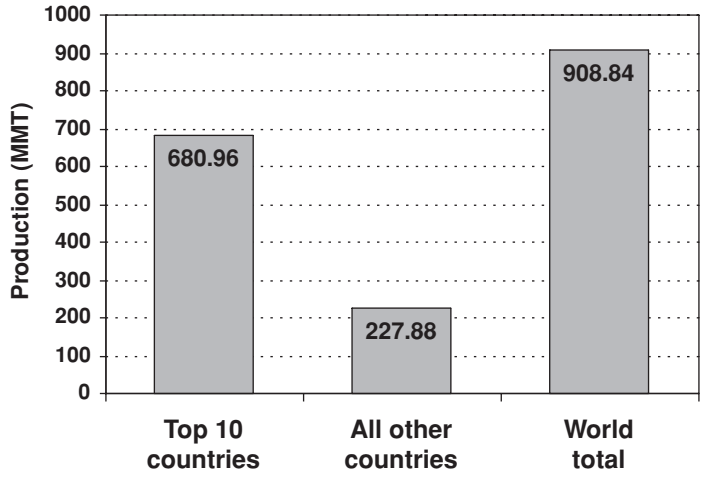

Figure 8.1 Vegetable production (including melons) in the top ten producing countries and world (2007).

3. Identify critical inputs (land, irrigation, labor, fertilizer, etc.).
4. Develop storage and transportation infrastructure including cold storage chains and refrigerated transports.
5. Develop packing houses in close proximity to production.
6. Develop competitive pricing models and markets.

Unlike the developed economies, availability and use of cold storage chains due to cost factor and electricity shortage can be a major barrier in controlling postharvest losses of vegetables in many parts of the world. However, countries such as China, India, Mexico, and Brazil have entered the global vegetable markets as a result of targeted investment in pre- and postharvest infrastructure systems. The improved cultivation practices have enabled these countries to grow vegetables such as broccoli, asparagus, Brussels sprouts, lettuce, and beans, which are grown predominantly in temperate regions. Tropical vegetables such as eggplant, okra, plantains, bitter gourd, gherkins, green papaya, and green mango are also gaining acceptance in the European and North American markets. However, exports of these products vis-à-vis production are about 2% for countries such as India. Adoption of phytosanitary practices to produce safe and good-quality vegetables and improvements in grading, packaging, and storage and transportation infrastructure can create new markets for many exotic tropical vegetables.

Table 8.1 Vegetable* production in leading countries (2007)

Country	Production (million metric tons)
China	451.63
India	77.24
USA	38.85
Turkey	25.71
Russian Federation	16.58
Egypt	16.04
Iran	15.99
Italy	13.50
Spain	12.72
Japan	12.70

Source: FAOSTAT (http://faostat.fao.org), Accessed on June 22, 2010.
*Including melons.

Postharvest Systems and Practices

The important physiological considerations to improve postharvest quality and extend shelf life of vegetables are respiration rate of vegetables; storage temperature and

Table 8.2 Classification of vegetables based on respiration rates

Class	Respiration rate at 5°C (ml CO_2/kg hr)	Vegetables
Very high	>30	Broccoli, mushroom, asparagus, sweet corn
High	20–30	Brussels sprouts, spinach, artichoke, green onions
Moderate	10–20	Okra, caulifl wer, eggplant, lima bean, snap bean, lettuce
Low	5–10	Radish, carrot, celery, cabbage, tomato, cucumber, etc.
Very low	<5	Onion, garlic, potato, turnip, watermelon, parsnip

optimal O_2/CO_2 concentrations of modified controlled atmosphere (MA/CA) storage; and ethylene, biotic, and abiotic stress. Vegetables are generally classifie with regard to their respiration rates, as given in Table 8.2.

According to Vont Hoff rule, for every 10°C rise in temperature, the respiration rates increase manifold, known as Q_{10} values. The Q_{10} values can be calculated by measuring respiration rates at different temperatures:

$$Q_{10} = \frac{(R_2)^{10/(T_2-T_1)}}{(R_1)}$$

where R_2 is the rate of respiration at T_2, R_1 is the rate of respiration at T_1, and T_2 and T_1 are temperatures in °C.

A study of the respiration rate of a vegetable at various temperatures is useful in the proper design of storage and packaging requirements. The recommended storage temperatures for selected vegetables are given in Table 8.3.

Vegetables are generally considered low producers of ethylene; however, many vegetables are highly sensitive to ethylene.

Table 8.3 Recommended storage temperature for selected vegetables

Temperature (°C)	Vegetables
0–2	Asparagus, cantaloup, water chestnuts, etc.
2–7	Green beans, lima beans, peas, summer squashes
7–13	Cucumber, eggplant, musk melons, okra, pumpkin, winter squash, ripe tomatoes
13	Watermelon, ginger, sweet potatoes, green tomatoes

Morgan and Drew (1997) and Fluhr and Mattoo (1996) have provided a comprehensive account of ethylene-induced stress on vegetative tissue, which includes degreening, wilting, and sprouting.

The postharvest handling practices of vegetables differ. For example, onions and potatoes require conditioning or curing prior to cold storage. Curing is a healing process for the bulbs and tubers to overcome minor bruises due to suberization of the skin/peel at controlled temperatures. Onions are usually fiel cured by covering the bulbs with the plants by layering the plants in a sequential manner prior to separation of bulbs and storage in semipermanent structures for ultimate bulk storage in chilled conditions. Onions are also subjected to heated air conditioning to minimize skin staining (Wright and Grant 1997). Storage of onions and potatoes in fiel structures equipped with cross-ventilation at 28–34°C in 70–75% relative humidity (RH) was found to be useful (Brice et al. 1995). In the case of potatoes, the optimal curing temperature was reported to be 15–18°C at 90% RH (Kim and Lee 1994). However, in case of most other vegetables, it is necessary to eliminate fiel heat through appropriate precooling in order to improve the beneficia effects of subsequent cold storage.

Harvesting

Salunke and Desai (1984) described the harvest indices of various vegetables (Table 8.4), which depend on several factors such as maturity, size, and end use. Knowing when to harvest and knowledge of optimal harvesting

Table 8.4 Harvesting indices for major vegetables

Vegetable	Harvesting indices
Eggplant	Eggplants must be picked as soon as they have attained the desired size, before they harden or show streaks of unusual color. The skin should be bright and glossy. The overmatured fruits are dull, seedy, and fibrous
Okra	Okra should be bright green, firm free from blemishes, and will not exceed 3 inches, and pods up to 5 inches are satisfactory but can be more fibrou than desirable.
Radish	Quick-growing spring cultivar requires 3–4 weeks while some of the Chinese cultivars require 8–14 weeks for optimal growth to ensure mild, tender rating quality.
Cucumber	Cucumbers are largely picked on the basis of size rather than age and the end use needs to be kept in picture for picking up appropriate size. For slicing, the appropriate size could be 6–10 inches length; for pickling, 2 1/2–6 inches.
Lettuce	The harvesting of lettuce should be completed before the leaves become tough and bitter and also before seeds start to protrude. The head of lettuce for market is grown to full size to develop a solid head.
Onion	The harvest maturity of onion depends on the purpose for which they are grown. Harvesting takes about 45–90 days from the fiel setting for green onions and 90–150 days for bulb onions depending on cultivar. The bulbs are considered mature when the neck tissues begin to soften and tops are decolorized.
Sweet corn	Sweet corn is harvested at the milk stage as soon as the kernels are well fille and plum and before the dough stage develops.

Source: Salunke and Desai 1984.

indices of vegetables are important for postharvest quality.

In order to manage fiel heat (especially in the tropical countries), harvesting of vegetables should preferably be carried out in the morning hours. Additionally, it is important to minimize bruising and damages during harvest. Field moisture can be regulated by monitoring irrigation schedules, so that the soil is not wet or muddy, which can cause build up of soil on the produce, making cleaning in the packing house more cumbersome. The harvested vegetables should be transported to the packing houses in ventilated crates. McGee (1995) reported the current state in potato storage. Several types of bulk containers for potatoes were also developed for marketable potatoes and seed potatoes which can be used for transportation of the produce from the fiel to the packing house and also for the cold storage of potatoes (Isman et al. 1998).

Vegetable Grading

Vegetable grading has become end-use specifi over the years. Kader (1992) gave a comprehensive description of grading measures. Abbott et al. (1997) described nondestructive measures of quality regulation. Besides size grading, specifi gravity, texture, soluble solids, pod to seed ratio in terms of mass or pod length to seed weight ratio, use of near infrared (NIR) spectroscopy, and color charts can be useful objective grading tools.

Sanitation and Phytosanitation

Sanitation and phytosanitation measures (SPS) are important in global trade of vegetables to ensure that these products are free of certain pests and diseases and meet maximum allowable limits for pesticides. Chlorinated water at 100 ppm is an accepted norm for cleaning fruits and vegetables (Pirovani et al. 2001). Hydrogen peroxide is also used for phytosanitation of fruits and vegetables (Sapers et al. 1999). Ozone in gaseous form bubbled through water at 0.1–1.0 ppm for 360 minutes, or at concentrations of up to 200 ppm for 10–15 minutes was found to signifi cantly reduce the microbial loads (Akbas and Ozdemir 2006). Ozone in combination with

lower levels of chlorine was found to be effective in the phytosanitation of carrots (Chauhan et al. 2007).

The various physical devices for cleaning of vegetables are mechanical rotatory brush, pressure spray, etc. The surface moisture after wet cleaning is removed by tunnel drying or basket centrifugation.

Precooling

Precooling and cold storage form an integral component in the postharvest handling of vegetables. The cold storage facility includes bulk storage and mobile units involving shipments by land, sea, and air routes. Certain terms describing the cooling rates are: (1) half cooling rate, the time required to reduce the difference between the mean temperature of the product and the temperature of the cooling medium by one-half, and is expressed as a constant for a particular set of precooling conditions; and (2) seven by eight cooling time is usually three times the half cooling rate, and is often used as a commercial standard for the total time for precooling.

The speed of cooling can affect the storage life of perishable commodities with high respiration rates. The different types of precooling techniques are described below.

Hydro-cooling

Hydro-cooling is based on moistening of produce/packages in showers of chilled water; the advantage lies in precooling the commodity with minimal moisture losses (Sargent et al. 1991). Immersion hydrocoolers are continuous fl w systems that are more useful for products that have higher density than water and therefore remain submerged. Low-density products such as cucumbers and tomatoes are cooled by floata tion in circulating water. Continuous systems use the immersion technique with variable water velocities, and the mobility of water is ensured by water-circulating pumps. Shower coolers involve spraying the produce with cold water, and can be of batch or continuous type. Water used for hydro-cooling is generally kept between 0°C and 0.5°C. Produce that is sensitive to chilling injury may be cooled in water at 0°C for a brief period.

Hydro-cooling is suitable for bulk and packaged produce, and is used commonly for melons, root and stem vegetables. Commodities that are hydro-cooled must be tolerant to contact with water and to the levels of chlorine in the sanitized water. Commodities such as grapes and most berries must be ventilated after hydro-cooling to remove surface water, which can otherwise cause decay (Thompson 1995). Hydro-cooling has often been described as a comparatively more efficien precooling method instead of room cooling or top icing for commodities such as broccoli (Gillies and Toivonen 1995; Timothy et al. 2003).

Vacuum Cooling

Vacuum cooling is a rapid cooling method for produce such as lettuce, sweet corn, and green beans that can be cooled within 20–30 minutes. Vegetables such as lettuce have overwrapping leaves, creating insulated air packets that reduce the efficien y of other cooling methods. The only drawback of vacuum cooling can be the limited capacities restricted to 4–10 pallets per batch. Kim et al. (1995) described the vacuum cooling of lettuce with several variations:

(a) Lettuce packaged in boxes and transported in a covered vehicle.
(b) Prepared lettuces wrapped and packaged in boxes and transported in cold storage vehicles (5°C).
(c) Prepared lettuces that were wrapped, packaged in boxes, vacuum cooled, and transported in cold storage vehicles (5°C).
(d) Prepared lettuces that were wrapped, packaged in boxes, vacuum cooled, and transported in insulated vehicles.

The studies on Q_{10} values and ascorbic acid losses showed (c) and (d) variations mentioned above to be highly effective in extending the shelf life. Vacuum cooling was also found to have positive effects on the enzymatic browning in mushrooms (Bae et al. 1995). In conventional vacuum cooling, the produce is placed in an airtight chamber and the pressure in the chamber is decreased to the point that water boils. As an example, a pressure of 0.61 kPa (4.6 mmHg) permits water to boil at 0°C; as a result, water evaporates, causing rapid cooling of the produce. Since moisture loss can have deleterious effects on produce quality, water can be sprayed as a fin mist prior to vacuum cooling. If the product is wrapped with a plastic film the fil must be perforated to obtain effective cooling (Cheyney et al. 1979).

Forced Air Cooling

Forced air cooling is the most commonly used precooling method for a number of fresh commodities, and has been found to be four to fi e times faster than room cooling with a uniform distribution of temperature in the pallet (Boyette 1996). It is also cost-effective compared to hydro-cooling and vacuum cooling. In forced air cooling, chilled air is forced by a static pressure gradient across the two sides of the product containers. The pressure gradient is in the range of 3–25 mm with a typical value of 12 mm (Fraser 1991). Forced air cooling is used for lettuce, spinach, and mushrooms.

Ambient Cooling

Room cooling is not comparable to many precooling techniques due to the low cooling rates, and typically it is not recommended for produce with high respiration rate or harvested during the warmer months. The cooling is done by conduction, through the container walls rather than by convection. Airfl w of at least 1–2 m/s is needed to remove fiel heat effectively. Effective air distribution can be achieved with several small evaporators evenly placed, rather than with a single large evaporator. Appropriate contact of the pallet bins with the cold air is ensured to maximize the rate of cooling. Room cooling is often used for several low- and moderate-respiring vegetables such as eggplant, okra, cabbage, and gourds.

Contact Icing

Contact icing is one of the oldest methods of cooling, which involves cooling of packaged containers or pallets with ice. The contact between ice and produce causes cooling. Contact icing is essentially a cooling method to assist cooling and to maintain high relative humidity. Top icing is a frequently used method to maintain produce quality during shipment for long-distance transportation. Liquid icing facilitates faster cooling than individual packaged top icing. However, liquid icing using ice slurry is a costlier method compared to conventional contact icing.

Cold Storage

Chilling and freezing injuries are often found during refrigerated storage of vegetables. Tropical produce is highly susceptible to chilling injury, and its threshold temperature for induction of chilling injury is higher compared with temperate commodities (Wang 1990). The tropical produce needs an optimal storage temperature of 10–15°C, below which they are susceptible to chilling injury; however, these threshold temperatures are above their freezing points (Lyons 1973). Temperate crops usually have threshold chilling injury temperature of <5°C (Bramlage and Meir 1990). During chilling injury, several irreversible metabolic changes occur, resulting in symptoms such as surface lesions, internal discoloration, water soaking of the tissue, and failure to ripen normally in the case of fruits (Saltveit and Morris 1990). These symptoms become more evident after a short time of

Table 8.5 General symptoms of chilling injury in some vegetables

Vegetables	Chilling injury symptoms
Asparagus	Dull, gray-green, limp tips
Lima beans	Rusty brown specks, spots or areas
Snap beans	Pitting and russeting
Cucumbers	Pitting, water-soaked spots, decay
Eggplants	Surface scald, alternaria rot, blackening of seeds
Ginger	Softening, tissue breakdown, decay
Okra	Discoloration, water-soaked areas, pitting, decay
Potatoes	Mahogany browning, sweetening
Pumpkins	Decay, especially alternaria rot
Tomatoes (ripe)	Watersoaking and softening, decay
Tomatoes (mature green)	Poor color when ripe, alternaria rot

storage at warmer temperatures. Vegetables that have undergone chilling injury may be particularly susceptible to decay. General symptoms of chilling injury in vegetables are summarized in Table 8.5.

Many pathogens such as *Alternaria* sp that usually grow readily on healthy tissues can attack tissues which have been weakened by low-temperature exposure (McColloch 1962). Storage temperatures below the threshold values and the duration of exposure to such temperatures determine the extent of chilling injury. Maturity at harvest also determines the chilling sensitivity in produce such as tomatoes (McColloch et al. 1966) and "Honey Dew" muskmelons (Lipton 1978). Many remedial measures have been advocated to minimize chilling injury, which include intermittent warming, high or low temperature preconditioning, CA storage, and pretreatments with ethylene, abscisic acid, methyl jasmonate, and other natural compounds. In addition to these, hypobaric storage, infusion of calcium, waxing, shrink packaging, and genetic manipulation by biotechnological methods can be some solutions to minimize chilling injury (Ryall and Lipton 1979; Wang 1993; Meir et al. 1996). Oftentimes, it is desirable to reduce the storage temperatures to enhance the shelf life significantl . Reduction in storage temperature by 1–2°C below the threshold value can result in substantial enhancement in shelf life of many of the tropical fruits and vegetables.

Freezing injury is another manifestation of suboptimal low-temperature storage and it occurs due to formation of ice crystals in the tissues. These temperatures are well below the threshold temperature for chilling injury. The most common symptoms of freezing injury are water-soaked appearance, loss of turgidity, and mushy appearance upon thawing (Parsons and Day 1971). Fruits and vegetables can be categorized into most susceptible (e.g., asparagus, cucumbers, eggplant, lettuce, okra, sweet peppers, potatoes, tomatoes, and sweet potatoes), moderately susceptible (e.g., broccoli, carrots, caulifl wer, celery, onion, parsley, peas, radish, and spinach), and least susceptible (e.g., beets, Brussels sprouts, cabbage, kohlrabi, parsnips, and turnips). The susceptibility to freezing injury may not be similar for the same type of vegetable. Leafy lettuce is highly susceptible to freezing injury whereas kale and cabbage can withstand light freezing without serious injury. Most fruits and vegetables can usually be cooled several degrees below their freezing point before they actually freeze. This type of cooling without freezing is known as super cooling. Commodities under these conditions start to freeze after a certain duration of storage and the same commodities can revert to original status upon storage at warmer temperatures (Hruschka et al. 1961). Frozen vegetables are highly susceptible to bruising and therefore need not be disturbed physically until warmer storage climate has been established. Freeze-injured vegetables are more susceptible to microbial infections and often fall short in textural requirements.

If composite storage of vegetables is unavoidable, categorization of vegetables into

three distinct groups of most susceptible, moderately susceptible, and least susceptible may be helpful in minimizing the incidence of chilling or freeze injuries.

Refrigeration

Some of the major vegetables requiring specifi cold storage conditions are listed in Table 8.6 (Ryall and Pentzer 1974; Boyette and Estes 1992).

The design of cold storages over the years has undergone qualitative changes in terms of energy efficien y and also temperature regulation and humidity control. Humidity-controlled cold storages with considerable storage capacities are being used throughout the world. Precooling techniques reduce moisture condensation, as the produce is equilibrated prior to placement in the cold storage. Surface coating of the produce and use of specifi packaging, besides use of surface additives to reduce chilling injury, are often resorted to for specifi commodities (Fallik et al. 1994). Efforts are also made to ensure ethylene-free atmosphere in the cold storages through physical or chemical scrubbing of ethylene. The physical means of ethylene scrubbing involve usage of zeolite-based ethylene traps and mechanical suction of air. The chemical methods include use of permanganate-based ethylene scrubber fabricated in the form of filte blankets as per the rated capacities of the cold room (Jayaraman and Raju 1992).

Table 8.6 Storage conditions for selected vegetables

Vegetables	Storage conditions
Caulifl wer	0°C, 95–98% RH
Eggplant	8–12°C, 90–95% RH
Lettuce	0°C, 95% RH
Mushrooms	0°C optimal (0–5°C)
Okra	7–12°C, 90–95% RH
Potatoes	3–10°C, 90% RH
Pumpkins	10–13°C, 70% RH
Radish	0°C, 90–95% RH
Spinach	0°C, 95–100% RH
Tomato	12–20°C, optimal 12°C
Turnip	0°C, 95% RH

Sources: Ryall and Pentzer 1974; Boyette and Estes 1992.

Certain essentials of cold storage such as calculation of refrigeration loads depending on the produce temperature, weight of the produce, the ambient temperature, and storage performance of the produce need to be considered to optimize the use of cold storage (Leteinturier 2001). The cold chains form an essential part of postharvest handling systems of fresh produce and their wholesale and retail marketing.

Zero-Energy Cooling

Storage of perishables under cooled conditions without use of conventional energy had led to several innovations in the form of evaporative cooling devices and solar-powered cooling devices besides other modes of refrigeration, such as the use of manual modes of refrigeration using suitable coolants which may not require electricity or hydrocarbon sources for the cooling purpose. Evaporative coolers are designed in various modes. The most primitive amongst them can be jacketed earthen pots, double brick-walled storage chambers, and light-weight jacketed containers made of reinforced plastics. These devices make use of the principle of evaporative cooling (Roy and Khurdiya 1982; Kumar et al. 1999).

The design of evaporative coolers takes into account several factors such as a moistening medium, the humidity buildup within the chamber, cross-ventilation, the efficien y of heat transfer, and the cost effectiveness of the device. These structures are of semipermanent nature and for use by small farmers to facilitate storage at fiel level prior to transportation to the packing houses. A temperature drop of 6–9°C had often been beneficia in extending the shelf life of perishable produce, inclusive of leafy vegetables and mushrooms. The evaporative cooling

devices were improved further by incorporation of computer-controlled evaporating devices and incorporation of solar-powered air circulation systems (Christenbury et al. 1995). Tuber crops such as potato were often subjected to solar-powered cooling at fiel level to maintain the keeping quality prior to bulk storage (Bishop and Stenning 1997). Energy audit and planning need to be emphasized in postharvest handling of fresh produce, and careful substitution of cooling devices based on nonconventional energy sources, which are otherwise known as zero-energy devices, can be a solution in the progressive direction.

Macro Climatic Modulatory Storage

Storage of fresh produce in whole and precut forms under controlled gaseous environment refers to macro as well as micro climatic changes. The macro climatic changes are inclusive of changes in O_2 and CO_2 concentrations in the storage environment, which ultimately results in similar changes in the micro climate prevailing in the near climate of the commodity, i.e., within the packages or within the vegetative tissue. Terms such as MA or CA essentially describe the changes in the gaseous composition within the storage climate. These techniques aim at multipronged beneficia effects with emphasis on retardation in metabolic rate, resulting in delayed senescence and also antimicrobial effects under specifi combinations of O_2 and CO_2.

Modified Atmosphere Storage

Modifie atmosphere (MA) storage of perishables is usually carried out following the passive or active modes. The passive generation of MA involves produce-generated atmosphere in which the produce modifie the atmosphere by its respiration wherein the O_2 concentration comes down and the CO_2 concentration goes up. The packaging and the interactions of the packaging material with the head space atmosphere also affect O_2 and CO_2 concentrations within the packages (Gariepy et al. 1986). Development of MA protocols for different vegetables and fruits involves studies with respect to the following:

(i) Produce respiration at the storage temperature.
(ii) Gas and water vapor permeability of the packaging material with emphasis on O_2, CO_2, and C_2H_4 permeability at specifi temperatures.
(iii) Fill weight, fil volume, and size of the package.
(iv) Produce susceptibility to specifi microbial attacks and under altered gaseous composition.
(v) Role of remedial measures such as use of ethylene, O_2, and CO_2 traps within the packages to enhance the effica y of MA.
(vi) Storage, transportation, and marketing plans with specifi targets of shelf life.
(vii) Measures to regulate the spoilage subsequent to storage under low O_2 and high CO_2 atmospheres.
(viii) Risk analysis with regard, to packaging failures and temperature abuses during bulk and retail storage.
(ix) Development of secondary packaging to facilitate appropriate ventilation for the primary packages.
(x) Cost estimates and supervision of various phases of postharvest handling using MA techniques.

Optimal O_2 and CO_2 concentrations have been established for several vegetables but the cultivar differences should be considered to use these concentrations (Table 8.7).

MA is instrumental in reducing the metabolic rate mediated by reduced respiration and ethylene release (Kader et al. 1989). MA in interaction with precooling and fungicides was found to enhance fungistatic

Table 8.7 Optimal O_2 and CO_2 concentrations for modified atmosphere storage of selected vegetables

Vegetables	O_2 (%)	CO_2 (%)
Scrap bean	3	4–7
Broccoli	1–3	5–10
Celery	2–4	3–5
Mushrooms	Normal	10–25
Okra	Normal	4–10
Radish	1–2	2–3
Tomato	3–5	0–3

nature of commodities (Ceponis and Cappelini 1979). MA storage was also known to reduce surface discoloration arising out of biotic and abiotic factors (Brecht et al. 1973).

Some of the commonly used film for MA are low-density polyethylene, low-density polypropylene, and oriented polypropylene with specifi gas permeability coefficient toward O_2 and CO_2.

MA in passive mode could be generated following a number of methods in the form of diffusion tubes, bulk containers, and selectively permeable packaging pouches. Bulk storage systems for passive generation of MA usually include diffusion areas using silicone membranes such as the Marceline system. The design of these containers includes features such as forced ventilation around the diffusion areas to maximize gaseous exchange between the interior of the container with the ambient atmosphere. These containers have refrigerated cooling facility and diffusion rates are controlled by various parameters inclusive of storage temperature, diffusion area, produce load, and produce respiration. Silicone window-based passive diffusion could be applied in other forms of packages such as polyethylene terephthalate (PET) jars.

Chauhan et al. (2006a) reported optimized MA protocols for the storage of whole bananas in PET jars with silicone membrane windows as the diffusion surface. Silicone membranes are made up of nylon fabrics with rubber coatings. These membranes have high diffusion rates for O_2, CO_2 as well as ethylene. However, the diffusion area in interaction with other MA variables needs to be optimized for different vegetables. Specialized films such as microporous film and antifog films are in use for effective generation of MA. The advantages of these film include absence of moisture condensation within the packages, resulting in antifog upkeep of the produce for better visibility and restriction of microbial spoilage within the packages. Watkins and Thompson (1992) described microperforated polyethylene bags to be effective in enhancing the keeping quality of "Cox's Orange Pippin" apples. Based on the physiological data, various copolymers have been developed, including vinyldine chloride copolymers for effective MA generation (Cassiday et al. 1990). Various other studies reported passive generation of MA during vegetable storage (Moleyar and Narasimham 1994; Tendaj and Tendaj 1997).

The active modes of MA generation involve flushin of the container/packages with known combinations of O_2, CO_2, and N_2. The advantage in the active mode is a quicker setting of equilibrated gas concentrations unlike the passive mode. Chauhan et al. (2006b) reported beneficia effects of active MA in fl xible pouches during the storage of papaya slices. Partial vacuum packaging could also be an effective active mode of MA generation, which is more cost-effective than the conventional active mode involving flushin of gas mixture in the packages.

The advent of microperforated and antifog film makes practice of MA less risky in terms of onset of anaerobiosis and microbial spoilage.

Controlled Atmosphere Storage

CA storage is an extension of MA storage, the major difference being continuous monitoring and adjustment of gaseous composition. In the CA storage, the same gaseous composition is continuously maintained with precision throughout the storage period by microprocessor-based gas composition

monitoring and adjustment systems. As a result, the cost of maintenance of CA chambers as a bulk storage system is higher than the MA storage. The advantage of CA storage lies in shelf life of 4–8 months, enabling use of the commodities beyond seasons and long-distance transportation of the produce by sea. An example is the export of Asian mangoes to Europe and beyond, which requires a minimum shelf life of 45–60 days during shipping. CA storage in reefer containers is an effective mode to obtain such a long shelf life. Therefore, the design and development of reefer containers with CA facility have gained increased popularity. Traditionally, CA storage is employed in the United States and Canada for bulk storage of apples and strawberries. A number of vegetables such as cabbage (24–26 weeks), savoy cabbage (1–2 weeks), kohlravi (2 weeks), caulifl wer (2–3 weeks), Brussels sprouts (2–3 weeks), Chinese cabbage (8–12 weeks), lettuce (1–2 weeks), asparagus (2 weeks), leeks (11–12 weeks), mushroom (1 week), and sweet peppers (3–4 weeks) were reported to be well suited for CA storage. Jones et al. (1991) described the engineering aspects in development of CA containers. Several patents have been obtained for the maintenance of optimal atmosphere and air purificatio systems (Torres et al. 1990).

Packaging of Vegetables

In the less developed countries, fresh vegetables are transported in vented plastic crates, gunny cloth sacks, and mulberry/bamboo baskets. The softer vegetables are given cushioning with dry grass or newsprints as a lining in nonrecyclable packaging materials. The types of containers used in vegetable packaging include fiel containers and shipping containers. The consumer packages include bags, i.e., plastic fil bags and mesh bags. Shrink fil wraps with or without consumer trays are a major advancement in the area and appropriate packaging film are available with antifog features for better display of the produce. The materials used for packaging should have the mechanical and barrier properties to protect the produce from mechanical damages and also to restrict microbial spoilage during bulk storage and transportation.

Apart from paper, a number of plastics are also used for packaging of vegetables. These materials include cellulose, polyethylene, polyester, polyamides, polypropylene, polystyrene, polyvinylchloride, polyvinylidene chloride, ethylene vinyl acetate, ethylene vinyl alcohol, ionomer films etc. (Brown 1992). A number of vegetables such as cabbage, Brussels sprouts, lettuce, beans, peppers, sweet corn, artichokes, broccoli, celery, carrots, mushrooms, and mixed salad green were reported to attain shelf life of 1–8 weeks due to the MA generated within the unit packages by application of selectively permeable packaging (Prince 1989).

Standards and Grades

Different standards are available for fresh vegetables and fruits, such as the European community norms for quality grading and quality inspection (Sierra 1994). In the United States, the Agricultural Marketing Service of the United States Department of Agriculture (AMS-USDA 2010) has grade specifi cations describing standards of identity for quality and conditions of vegetables meant for sale. Typically, the US grades of vegetables are: US Fancy; US No. 1; US No. 2. The grades reflec quality such as texture, form, size, color and appearance, absence of defects, discoloration, sunburn, woodiness, dry rot, disease, and insects. The level of pesticides is a major concern, as several vegetables often show conspicuous levels of organochlorine, as well as organophosphorus insecticides and fungicides. The common organochlorine insecticides include heptochlore and dicofol. The organophosphorus insecticides include chlorpyriphos, pyridaphention, and diazinonand. The minimum

residual levels (MRL) of pesticides used are monitored as required by the international trade (Ito et al. 1999).

The chemical specification of minimally processed vegetables address the maximum permissible limits for additives such as sulphur dioxide (E220; MRL 50 mg/kg or litre; in onion, garlic shallot pulp 300 mg/kg), benzoates (E210 Benzoic acid, E211 sodium benzoate, E212 potassium benzoate, E213 Calcium benzoate; MRL 200 mg/kg), ascorbic acid (E300; MRL *quantum satis*), citric acid (E330; MRL *quantum satis*), and calcium chloride (E509; MRL 0.05%).

Conclusion

This chapter discussed the principles and practices of postharvest systems for vegetables, including grading, phytosanitation, precooling, cold storage, and MA storage needs. The organic vegetable production sector can also benefi from the technologies discussed here.

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Chapter 9

Postharvest Physiology of Vegetables

Peter M. A. Toivonen

Introduction

Vegetables are cited as being an important part of a healthy diet (Ekman and Patterson 2005). Managing retention of the quality and healthful constituents in vegetables requires a significan depth of knowledge of the postharvest physiology of these products in order to control the target processes that are responsible for constituent and quality change (Bartz and Brecht 2003). Quality is of underlying importance since poor-quality product will not be acceptable for consumption, no matter what the nutritional value of the product. The discussion in this chapter will focus on the physiological processes that determine changes in both perceptible quality and nutrient and functional constituents. The impact of the knowledge on postharvest handling considerations will be touched upon to bridge the gap between theory and practice that is also discussed in other chapters of this volume.

There are at least two recently published entire volumes devoted to in-depth discussion of the physiology of vegetables and which provide a very detailed description of the postharvest physiology of vegetables (Bartz and Brecht 2003; Lamikanra et al. 2005). In this chapter the intent is to provide an overview and perspective of the subject, which should give a solid basis by which to understand the relevant issues surrounding quality change.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Classification of Vegetables

The classificatio of what are termed vegetables encompasses a great diversity of physiological stages in plant development. As a consequence, the postharvest physiology and postharvest handling practices vary widely. To add complication to the issue, some fruits are considered to be fruit-vegetables and may have significantl differing physiology than most other vegetables due to their respiratory behavior (e.g., climacteric ripening in tomato). Therefore, it is important to defin the types of vegetables according to their anatomical derivation, developmental stage, and their respiratory behavior. Table 9.1 outlines the differing types of vegetables and their respiratory characteristics. Several issues become clear from this table: (1) very few vegetables have low basal rates of respiration at commercial maturity; (2) most vegetable types have members which represent basal respiration rates for many of the class ranges from low to extremely high; and (3) most mature fruit-vegetables have a relatively low basal respiration at commercial maturity and are climacteric in ripening pattern. The term climacteric will be define later in the discussion pertaining to respiration. These issues represent the challenge which is faced when one wishes to discuss postharvest physiology of vegetables, and that is the wide range in respiratory physiology even within a single vegetable type. This reality explains the wide range of commercial handling

Table 9.1 Classification of vegetable types by anatomical description and respiratory rate class at commercial maturity

Vegetable type	Respiratory rate class	Range of respiration rates at 10°C (50°F)(mg CO_2 kg^{-1} h^{-1})	Common name listing of examples
Root	Low	<15	Turnip
	Moderate	15–30	Carrot (topped), celeriac, beet, parsnip, rutabaga, radish (bunched)
	High	30–50	Carrot (bunched), chicory root, radish (topped)
Bulb	Low	<15	Onion
	Moderate	15–30	Garlic
Tuber	Moderate	15–30	Celeriac, potato (cured)
	High	30–50	Potato (immature)
Stem	Moderate	15–30	Kohlrabi, fennel
	Extremely high	>70	Asparagus
Leafy	Low	<15	Chicory
	Moderate	15–30	Celery, Chinese cabbage, head lettuce, bok choy, cabbage, rhubarb, Swiss chard, radicchio
	High	30–50	Leaf lettuce
	Very high	50–70	Savoy cabbage, leek
	Extremely high	>70	Brussels sprout, parsley, spinach, endive, watercress
Floral	High	30–50	Caulifl wer
	Very high	50–70	Artichoke
	Extremely high	>70	Broccoli
Immature fruit	Low	<15	Pepper, tomatillo
	Moderate	15–30	Cucumber, eggplant
	Very high	50–70	Summer squash
	Extremely high	>70	Pea, sweet corn, mushrooms, snap bean, okra
Mature fruit	Low	<15	Muskmelon*, tomato*, honeydew*, watermelon
	Extremely high	>70	Winter squashes

Source: Compiled from Gross et al. (2004).
* Fruits that have climacteric respiratory behavior when harvested at their commercial maturity.

recommendations that exist for vegetables even within a type category.

Beyond basal metabolism (respiration), there are other unique physiological characteristics of specifi vegetables which result in differing considerations in postharvest handling. These characteristics include climacteric ripening behavior, chilling sensitivity, and ethylene sensitivity. All these considerations will be discussed in addition to basal metabolism.

A recent consideration in fresh vegetable physiology is the physiology of minimal processing, which is largely associated with cutting-induced injuries (Toivonen and DeEll 2002). A discussion focusing on recent advances in knowledge with respect to minimally processed vegetables and vegetable mixes will also be included in this chapter.

Respiration and Storage Potentials

Respiration rates vary significantl with the types of vegetables (Table 9.1). The relationship between respiratory rate and shelf life is that respiration rate and potential storage

life are inversely correlated (Saltveit 2004). Therefore, vegetables with low respiration rate, such as potato and onion, have intrinsically long storage potential while rapidly respiring broccoli and spinach have a very short storage potential.

Approaches to enhance storage life of many vegetables have revolved around the principle of trying to control respiration rate by various means such as low storage temperatures and/or modifie storage atmospheres (Watkins and Ekman 2005). As an example of this principle, Figure 9.1 shows the effects of temperature on respiration rates of broccoli and onion which are vegetables having extremely high and low relative rates of respiration, respectively.

Broccoli has a storage life measured in weeks whereas onion's storage life is measured in months (Morris and Brady 2005). In terms of response to lowering of temperature, it firs appears that temperature has a greater effect on broccoli respiration than onion respiration. However, calculation of percent change in respiration associated with lowering of temperature shows that lowering temperature has a similar relative effect on respiration in both commodities (Figure 9.1). This example serves as a good demonstration of the fact that respiration has a very similar nature in all vegetables. There is some variance to this relationship since it has been shown the some vegetables have quite different respiratory quotients (Saltveit 2004).

Despite the general relationship between respiration rate and storage potential, good cooling to minimize respiration can only optimize the inherent storage potential of a particular vegetable. For example, proper cooling of broccoli and onion to 0°C will reduce their respiration rates by similar relative amounts; however, that does not result in similar storage potentials for both the commodities. When cooled and held at 0°C, broccoli's shelf life potential is two to three weeks, whereas onion can last up to 8 months when stored at that temperature (Morris and Brady 2005).

An important feature of the absolute respiration rate of a vegetable has direct implication on cooling requirements since the process of respiration generates heat, often termed "heat of respiration" or "vital heat." Vital heat of a vegetable can be directly calculated from respiration values (Kader and

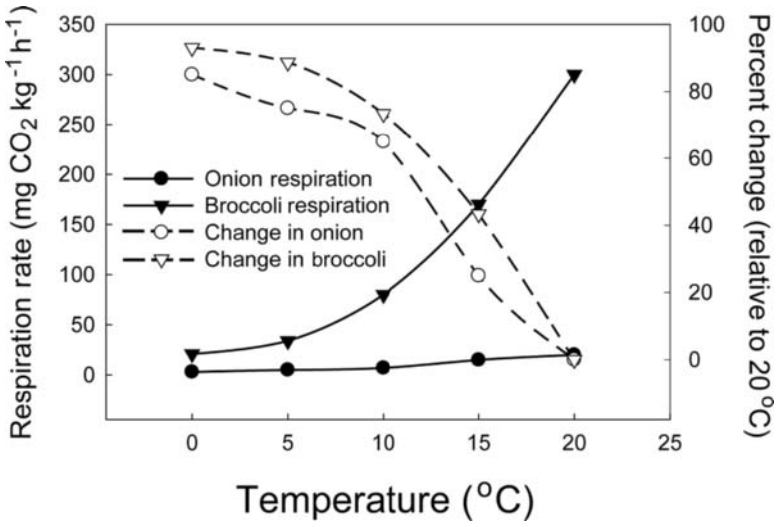

Figure 9.1 Absolute and relative (relative to rate at 20°C) changes in respiration of broccoli and yellow bulb onions when held at different temperatures ranging from 0 to 20°C. (Data extracted from Gross et al. (2003).)

Saltveit 2003a), and hence respiration and vital heat follow identical patterns of change with temperature. The vital heat produced by a vegetable will partially determine the cooling capacity requirement for that vegetable. Vegetables showing very high respiratory rates in Table 9.1 will require high capacity precooling approaches such as hydrocooling or top-icing (e.g., broccoli) whereas low respiring vegetables such as onions can be effectively room-cooled in the storage cold room (Morris and Brady 2005). Therefore, understanding of the respiratory characteristics of a vegetable is important to developing the appropriate postharvest cooling strategy. Accordingly, much effort has been placed on the development of cooling strategies of vegetables to optimize quality retention (Morris and Brady 2005).

Another direct implication of respiratory rate of a vegetable will be in determining the appropriate semipermeable packaging fil for packaging that vegetable (Toivonen et al. 2009). Packaging whole or minimally processed vegetables requires the design and matching of the packaging fil permeability with the rate of respiration of the vegetable product to achieve the beneficia target atmosphere that will optimize the storage quality retention of the vegetable (Toivonen et al. 2009). In general, a vegetable or vegetable product having a high respiratory rate will require a fil with high permeability to oxygen as compared with a vegetable product that has a low respiratory rate. Since temperature influence respiratory rate, the stipulation of temperature is also required in the specifica tion of package design and use.

Respiratory Climacteric

Most fruit-vegetables harvested at ripe maturity have climacteric respiratory behavior (Table 9.1). The understanding of their climacteric respiratory behavior is important for managing the quality of fruit-vegetables. Figure 9.2 shows the normal respiratory behavior of a vegetable as it matures and reaches senescence—the respiration of such vegetables tends to decline until cell death ensues. In contrast, climacteric fruit-vegetables will initiate a significan rise in respiration

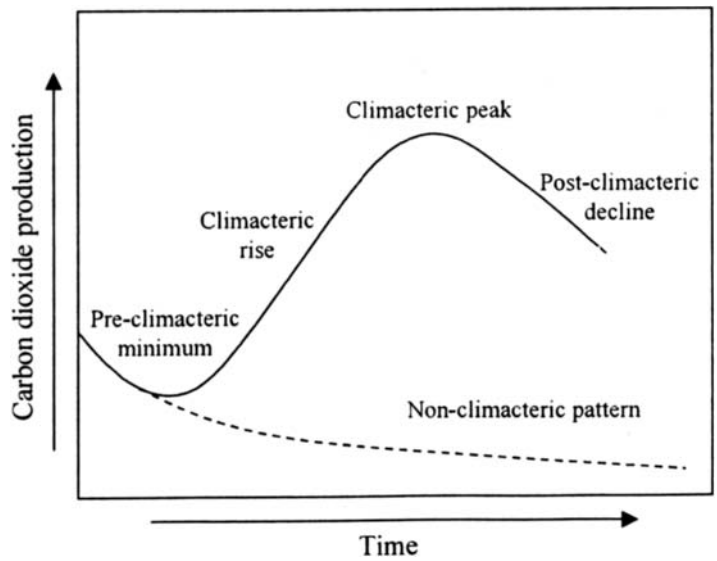

Figure 9.2 Climacteric patterns and non-climacteric patterns of respiration as vegetables mature, ripen, and senesce. (From Saltveit (2004)).

rate as they reach full maturity and begin to ripen (Figure 9.2). Subsequent to ripening and reaching a maximal respiratory rate, the respiration declines until cell death ensues. Much of this climacteric respiratory behavior is linked with ethylene physiology, which is discussed in the following section. The implications are that if the fruit is harvested while it is beginning to ripen, there will be significan vital heat generated that needs to be taken into account with regard to cooling. Generally, fruit-vegetables are harvested at preclimacteric or very early climacteric stages and have relatively low cooling requirements. Also, refrigerated storage and modifie atmosphere technologies are used to manage the rate of ripening and consequently the respiration rates of these fruit vegetables. A full discussion of modifie atmosphere effects on respiration has been published previously (Kader and Saltveit 2003b).

Ethylene Production and Response Physiology

The plant hormone ethylene has been probably the most extensively studied plant hormone (Abeles et al. 1992; Martínez-Romero et al. 2007) since it has significan effects on quality retention in fruits and vegetables (Saltveit 1999; Martínez-Romero et al. 2007). Ethylene production and response physiology plays a key role in determining the onset of ripening in mature fruit-vegetables and senescence in most other vegetables. As with respiration, there is a wide range of ethylene production rates among different vegetables and there are also differences in relative sensitivity to ethylene amongst vegetables. Table 9.2 provides a characterization of ethylene production and sensitivity of a wide range of vegetables.

For most green-colored vegetables the response to ethylene is onset of senescence which is characterized by the yellowing of green tissues (Saltveit 1999; Martínez-Romero et al. 2007). Other effects on quality of vegetables are also associated with ethylene. In carrots and parsnips, exogenous ethylene exposure leads to the accumulation of bitter isocoumarin and furanocoumarin compounds, respectively (Shattuck et al. 1988; Lafuente et al. 1996), and so exposure to exogenous ethylene produced by ethylene-producing products or forklifts must be avoided to ensure edibility of these two vegetables (Saltveit 1999). In climacteric fruit-vegetables, exposure to ethylene will lead to accelerated ripening and shorter storage and shelf life (Saltveit 1999; Martínez-Romero et al. 2007). As a consequence, exposure to very low exogenous levels of ethylene can significantl reduce the potential market life of most vegetables (Wills et al. 1999) with the exception of those vegetables which have low sensitivity to ethylene (Table 9.2).

Sensitivity of ethylene has been generally associated with a minimum response threshold of 0.01 $\mu L\ L^{-1}$; there is some evidence suggesting that levels less than 0.005 $\mu L\ L^{-1}$ can shorten the potential storage life of some vegetables by as much as 60% (Wills et al. 1999). As such there are many instances where ethylene can become a problem for quality retention, e.g., where ethylene-generating vegetables and fruits are co-stored with ethylene-sensitive vegetables. This scenario describes much of the reality of modern vegetable transport and distribution chains (Saltveit 1999; Wills et al. 1999; Martínez-Romero et al. 2007).

There have been many approaches developed to reduce ethylene accumulations in co-storage situations, such as transport trailers and distribution/retail storage rooms using ethylene-absorbing materials (Martínez-Romero et al. 2007). Other approaches are to either store sensitive products separately (which is generally impractical) or to chemically block ethylene action (Martínez-Romero et al. 2007). Ethylene action can be reversibly blocked with high carbon dioxide atmospheres (Kader and Saltveit 2003b). However, not all vegetables have

Table 9.2 Classification of vegetable types by anatomical description, ethylene production rate, and relative sensitivity to ethylene at commercial maturity

Vegetable type	Ethylene production rate class*	Relative sensitivity to ethylene†	Common name listing of examples
Root	Very low	Low	Turnip, beet, radish (topped and bunched), rutabaga
	Very low	High	Carrot (topped and bunched), parsnip
Bulb	Very low	Low	Onion, garlic
Tuber	Very low	Low	Celeriac
	Very low	Medium	Potato (early crop), potato (late crop)
Stem	Very low	Low	Kohlrabi
	Very low	Medium	Asparagus
Leafy	Very low	Low	Rhubarb
	Very low	Medium	Chicory, celery, leek, endive
	Very low	Medium to high	Chinese cabbage
	Very low	High	Leaf lettuce, cabbage, head lettuce, savoy cabbage, bok choy, Swiss chard, Brussels sprout, watercress, spinach, parsley
Floral	Very low	Low	Artichoke
	Very low	High	Broccoli, caulifl wer
Immature fruit	Very low	Very low	Sweet corn
	Very low	Medium	Tomatillo, pea, mushrooms
	Low	Low	Pepper
	Low	Medium	Eggplant, chili pepper, summer squash, snap bean, okra
	Low	High	Cucumber
Mature fruit	Very low	High	Tomato (mature green), watermelon
	Low	Medium	Winter squashes
	High	Low	Tomato (fir ripe)
	High	Medium	Muskmelon, honeydew

Source: Compiled from Gross et al. (2004).
*Ethylene production rate classes are define as (at 20°C): Very low = <0.1 μL kg^{-1} h^{-1}; Low = 0.1–1.0 μL kg^{-1} h^{-1}; and High = 10–100 μL kg^{-1} h^{-1}.
†Ethylene sensitivity ranking is primarily anecdotal information.

the same tolerance to carbon dioxide (Kader and Saltveit 2003b). A recently commercialized ethylene action blocking molecule is 1-methylcyclopropene (1-MCP) which has found wide application potential in many edible horticultural products (Watkins 2008). The application of 1-MCP appears to irreversibly block ethylene receptor sites when applied as a gas at very low concentrations.

The ethylene inhibitor 1-MCP has been found to be an effective control for ripening of climacteric fruits and fruit-vegetables such as tomato (Mostof et al. 2003). Theoretically there should be no benefi from the application of 1-MCP to non-climacteric vegetables, and some research suggests that is the case (Able et al. 2003; Bron et al. 2005; Porter et al. 2005). However, the application of 1-MCP to non-climacteric vegetables has proven to be very efficaciou in extending shelf life and slowing senescence in cases where there is an exogenous source of ethylene (Ku and Wills 1999; Fan and Mattheis 2000a, 2000b; Able et al. 2002, 2003; Ella et al. 2003; Koukounaras et al. 2006). Hence, it is important to not only look at the ethylene biology of the produce in question, but also to examine the ethylene biology of all other products with which it may be co-stored. In the case of fresh-cut vegetable salads, there is a need to develop technologies to allow co-packaging ethylene-incompatible vegetables, such as

ethylene-producing cherry tomatoes with an ethylene-sensitive leafy salad mix. A technology involving a co-release of 1-MCP along with antimicrobial volatiles has shown potential to enhance quality retention and shelf life of such salad mixes containing ethylene-incompatible products (Toivonen and Lu 2007; Toivonen 2008). Continued development of 1-MCP-based technologies to block ethylene action in sensitive vegetables could lead to better quality retention in storage of both whole products and mixed vegetable minimally processed salads.

Role of Other Phytohormones in Vegetable Physiology

Phytohormones are a fundamental component of plant growth and development. Because vegetables are derived from differing plant anatomical parts and at different developmental stages, there is a wide range of phytohormone physiologies that need to be considered (Ludford 2003). Vegetables derived from leaf, stem, and flora parts are subject to hormone physiologies relating to advance of senescence. Mature fruit such as tomatoes have physiology associated with ripening followed by senescence. In contrast, tubers, bulbs, and fles y roots have hormone physiologies predominantly associated with induction of dormancy since these are fles y storage organs which under undisturbed conditions would extend the survival of the plant through winter. As a consequence, hormone changes associated with quality decline in vegetables are dependent on the anatomical and developmental criteria used for commercial utilization of the vegetable under consideration.

Past work with regard to phytohormones and vegetables has been devoted to monitoring the changes in endogenous hormone contents under postharvest handling conditions (Ludford 2003). The most complete results are those dealing with the storage of winter cabbage, which is classifie as a leafy vegetable but also has characteristics similar to bulb-type vegetables since it is a tightly packed and bulky biennial plant organ. Isenberg et al. (1974) demonstrated asynchronous variations in different classes of phytohormones in cabbage held in long-term storage. In addition they showed that only giberrellic acids and auxin contents were differentially affected by normal air storage versus controlled atmosphere storage (5 kPa CO_2, 2–3 kPa O_2). The end of optimal quality in stored cabbage was also linked to the decline in what Isenberg et al. (1974) labeled as "inhibitors," now known to be abscissic acid (Ludford 2003). The relative content of abscissic acid and auxins was later correlated to the end of useful storage life in cabbage, i.e., the time at which the apical bud in the middle of the head begins to grow. The ratio of these two hormones was affected by controlled atmospheres, and a consequent storage life increase has been demonstrated (Ludford 2003).

Brussels sprout is a leafy vegetable that is susceptible to yellowing and senescence, and this has been associated with declines in cytokinin levels and increases in gibberellic acid levels (Thomas 1977). Cytokinin declines are often correlated with development of yellowing and senescence in green tissues (Ludford 2003).

Bulb vegetables such as onion show a differing pattern of changes for all the major classes of phytohormones (Isenberg et al. 1974). Cytokinin levels initially decline in the firs three months of air storage and then rise in subsequent months of storage. Both auxins and gibberellins continuously rise over time in storage whereas abscissic acid levels continuously decline with time in storage. Thomas (1981) concluded that the rise in cytokinin levels after three months in storage was associated with initiation of propensity to sprouting.

In mature fruit vegetables, the most studied phytohormone is ethylene, which has been discussed in a previous section of this chapter.

However, other phytohormone changes have been studied in relation to tomato maturation (Abdel-Rahman et al. 1975). In general cytokinin, auxin, and gibberellins were highest in the early stages of tomato fruit growth and development, and declined in levels as the fruit reached ripening maturity. In contrast, abscissic acid gradually increased as the fruit developed and reached maximal levels as the fruit began to ripen.

Very little recent research has been conducted to better understand endogenous phytohormone contents and balance in relation to postharvest quality and storage life management. However, there have been significant activities devoted to application of exogenous phytohormones to control quality and storage life. There have been numerous commercial uses developed for application of phytohormones to improve postharvest quality and storage life of fruits. Despite much research showing the benefit of exogenous hormone applications to vegetables (Ludford 2003), relatively little work has been reported for commercial application to vegetables (Klein and Goldschmidt 2005).

Effect of Controlled or Modified Atmospheres on Vegetable Physiology

The general impact of controlled or modified atmospheres on extending storage life is dependent on the characteristics of the vegetable under consideration. Tables 9.1 and 9.2 demonstrate the large variations in respiratory and ethylene response characteristics for the different types of groupings of vegetables. Since controlled or modified atmospheres generally control respiratory rates and ethylene response (Kader and Saltveit 2003b; Brecht 2009), it is expected that application of this technology will have the greatest impact on those vegetables with the highest respiration rates and greatest sensitivity to ethylene. However, this is not consistently the case and there may be many reasons for the lack of consistency. A comparison of broccoli and bulb onion provides an example where the general expectation is true. The respiration rate and ethylene sensitivity data (Tables 9.1 and 9.2) would suggest that broccoli should benefit from controlled atmospheres since it has a high respiratory rate and very high sensitivity to ethylene, whereas the opposite is the case for onion. And it does logically follow that controlled atmospheres are considered to be beneficial for storing broccoli but not for onion (Kader and Saltveit 2003b; Brecht 2009). In contrast, mushroom is a vegetable with a high respiration rate and moderate sensitivity to ethylene but controlled atmospheres are not recommended for extending storage since high carbon dioxide levels can cause discoloration and low oxygen atmospheres can encourage *Clostridium botulinum* growth on the mushrooms (Adamicki 2004). *C. botulinum* is the causal agent of botulism food poisoning and therefore any postharvest practice which increases the risk of growth for this bacterium must be avoided and cannot be recommended. Hence, respiration response and ethylene sensitivity are not the only considerations determining the level of potential benefit from controlled or modified atmosphere application in vegetables.

There is limited information regarding the impact of controlled or modified atmospheres on nutrient retention in many vegetables. Micronutrients, including minerals, carotenoids, vitamins B1, B2, and B6, and vitamin C were best maintained in green beans stored in an atmosphere of 3 kPa O_2 + 3 kPa CO_2 as compared with air and 5 kPa O_2 + 3 kPa CO_2 at 8°C (Sánchez-Mata et al. 2003b). The same workers found that macronutrients were also better maintained by that same atmosphere (Sánchez-Mata et al. 2003a). Amanatidou et al. (2000) found that all the high CO_2 modified atmospheres they tested resulted in a significant inhibition of phenolic accumulation but also showed a significant increase in sucrose accumulation in fresh-cut carrots when compared with an air control. Similar

inhibition of phenolic accumulation in fresh-cut and whole lettuce has been attributed to the direct inhibition of phenylalanine ammonia lyase (PAL) activity by high CO_2 atmospheres (Mateos et al. 1993). PAL is the firs enzyme in the phenylpropanoid pathway that is responsible for the synthesis of phenolic compounds (Saltveit 2003b). Clearly this is an area of research which has not received much attention and future work on the effects of storage atmospheres on nutritional and functional value of vegetables should be encouraged.

The use of controlled and modifie atmospheres is limited by the physiological tolerance of each commodity to both low O_2 and high CO_2 levels (Kader and Saltveit 2003b; Brecht 2009). In regards to O_2, the range of tolerance for different vegetables is relatively narrow (somewhere around 2 kPa), whereas the tolerance by different vegetables to high CO_2 has quite a wide range (Kader and Morris 1977). One major risk of using low O_2 is the development of off-fl vors due to induction of anaerobic metabolism when levels are too low. One example is green beans where it has been shown that sensory quality and nutrition value were best retained using 3 kPa O_2 + 3 kPa CO_2 or 1 kPa O_2 + 3 kPa CO_2 atmospheres at 8°C. However, green beans stored in the latter atmosphere developed off-fl vors (Sánchez-Mata et al. 2003a, 2003b). Controlled atmospheres with 1 kPa oxygen have also been shown to lead to accumulations of acetaldehyde and ethanol in fresh-cut carrots (Kato-Noguchi and Watada 1997; Amanatidou et al. 2000). High CO_2 has been shown to stimulate ethanol, acetaldehyde, and ethyl acetate accumulations in lettuce and broccoli (Mateos et al. 1993; Toivonen and DeEll 2000). However, high CO_2 can also lead to the development of many other physiological disorders as well, including brown stain in lettuce, pitting in asparagus, increased susceptibility to freezing injury in cabbage, internal browning in Chinese cabbage, increased chilling injury in peppers, and blackheart in potatoes (Lougheed 1987). In addition high O_2 and CO_2 can interact to produce additive or synergistic levels of defects in vegetables and this response can be influence by storage temperature and ethylene levels in the atmosphere (Lougheed 1987).

Fresh-cut vegetables may or may not respond to controlled or modifie atmospheres to a similar degree as the whole vegetable. One characteristic that can change when a vegetable is fresh-cut is the tolerance to low O_2 and high CO_2 (Kader and Saltveit 2003b; Brecht 2009). Mateos et al. (1993) found that whole iceberg lettuce was more sensitive in terms of production of ethanol and acetaldehyde in response to CO_2 than fresh-cut lettuce made from iceberg lettuce. In contrast, fresh-cut iceberg showed greater inhibition of phenolics accumulation in response to high CO_2 than whole lettuce (Mateos et al. 1993). Differences in levels of response to either low O_2 or high CO_2 may be largely associated with the physical changes effected by the fresh-cutting process. In general, the fresh-cutting process increases the ease of diffusion of both gases in the tissue because barriers to diffusion are breached (i.e., skin or periderm is cut or removed) and the tissue bulk is lessened (Kader and Saltveit 2003b).

Chilling Sensitivity and Membrane Integrity

The overall strategy to reduce respiration, metabolism, and ripening is predominated by the general principles of product precooling and low temperature storage (Nunes and Emond 2003; Morris and Brady 2005). While this is a very effective strategy to prolong storage and shelf life of most vegetables, there is a group of vegetables which is chilling sensitive and which will develop market-limiting defects when stored at low temperature (Table 9.3). There have been two general approaches to dealing with susceptibility to chilling injury: (1) developing treatments to ameliorate the susceptibility, and (2) using nonchilling

Table 9.3 Classification of vegetable types by anatomical description, chilling sensitivity class, and recommended storage temperature range at commercial maturity

Vegetable type	Relative sensitivity to chilling*	Recommended storage temperature range (°C)	Common name listing of examples
Root	Low	0	Turnip, radish (topped and bunched), rutabaga, carrot (topped and bunched), parsnip
	Low	1 to 2	Beet
Bulb	Low	−2 to 0	Onion, garlic
Tuber	Low	0 to 2	Celeriac
	High	7 to 10	Potato (table)
	High	10 to 15	Potato (frying)
	High	15 to 20	Potato (chipping)
Stem	Low	0	Kohlrabi
	Moderate	0 to 2	Asparagus
Leafy	Low	0	Leaf and head lettuce, cabbage, rhubarb, chicory, celery, leek, endive, savoy cabbage, bok choy, Swiss chard, Brussels sprout, watercress, spinach, parsley
	Moderate	0	Chinese cabbage
Floral	Low	0	Artichoke, broccoli, caulifl wer
Immature fruit	Low	0	Sweet corn, pea, mushrooms
	High	5 to 10	Tomatillo, summer squash
	High	5 to 7.5	Snap bean
	High	7 to 13	Pepper, chili pepper, okra
	High	10 to 12	Eggplant, cucumber
Mature fruit	High	2 to 7	Muskmelon
	High	7 to 10	Honeydew melon
	High	10 to 15	Tomato (fir ripe), watermelon
	High	10 to 13	Winter squashes
	High	12 to 20	Tomato (mature green)

Source: Compiled from Gross et al. (2004).
*Relative chilling sensitivity is define as: Low = not chilling sensitive and generally stored at as low a temperature as feasible without risking freeze injury; Moderate = chilling sensitive at lower temperatures (< 2 °C) and may show chilling injury when stored for prolonged periods at recommended temperatures; and High = chilling sensitive at warmer temperatures and stored at temperatures above those causing chilling injury.

temperatures and accepting a shorter storage life. The mechanism for chilling-induced injuries is largely associated with membrane effects, and so the discussion of membrane integrity is intertwined with the discussion on chilling injury.

The initial events surrounding the onset of chilling injury symptoms are largely correlated with changes in the functioning of membranes in affected tissues (Saltveit 2003a). One of the initial events is labeled as "phase transition" from liquid-crystalline to solid gel. With this "phase transition" comes a host of physiological changes due to the impairment of normal membrane functions, including enzyme reactions, loss of protoplasmic streaming, imbalance in metabolic processes, increased membrane permeability, and accumulation of toxic metabolites (Saltveit 2003a). Prolonged exposure to chilling temperatures will result in cell injury and death, which becomes visible as surface lesions, internal discoloration, water-soaking, and failure to ripen in a normal pattern (Saltveit and Morris 1990). Often, decay organisms will invade, resulting in secondary infections at sites of chill-induced injuries. Secondary infections are a common expression of chill injury in chilling-sensitive vegetables such as squash and tomatoes (McColloch and Worthington

1952; McColloch 1962). In addition, in tomatoes it has been suggested that loss of fl vor is the most sensitive change seen in response to chilling (Maul et al. 2000). The extent of injury caused by chilling temperatures increases with time of exposure to the chilling temperature. However, often the onset of visible symptoms occurs after the exposure to chilling temperatures, only when there has been significan water loss by the produce and this usually happens when the product is placed into warmer retail shelf conditions (Wang 1993). Symptoms such as pitting require water loss to occur before the damaged tissues collapse and become the visible symptom associated with chilling injury (Lyons 1973). In addition, fruit-vegetables such tomatoes and melons become less sensitive to chilling injury as they mature and ripen (McColloch et al. 1966; Lipton 1978).

Treatments to ameliorate chilling injury symptoms have been extensively studied and reported in the literature; however, no completely satisfactory treatments have been developed (Wang 1993; Saltveit 2003a). The basis of most of these treatments is to enhance membrane stability and membrane resistance to oxidative injury (Wang 1993; Wismer 2003). The chilling response mechanism is complex and involves a wide range of metabolic upheavals in the affected tissue, and it is therefore difficul to understand how a small set of specifi molecular or biochemical changes that occur in response to amelioration treatments can lead to a consequent increase in chilling tolerance (Saltveit 2003a). Clearly, more research is justifie to resolve this ongoing problem for vegetable handling in chilling-sensitive vegetables.

Effect of Water Loss

Water loss is one of the most visible changes in vegetables, often being the factor that limits marketing life (Ben-Yehoshua and Rodov 2003; Shamaila 2005). Notional estimates of threshold water loss that renders a particular vegetable unacceptable have been listed in older publications and some of these values are presented in Table 9.4. The table illustrates several general principles about the morphology of a vegetable and the threshold for water loss before the quality is visually unacceptable. First, bulky organs such as tubers, bulbs, head-forming leafy vegetables, and topped root vegetables have a relatively high threshold of water loss, whereas loose leafy vegetables and bunched root vegetables (i.e., vegetables having leafy tops attached) have relatively lower threshold values for

Table 9.4 Classification of vegetable types by anatomical description, and maximum permissible water loss threshold for saleability of selected vegetables at commercial maturity

Vegetable type	Maximum percent water loss	Common name listing of examples
Root	4	Carrot (bunched), beet (bunched)
	7–8	Carrot (topped), beet (topped), parsnip
Bulb	10	Onion
Tuber	7	Potato (cured and immature)
Stem	8	Asparagus
Leafy	3–5	Lettuce, spinach, rhubarb
	7–10	Celery, cabbage, leek, watercress, Brussels sprout
Floral	4	Broccoli
	7	Caulifl wer
Immature fruit	5	Peas, cucumber, snap beans
	7	Peppers, sweet corn
Mature fruit	7	Tomato

Source: Data extracted from Robinson et al. (1975).

unacceptable water loss. A large part of this difference is that loose leafy structures are more prone to show wilting than bulky organs (Ben-Yehoshua and Rodov 2003).

Wilting is the most easily detected effect of water loss and it can be controlled with proper and rapid precooling and storage humidifica tion. In chilling-sensitive vegetables, control of water loss is more difficul since they can be stored at warmer temperatures and as such are subject to much greater potential for water loss.

Water potential is easily calculated using an equation derived from Fick's firs law of diffusion:

$$J_v = -p_v \times A_v \times (P_i - P_{atm}) \qquad (9.1)$$

where J_v is the flu of the water loss for the vegetable, p_v is the permeability characteristics of the vegetable, A_v is the surface area of the vegetable, P_i is the internal water potential of the vegetable, and P_{atm} is the atmospheric water potential. The term $p_v \times A_v$ has been empirically derived for many vegetables and is labeled as a transpiration or water loss coefficien (Ben-Yehoshua and Rodov 2003). The driving force of water loss is the water vapor pressure defici (Ben-Yehoshua and Rodov 2003) and that is represented by the term $P_i - P_{atm}$ in the equation. It is possible to estimate the transpiration coefficien empirically for any vegetable and this allows easy modeling of water loss in any postharvest situation where the water vapor pressure defici can be defined The estimation of water loss is further improved by definin the two components which determine the water potential. The water potentials of the vegetable and the atmosphere surrounding it are determined by their temperatures as well as the relative humidity for intercellular spaces of the vegetable and for the atmosphere (Ben-Yehoshua and Rodov 2003). Water potential at a particular temperature ($P_{w\text{-}t}$) is generally calculated as

$$P_{w\text{-}t} = RH_t \times P_{sat\text{-}t} \qquad (9.2)$$

where RH_t is the measured relative humidity at that temperature expressed as a ratio, and P_{sat-t} is the saturated vapor pressure at that temperature.

To complicate the issue, the vegetable core temperature is partially determined by the vital heat of the vegetable and so the most accurate models of water loss will measure vital heat and include that component in estimating the water potential of the vegetable (Kang and Lee 1998). Generally a vegetable will be sensibly slightly warmer than the surrounding ambient air temperature and the values for RH_t and P_{sat-t} need to be adjusted to account for this vital heat for that vegetable at that ambient air condition. As a result, the temperature base for calculating P_i will be different than the temperature base for P_{atm} in Equation 9.1.

In general, three important points must be emphasized with regard to temperature management and water loss (Ben-Yehoshua and Rodov 2003): (1) warm product loses water at a faster rate when placed in a cold room, and so it is important to rapidly pre-cool a vegetable before placing it in a storage room; (2) delays in precooling will result in unnecessary water loss for a vegetable, and so delays from harvest to precooling should be kept as short as possible; and (3) cooler storage temperatures and higher storage humidities will generally minimize water loss of a vegetable.

Much of the water loss research has focused on its effect on visible quality loss; however, nutritional value is also very much affected (Ben-Yehoshua and Rodov 2003; Shamaila 2005). Unfortunately, there has been limited research evaluating the impact of water loss specificall on the nutritive value of vegetables. Barth et al. (1990) found that misting of broccoli in a simulated retail display case resulted in significan retention of ascorbic acid. Ezell and Wilcox (1959, 1962) found that water loss was associated with significan losses of both vitamin C content and carotene in a wide range of vegetables (kale, collards, turnip greens, spinach, cabbage, and

snap beans). Water loss is clearly an important factor in retention of nutritional quality in vegetables and must be mitigated to whatever extent possible in storage, handling, and distribution systems.

Wounding Responses

Conversion of vegetables to fresh-cut products results in significan wounding and the consequences of this is wide ranging in relation to tissue physiology (Toivonen and DeEll 2002; Saltveit 2003b). The initial response is the initiation of the wounding signaling pathway, a process that is not completely understood (Saltveit 2003b). Four primary responses occur over time: (1) increases in respiration, (2) increases in ethylene production, (3) increases in phenolic production, and (4) initiation of wound-healing metabolism. These processes then result in quality changes such as loss of nutritional value and fl vor, softening through ethylene-induced ripening, browning and toughening due to lignificatio metabolism (Saltveit 1997). In some cases this wounding response can be modulated by removing products associated with the early phase of wound response. For example, in fresh-cut sweet bell pepper, wounding leads to accumulation of acetaldehyde, which is a biologically active compound, and repeated washing can reduce levels on the cut surface, leading to improved quality retention (Toivonen and Stan 2004). Wounding response can also be minimized by the use of the sharpest cutting blades as shown with fresh-cut carrots (Barry-Ryan and O'Beirne 1998). In minimally processed Swiss chard, it was shown that as piece size decreases that proportional area of damage increases and rate of quality loss increases (Roura et al. 2000). In cos lettuce, wounding results in significantl increased soluble protein content in leaf tissue (Masih et al. 2002). Heat treatments can also modulate wound response (Saltveit 2003b).

It is important to identify the nature of the wound responses leading to quality loss and develop strategies to minimize them, but in fresh-cut products there must also be a balanced view on safety as well as quality. In one example, the wounding process in lettuce is known to produce anti-listerial factors which inhibit the growth of *Listeria monocytogenes* on cut lettuce surfaces (Wen et al. 2003; Delaquis et al. 2006). Warm water treatments have been shown to be very effective in controlling cut-edge browning of fresh-cut lettuce (Loaiza-Velarde et al. 1997). Further microbial analysis of this process has determined that the reduction in browning leads to increased risk for the growth of human pathogens on the cut lettuce (Delaquis et al. 2002). This example provides a good argument for ensuring that other disciplines along with postharvest physiology are applied to developing approaches to new processing strategies for fresh-cut vegetables.

Influence of Breeding and Genetics

Physiology of many processes leading to quality change in vegetables can be modulated through cultivar selection (Toivonen and DeEll 2002; Bartz and Brecht 2003). The proper selection of a cultivar will often diminish or resolve postharvest handling problems in a particular vegetable in its whole form or as a fresh-cut product.

Responses to controlled or modifie atmospheres can vary depending on the cultivar. Hayes and Liu (2008) tested lettuce selections against O_2 concentrations ranging from above the anaerobic threshold to below that threshold and found that there was a considerable variation in quality retention for the cultivars tested. They concluded that this variation was directly associated with differing sensitivities to low O_2.

Using physiological or molecular markers for storage and shelf life as criteria, breeding selection could significantl improve postharvest quality retention. Cherry tomatoes with lowest pectin methylesterase and polyphenol

oxidase tissue levels have been found to have the greatest shelf life potential (Barbagallo et al. 2008). These two enzymes were directly associated with postharvest degradation of the cherry tomatoes. Similarly, Coolong et al. (2008) associated tissue levels of pectin methylesterase and polygalacturonase in onions with rates of softening in different cultivars during longer-term storage. They suggested that higher levels of these enzymes were directly related to higher susceptibility to softening for the cultivars tested.

It must also be stated that differing physiologies may not result in improved quality. In one case, Cantos et al. (2001) found large differences in phenolics pathway enzyme expression and phenolics oxidizing enzyme expression in six cultivars of lettuce. However, those large differences were not associated with differences in susceptibility to cut-edge browning in those lettuces. The reason for this may be that some of the enzymes such as polyphenol oxidase are not rate-limiting to browning (Toivonen and Brummell 2008) and that other endogenous factors are involved in determining the level of browning (Cantos et al. 2001).

There is some evidence that breeding and cultivar selection may enable improved retention of nutritional value for vegetables in storage. Some yellow bulb onions have better retention characteristics for quercetin glycosides than others, depending on the growing season (Mogren et al. 2007). Albrecht et al. (1990) found that ascorbic acid retention in six broccoli cultivars held at 2°C and 95–100% RH varied from 46–98%. This suggests that there can be significan gains made in vitamin C retention with broccoli cultivar selection.

The development of genetically transformed vegetables has been suggested as a new approach to achieving better quality and nutrition (Pech et al. 2005). There are a wide range of possibilities for improving quality with single gene transformations including inhibition of ethylene-mediated senescence, improving sensory quality, increasing resistance to chilling, browning, and bruising injuries, and enhancing nutritional constituent contents. Some quality characteristics can readily be enhanced with single gene transformation such as insertion of the L-gluconoγ-lactone oxidase gene into lettuce, which results in a seven-fold increase in vitamin C content (Jain and Nessler 2000). However, many quality characteristics such as chilling injury resistance are complex in nature (Saltveit 2003b) and would likely involve multigene responses, and hence genetic engineering approaches would need to evolve into multigene platforms, something that may be not possible in the near future (Pech et al. 2005). While this technology has the potential to effect significan improvement in vegetables very rapidly, there continues to be a social debate surrounding the use of this approach and so greater commercial adoption of genetically transformed vegetables will likely proceed slowly until issues surrounding genetic transformation are resolved (Pech et al. 2005).

Implications of Physiology on Postharvest Handling

The understanding of the physiological bases of quality retention in vegetables provides good guidance to the issues which limit the storage or shelf life of a vegetable and also good guidance to the limitations that may exist for application of certain approaches. Examples of the limitations which may exist are that sensitivity to chilling injury or high CO_2 would preclude the use of low storage temperatures or high CO_2 controlled atmospheres for such a vegetable. Therefore, it is important to defin the characteristics of the vegetable in question using existing information and then develop possible strategies to enhance storage life potential as define by whatever criterion is important (sensory quality, nutritional quality, or functional quality).

Low temperature storage-induced chilling injury may be more subtle in nature than development of visual defects in vegetable. In many cases these subtle effects can be noted as changes in processing quality induced by low storage temperatures. A good example is potato which is known to sweeten in response to low temperature storage (Barichello et al. 1990). Consequently, the storage temperature recommendations for potatoes vary significantl according to the end-use cooking method (Table 9.3). At low temperatures the storage starch is converted to sugars and therefore the potato will tend to be susceptible to unacceptable levels of browning under normal chipping conditions (Sowokinos et al. 1987). Another consequence of this sweetening is on the pasting quality attributes when the potatoes are being used for potato flou or starch manufacture. Low temperature storage starch loss significantl reduces the pasting quality of flou made from those potatoes (Kaur et al. 2007). It is therefore important to understand the physiological responses of vegetables to the storage conditions in direct relation to the end use for which they are intended.

If water loss is identifie as a quality issue for vegetables, it can easily be resolved by "recharging" the vegetable with water, a practice that is prevalent via overhead misting systems in North American retail produce displays. The practice of misting is supported by research literature. It has demonstrated that water content can be increased and quality maintained by "recharging" carrots with cold water under simulated retail display conditions (Shibairo et al. 1998). Barth et al. (1990) found that misting broccoli under simulated retail conditions not only maintained visual quality, but also enhanced ascorbic acid retention. From these examples it can be seen that water loss is potentially a simple problem to resolve by "recharging;" however, if level of loss exceeds a cell injury threshold, rehydration may not be possible (Shibairo et al. 1998, 2002).

Another aspect of water loss is that the size of the vegetable has a significan influence Generally, smaller vegetables have a higher surface area to volume ratio (Shibairo et al. 1997; Ben-Yehoshua and Rodov 2003). Consequently, vegetables such as carrot and pepper will have greater weight loss when they are less mature and smaller in size (Shibairo et al. 1997; Díaz-Pérez et al. 2007). Therefore, size grades of vegetables will have differential shelf life potentials based on water loss rates.

The response of an individual vegetable to controlled or modifie atmosphere may determine what the optimal atmosphere is and also whether it should be co-packaged with another vegetable, even if they are closely related botanically. For example, it was found that an atmosphere of 8 kPa O_2 + 14 kPa CO_2 best maintained aliphatic and indole glucosinolates in packaged mini broccoli whereas an atmosphere of 1 kPa O_2 + 21 kPa CO_2 was best for retaining indole glucosinolate in packaged mini caulifl wer (Schreiner et al. 2006). The authors concluded that these two vegetables should not be co-packaged if the goal was to maintain the best nutritional value.

In the end, selection of cultivars for their suitability for either storage or processing normally requires a complete analysis of all the physiological characteristics that defin the vegetables suitability for the desired use. For example, in selecting butterhead lettuce for fresh-cut use, it was established that cultivars having both lower respiration rates and lower sensitivity to high carbon dioxide injury were the most suitable (Varoquaux et al. 1996). Most often there is more than one physiological characteristic that determines the overall acceptability of a vegetable cultivar for the intended use. If all the characteristics required are identifie when selecting new cultivars, then there is a greater chance that that cultivar will have a consistent acceptability for that intended use over the long term. Genetic transformation platforms may provide avenues to accelerate vegetable quality

improvement for fresh storage and processing uses in the future, once the molecular mechanisms for quality are better understood (Pech et al. 2005).

Conclusions

Vegetable quality and nutritional value are determined by the physiological characteristics of the vegetable. Suitability for end use, including storage capability, shelf life potential, and acceptability for processing (either minimal or secondary processing) are also very much determined by the physiological characteristics. Therefore, knowledge of the physiological profil of the selected vegetables can be a powerful tool to assist in optimizing commercial utilization.

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Part III

Processing and Packaging of Vegetables

Chapter 10

Fresh-Cut Vegetables

W. Krasaekoopt and B. Bhandari

Introduction

Fresh-cut vegetables are minimally processed, ready-to-use trimmed and/or peeled, and/or cut parts of vegetables. These vegetables are usually prepackaged for convenience and to retain freshness. Lettuce and prepared salads are the most common fresh-cut vegetables. However, carrot, tomato, broccoli, caulifl wer, and cabbage are also available in fresh-cut form. The shelf life of fresh-cut vegetables is about a week. Fresh-cut vegetables fulfil rising consumer demand for healthy, palatable, safe, and easy to use/serve plant foods. This chapter will review various aspects of fresh-cut vegetables including sensory, physiological, microbial, and manufacturing details.

Consumption Trend

The market for fresh-cut ready-to-eat salads continues to grow in the United States with its estimated value in 2008 at about $15.5 billion. In Europe, United Kingdom leads, followed by Italy and France (Table 10.1). In Australia, the estimated sale of fresh-cut produce was $1.2 billion. The fresh-cut produce market in Japan and Korea was approximately $3.7 billion in 2008. In Thailand, fresh-cut vegetables for local market are not as popular compared to the United States and Europe due to the differences in price between fresh-cut and whole fresh produce. However, the export market is growing. One of the most famous companies, Kamphaeng-Saen Commercial Co., Ltd. (KC Fresh), Thailand, currently ships 75% of its produce, totaling about 180 tons per month, to leading supermarkets in England, the Netherlands, Switzerland, Australia, Russia, Hong Kong, and Japan, whereas local sales contribute 25% of the company's sales. (Figure 10.1)

Processing of Fresh-Cut Vegetables

To obtain fresh-cut vegetables, the basic premise is minimal processing to retain fresh-like texture, color, and fl vor, and safe-to-use quality. The normal processing steps for fresh-cut vegetables are illustrated in Figure 10.2.

After receiving them through a certifie supplier of vegetables, the fresh vegetables are inspected for quality, washed (to remove any dirt and debris from the fiel and reduce microbial loads), peeled, trimmed, cut/shredded, washed, and packaged. Washing with fl wing water is preferable. The wash water must have good microbial quality and low temperature (below 5°C). For peeling/cutting large volumes of vegetables, such as lettuce, mechanical cutters are employed. However, manual preparation generally results in superior quality. For example, cutting romaine by hand can eliminate defects (tip burn). Some vegetables such as caulifl wer and broccoli are only cut manually. After

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Table 10.1 Market of fresh-cut vegetables in selected countries

Country/Region	Estimated value (billion US$) in 2006–2008	References
United States	15.5	Cook (2008)
Europe	4.5	Palmer (2009)
United Kingdom	1.5	Palmer 2009
France	0.8	Nielsen (2007)
Italy	1.1	Nielsen (2007)
Australia	1.2	Australian Food Statistics (2007)
Japan and Korea	3.7	Kim (2007)
Thailand	0.4	Kittikanya (2008)

washing, water is gently removed from vegetables through shakers/spinners or centrifuges. Fresh-cut vegetables are then packed in appropriate size packages for sales. The packaging materials are mainly coextruded, laminated, or EVA-LDPE plastic bags.

Quality of Fresh-Cut Vegetables

Fresh-cut vegetables can be ready-to-serve type (with or without dressing and dips) or ready-to-cook type. The quality of a product is distinguished by sensory properties, such as color, firmness and tastes. Changes in these properties would influenc the shelf life and acceptance of a product, particularly if these attributes drop below the acceptable level under standard storage condition. The major causes of quality loss of some fresh-cut vegetable are presented in Table 10.2.

Color and Appearance

The appearance includes color, gloss, shape, size, and absence of defects and decay. The defects can be either preharvest defects, such as insect or rodent bite, or postharvest defects (morphological, physical, and physiological). Morphological defects are sprouting and rooting (onion), elongation (asparagus), and flore opening (broccoli). Physical defects include mechanical injuries such as puncture and scratches. Examples of physiological defects are chilling injury, freezer burn, and puffiness

Biochemical processes such as chlorophyll and carotene degradation, and enzymatic browning can affect color of vegetables. Cutting and trimming induce enzymes responsible for enzymatic browning. For example, lettuce can have edge browning and russet spotting (Lopez-Galvez et al. 1996). Although browning is not as common in fresh-cut vegetables as in fresh-cut fruits, if present it can affect their shelf life and marketability. In carrots, environment and postharvest stress is reported to initiate the synthesis of phenolic compounds together with lignin (Talcott and Howard 1999). Lignin formation increases whiteness of carrots similar to dehydration of carrot's surface.

Texture

As indicated before, fresh-cut vegetables are produced by a minimal process to maintain texture which includes firmness crispness,

Figure 10.1 Fresh-cut vegetables in Thai supermarket.

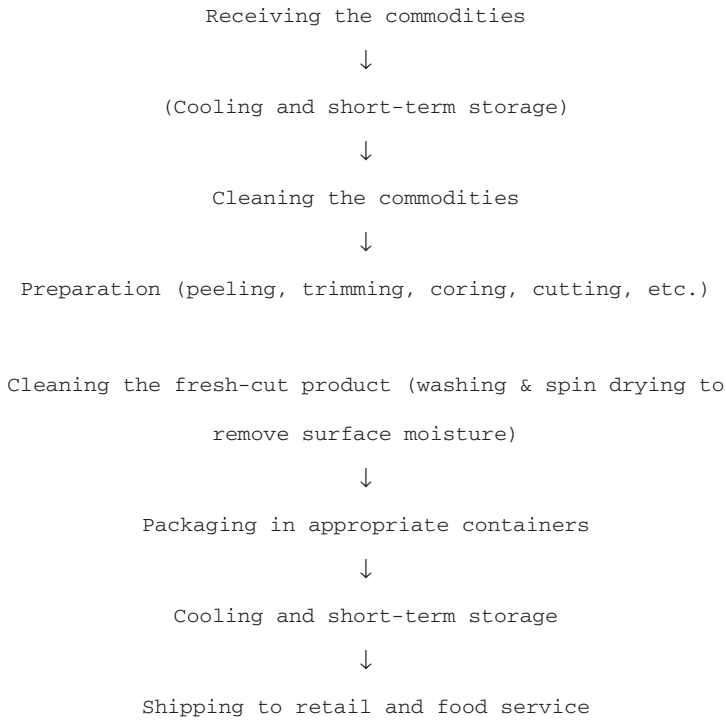

Figure 10.2 Typical processing steps for preparing fresh-cut vegetables.

juiciness, mealiness, and toughness. Changes in texture are related to both the enzymatic and nonenzymatic reactions. Enzymes, such as pectin methylesterase (PME) and polygalacturonase (PG), can degrade pectin, resulting in soft-textured product. Addition of cations such as Ca^{2+} either calcium chloride or calcium lactate can improve the texture of the product by forming a bridge between cation and pectin. Nevertheless, after cutting, undesirable biochemical reactions related to wounding can cause changes in texture. Even under the optimal storage conditions, the texture of fresh-cut vegetables is rarely maintained for more than 10 days (Watada and Qui 1999). Lignificatio also adversely influ ences the texture of many fresh-cut vegetables. In addition, texture can be affected by loss of moisture/fluids

Table 10.2 Main causes of quality loss of some fresh-cut vegetables

Produce	Main cause of degradation
Lettuce	Browning
Green leafs	Loss of moisture and darkening
Carrot	Browning, loss of moisture, lignin formation
Cabbage	Chlorophyll degradation, browning
Broccoli	Chlorophyll degradation
Caulifl wer	Browning
Cucumber	Soft texture, fermentation
Onion	Browning, soft texture

Flavor

Flavor includes tastes like sweet, sour, astringent, bitter, aroma, and off-fl vors. It is influ enced by the vegetables composition (sugar, organic acids, phenolic compounds, volatile compounds, etc.), genetic factors, maturity at harvest, and postharvest treatments. Table 10.3 shows factors affecting the fl vor quality of fresh-cut vegetables.

Table 10.3 Factors affecting the flavor quality of fresh-cut vegetables

Factors	Flavor changes
Browning	Astringency
Changes in the microenvironment	Fermentative flavor such as sour taste and alcoholic smell
Microbial growth	Putrid smell, sour taste, and rot smell
Conversion of starch to sugar or vice versa	Increase in sweetness of carrot or loss of sweetness of peas and corn

The shelf life of vegetables based on flavor following harvest can be shorter than based on appearance and texture. Therefore, harvesting at the proper maturity or ripeness and good postharvesting practices are important to ensure good flavor quality products (Kader 2008).

In addition, storage conditions and microbial growth can cause flavor defects. An exposure to high (10–20%) CO_2 levels was reported to cause suppression of various metabolic processes (Watkins 2000). Similarly, a lack of O_2 was shown to cause off-flavors in fresh-cut vegetables (Beaudry 2000). Some microorganisms such as lactic acid bacteria and yeast can cause flavor issues as they are responsible for the production of organic acids such as lactic acid, acetic acid, CO_2, ethanol, and volatile esters (Jacxsens et al. 1999).

Nutritional Quality

Physical damage, extended storage, high temperatures, low relative humidity, and chilling injury of commodities can affect vitamin C (Lindley 1998). However, the conditions for maintaining desirable sensory qualities also have positive effect on nutrients. Differences in levels of ascorbic acid, carotenoids, and polyphenols reflect variations in relative antioxidant property of vegetables (Lana and Tijskens 2006). During the fresh-cut processing these nutrients may also undergo changes. Gil et al. (1999) reported a decrease in antioxidant activity of fresh-cut spinach after processing. Conversely, Kang and Saltveit (2002) reported an increase in antioxidant activity of iceberg and romaine lettuce due to wounding.

Physiological and Biochemical Changes in Fresh-Cut Vegetables

Wounding or injury associated with processing and handling fresh-cut vegetables can cause physiological changes which influence ethylene production, respiration rate, discoloration, deterioration of texture, and water loss.

Ethylene Production

The time for the initiation of ethylene production ranges from a few minutes to an hour after cutting, with maximal rates between 6 and 12 hours (Abeles et al. 1992). Ethylene can accumulate in packages of fresh-cut vegetables, leading to undesirable quality during the storage (Saltveit et al. 2005). Ethylene can also stimulate and accelerate membrane deterioration, loss of vitamin C and chlorophyll, abscission, toughening, and undesirable flavor changes (Kader 1985). Except tomatoes, ethylene production in fresh-cut vegetables is lower than fresh-cut fruits. High level of ethylene production of tomato (*Lycopersicon esculentum* Mill.) has been found after cutting (Artes et al. 1999). Unpeeled carrots when exposed to ethylene become bitter due to the synthesis of isocoumarin. However, the peeled carrots do not produce this compound because it is formed mainly in the peeled tissues (Cantwell and Suslow 2002). Removal of ethylene from the storage environment by ethylene inhibitor 1-methylcyclopropane (1-MCP, blocks ethylene receptors) may help in preserving product quality (Yueming and Jiarui 2000).

Respiration

Respiration is accelerated by processing fresh-cut vegetables, but the initiation of this

response is delayed compared to ethylene production. The respiration rate of fresh-cut vegetables is higher than that of whole vegetables. For example, the respiration rate of shredded lettuce and cabbage is 200–300% greater than the intact one, and 20–40% higher for cut iceberg and romaine lettuce than that of the intact head (Cantwell and Suslow 2002). Higher respiration rate can result in more rapid loss of acid, sugar, and other components related to fl vor quality and nutritive value. Respiration rate can be slowed by quickly cooling and storing at 5°C or below. Apart from temperature, there are other factors affecting respiration rate, such as maturity and size of the vegetables. Young leaf tissue appears to have higher respiration rate than fully mature leaves. The respiration rates of chopped kale (size: 2×2 cm^2) and shredded kale (0.3×0.3 cm) at 10°C were reported to be 46 mL CO_2 kg^{-1} h^{-1} and 59 mL CO_2 kg^{-1} h^{-1}, respectively (Cantwell and Suslow 2002).

Discoloration

Enzymatic browning of leafy vegetables is considered one of the most important defects because it is easily noticeable (Figure 10.3). Browning reactions are due to the polyphenol oxidase (PPO) enzyme, although some attribute at least a partial role of peroxidases (POD). An increase in phenylalanine ammonia lyase (PAL) activity was found to correlate with the susceptibility to browning in fresh-cut lettuce (Saltveit 2000), and PAL has been suggested as a marker for shelf-life monitoring in some fresh-cut products (Degl'Innocenti et al. 2005).

Different treatments are used for browning reduction in fresh-cut vegetables, such as the use of sulfites chemical inhibitors of PPO and/or POD, or the use of modifie atmosphere packaging to exclude oxygen (Saltveit 2000). Ascorbic acid is reported to be an effective inhibitor of enzymatic browning because it reduces quinones to phenolic compounds, thus preventing the synthesis of the brown pigments.

Yellowing, or loss of green color, is due to chlorophyll degradation revealing preexisting yellow carotenoid pigments. Cabbage in coleslaw changes from green to a lighter white color because it lacks yellow pigments. Degradation of chlorophyll in fresh-cut vegetables can be initiated by wound-induced ethylene or by free radical products of membrane lipid peroxidation (Shewfelt and Del Rosario 2000).

Increasing "white blush" is a reversible surface dehydration of the outer layers in

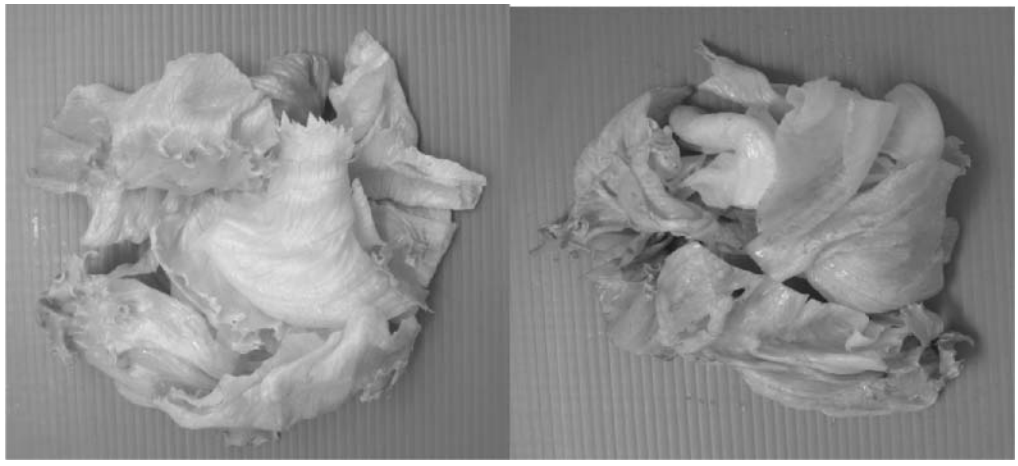

Figure 10.3 Discoloration of fresh-cut iceberg lettuce.

fresh-cut carrots (Cisneros-Zevallos et al. 1997). Moreover, accumulation of lignin, converted from syringaldazine, caused by wounding can also lead to "white blush." The use of fin abrasives (Bolin and Huxsoll 1991) and sharp cutting (Tatsumi et al. 1991) in carrot peeling can reduce the wound response and lignin accumulation. In addition, white blush can be controlled by treatments with citric acid and L-cysteine hydrochloride, which reduce tissue pH and thus enzymic activity (Bolin 1992).

Deterioration of Texture

The secondary cell walls of vegetables generally make them firme and less susceptible to softening as compared to fruits. Thus, natural softening is not common in vegetables. However, the loss of texture can be due to senescence, water loss, reduced turgor, and wounding. In fresh-cut vegetable processing, cutting operation opens the cells releasing cell exudates. Calcium chloride or calcium lactate is commonly used to improve firmnes of fresh-cut vegetables such as carrot and lettuce (Rico et al. 2007). Calcium ions form cross links or bridges between free carboxyl groups of pectin chains strengthening the cell wall. Calcium ions also reduce senescence-associated membrane lipid changes in shredded carrots (Picchioni et al. 1996). Calcium dips are often combined with chemicals such as ascorbate or cysteine to prevent browning.

Water Loss

The texture is also affected by loss of water and osmotic changes (Saladie et al. 2007). The loss of water results in the loss of cell turgor and crispness. The water loss can be due to: (1) a reduction in size, increasing surface area to volume ratio, and (2) removal of protective peel tissues. Increased rate of water loss results in greater susceptibility to wilting and/or shriveling. Peeled "Majestic" potatoes had a water loss rate of 3.3–3.9 mg H_2O cm^{-2} mbar wpd^{-1} h^{-1}, while unpeeled, cured potatoes had a moisture loss rate of 0.007 mg H_2O cm^{-2} mbar wpd^{-1} h^{-1} (Ben-Yehoshua 1987). Abrasion peeling causes three times greater water loss than hand peeling in carrots. Machine-sliced carrots lost water 30% faster than manually sliced carrots (Barry-Ryan and O'Beirne 1998). The water loss can be minimized by appropriate packaging. Nevertheless, lack of membrane integrity leads to the leakage of cellular osmotic solutes into the intracellular space, resulting in water movement and turgor loss. Washing of green bell pepper slices after cutting removes solutes from the cut surfaces, resulting in improvement of firmnes retention (Toivonen and Stan 2004).

Microbiology and Safety of Fresh-cut Vegetables

Fresh-cut vegetables are the wounded products; therefore, they are susceptible to growth of a wide array of microorganisms including mesophilic bacteria, lactic acid bacteria, coliforms, and yeasts and molds, and can be a vehicle for the transmission of bacterial, parasitic, and viral pathogens causing disease (Ongeng et al. 2006). The microflor of fresh-cut vegetables is the environmental flor where the produces are grown. Consequently, it is expected that these products contain little pathogenic agents (such as *Bacillus cereus* and *Listeria monocytogenes)* from soil and environment. The incidence of foodborne outbreaks caused by fresh-cut vegetables has increased in recent years (Mukherjee et al. 2006). The pathogens most commonly linked to outbreaks include bacteria (*Salmonella*, *Escherichia coli)*, viruses (Norwalk-like, hepatitis A), and parasites (Cryptosporidium, Cyclospora) (Table 10.4)

Salmonella and *E. coli* O157:H7 are the leading causes of the outbreaks in the United States (Olsen et al. 2000). Many outbreaks caused by consumption of fresh-cut vegetables have also been reported in Japan (National Institute of Infectious Diseases 1997) and the European Union (Emberland

Table 10.4 The possible pathogenic contamination in fresh-cut vegetables

Pathogenic microorganisms	Produces
Bacteria	
Clostridium botulinum	Shredded cabbage, cubed butternut squash, sliced onions
Salmonella sp.	Chopped or sliced tomatoes, bean sprout
Shigella spp.	Shredded lettuce, green onions, shredded cabbage, chopped parsley
Escherichia coli O157:H7	Lettuce, sprout, mixed vegetables, cilantro, coriander, and celery
Listeria monocytogenes	Cabbage salad, asparagus, broccoli, butternut squash, coleslaw, and caulifl wer
Staphylococcus aureus	Ready-to-eat vegetable salads
Yersinia enterocolitica	Mung bean sprouts, grated carrots, lettuce
Campylobacter jejuni	Salad, lettuce
Parasites	
Cryptosporidium spp.	Lettuce, onions
Cyclospora spp.	Lettuce
Viruses	
Hepatitis A	Lettuce, diced tomatoes, green onion
Norwalk/ Norwalk-like virus	Coleslaw, green salad

et al. 2007). *L. monocytogenes*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa* (Viswanathan and Kaur 2001) have also been isolated from these products. In addition, Abadias et al. (2008) conducted a survey of fresh-cut vegetables in Spain. They found the presence of *E. coli* and *L. monocytogenes* counts as well as the presence of *Salmonella*, *E. coli* O157:H7, *Yersinia enterocolitica*, and thermotolerant *Campylobacter*. Similar results were obtained by Nguz et al. (2005) in Zambia and Johannessen et al. (2002) in Norway.

Good manufacturing practice (GMP) and Hazard Analysis and Critical Control Points (HACCP)-based production and handling, and proper documentations related to sourcing, processing, quality checking, packaging, and storage are important to ensure the safety and traceability of fresh-cut vegetables. National microbiological guidelines have been published for ready-to-eat food in countries such as the United Kingdom, Spain, France, Germany, and Japan (Lund 1993; Nguyen-The and Carlin 1994; Food and Environmental Hygiene Department 2002).

Antimicrobial Substances Used in Washing of Fresh-cut Vegetables

Antimicrobial agents or substances can be used in wash water for reducing microbial load and inhibiting enzymatic activity. A number of disinfectants or biocontrol processes used to reduce the microbial load in fresh-cut vegetables are given in Table 10.5.

Disinfectants

Disinfectants are distinguished from antibiotics (destroy microorganisms within the body) and from antiseptics (destroy microorganisms on living tissue). The disinfectants used for decontamination of fresh-cut vegetables are: chlorine, chlorine dioxide, ozone, peroxy acetic acid, acidifie sodium chlorite, and electrolyzed water (EW).

Wash water disinfectant is used for the prevention of cross-contamination and reduction of microbial load in the products. The

Table 10.5 Different chemicals used for sanitizing fresh-cut vegetables

Chemicals	Concentration and pH
Chlorine	100–150 ppm, pH 6–7
Chlorine dioxide	3 ppm, pH 8.7–10
Acidifie sodium chlorite	500 to 1200 ppm, pH 2.5–2.9
Ozone	0.1–0.3 ppm
Peroxyacetic acid	Up to 80 ppm, pH up to 7.5
Acidic electrolyzed water (AEW)	10–90 ppm (free chlorine), pH 2.1–4.5
Neutral electrolyzed water (NEW)	50–120 ppm (free chlorine), pH 7.5–8.5

efficien y of disinfectants is influence by: concentration, exposure time, temperature, pH, organic matter load, type and number of microorganisms, and type of disinfectant used. The properties of the ideal wash water disinfectant are as follows:

- Ability to destroy microorganisms rapidly and/or posses residual effect
- Ease of preparation and measurement of its efficien y
- Water soluble and stable
- Tolerant to hard water
- Environmentally compatible and non-toxic
- Non-corrosive to the container of equipment used
- Acceptable color and odor
- Economical and safe to use

Chlorine

The most commonly used disinfectant in fresh-cut vegetables is chlorine. Chlorine has a broad spectrum of activity; it can destroy yeast, mold, bacteria, and viruses. In solution, chlorine forms hypochlorous acid (HOCl), a powerful oxidizing agent that destroys microorganisms by disrupting their cell walls. Chlorine can be used in the form of hypochlorite salts (either sodium or calcium) or chlorine gas (Cl_2). The pH of the solution controls the relative proportions of hypochlorous acid (HOCl) and hypochlorite (OCl^-), the other reaction product of chlorine in water. The proportions of HOCl and OCl^- are equal at pH 7.9 and at 0°C. As the pH decreases, the concentration of HOCl increases. However, at low pH, the water becomes corrosive on the equipment used. Therefore, it is important to monitor pH levels during washing to protect the equipment. Chlorine can tolerate hard water and can be used at low temperatures. In addition, chlorine is relatively inexpensive. However, when chlorine is used, cut vegetables should be rinsed to reduce the chlorine concentration to the same level as in drinking water to maintain sensory quality. A maximum chlorine level of 100–150 ppm at pH 6 to 7 is recommended (International Fresh-cut Produce Association 2004).

Washing fresh-cut vegetables with chlorinated water not only reduces bacterial pathogens, such as *E. coli* O157:H7 (Li et al. 2001), *L. monocytogenes* (Zhang and Farber 1996), and *Y. enterocolitica* (Escudero *and others* 1999), but also reduces population of microflor as indicated by 3 logs reduction in aerobic counts in lettuce (Garg et al. 1990).

However, the use of chlorine as disinfectant for fresh-cut vegetables can be limited by several factors. It is difficul to destroy microorganisms in creases, pockets, and natural openings of vegetables, such as cabbage, due to poor diffusion of chlorine. The hydrophobic waxy cuticle of vegetable is also an obstacle. In addition, if chlorine is not used between pH 6.0 and 7.5, it becomes ineffective or too corrosive. Chlorine has a potential to form toxic chlorine gas which is irritable to the operators. Chlorine can bind with organic matter in the wash water, resulting in a lower effective concentration and, more importantly, formation of potentially toxic compounds, such as the carcinogenic trihalomethanes (White 1992). In some EU countries (Germany, Belgium, and the Netherlands), the use of chlorine has been prohibited (Varoquaux and Mazollier 2000). Moreover, the new and more tolerant pathogens have raised doubts in relation to the use of chlorine by the fresh-cut industry (Singh et al. 2002).

Chlorine dioxide

Chlorine dioxide (ClO_2), a synthetically produced water-soluble yellowish-green gas with an odor similar to chlorine, is approved by the Food and Drug Administration (FDA) for use in fresh-cut vegetables. Unlike chlorine, ClO_2 does not hydrolyze in water and react with organic matter to form toxic compounds, but may produce other potentially hazardous by-products, such as chlorite and chlorate.

Chlorine dioxide is reported to be 2.5 times more effective than chlorine for destruction of microorganisms (Christie 2009). A maximum of 200 ppm ClO_2 is allowed for sanitizing processing equipment and 3 ppm for washing whole produce (FDA 2008). Only 1 ppm ClO_2 is permitted for peeled potatoes (Parish et al. 2003).

ClO_2 cannot be compressed and stored under pressure because it is explosive; therefore, the shipping of ClO_2 gas is impossible, and it is generally generated on-site. The commercial ClO_2 generator consists of two sachets, sodium chlorate ($NaClO_3$) and a mixture of concentrated hydrogen peroxide (H_2O_2) and concentrated sulfuric acid (H_2SO_4).

ClO_2 is generated by mixing these compounds (Sy et al. 2005).

ClO_2 can be used for decontamination of fresh-cut vegetables in aqueous and gas forms (Gomez-Lopez et al. 2009). In the aqueous form, Pao et al. (2007) reported a reduction of aerobic count by 5 logs. Wounds limit the effectiveness of gaseous ClO_2 due to diffi culty of penetration; however, prerinsing can increase the effica y (Singh et al. 2002). Recently, Kim et al. (2009) reported a reduction of spoilage microorganisms and *E. coli* O157:H7, *S. typhimurium*, and *L. monocytogenes* on broccoli sprouts treated with a combination of aqueous chlorine dioxide and fumaric acid.

In general, the effectiveness of gaseous ClO_2 is higher than aqueous, and can be as high as >8 logs (Han et al. 2001). Studies on the effect of ClO_2 gas showed a significan reduction of microbial population in tomatoes, onions (Sy et al. 2005), shredded iceberg lettuce, and white cabbage (Gomez-Lopez et al. 2008). Sy et al. (2005) also reported effectiveness in destruction of *Salmonella, E. coli* O157:H7, and *L. monocytogenes* on fresh-cut lettuce, cabbage, and carrots. They observed 3–6 log reduction of pathogenic microbial counts in carrots, cabbage, and tomatoes treated with 4.1 ppm ClO_2 gas. However, only 1–2 log reductions were achieved in fresh-cut lettuce and onions; besides, the treatment had an adverse effect on odor of the products. Gomez-Lopez et al. (2007) also achieved approximately 2 log reductions in the mesophilic counts of carrots treated with 1.3 ppm ClO_2 gas for 30 seconds. ClO_2 was also found to be effective in killing pathogens without interfering with the visual quality of lettuce. Furthermore, Mahmoud and Linton (2008) found reduction in psychrotropic bacteria, yeast and mold, *E. coli* O157:H7, and *S. entrica* in shredded lettuce.

Acidified Sodium Chlorite

Acidifie sodium chlorite ($NaClO_2$ + citric acid) is another chlorine-based disinfectant approved by the FDA and Environment Protection Authority (EPA) for application in fresh-cut vegetables as a spray or dip in the range of 500 to 1200 ppm. The biocide activity is due to the generation of chlorous acid ($HClO_2$), possessing strong oxidizing capacity with broad spectrum germicidal activity. Similar to chlorine dioxide, the use of chlorite does not cause toxic compound formation (Agency for Toxic Substances and Disease Registry 2002). Currently, acidifie sodium chlorite is commercially supplied as a kit containing citric acid and sodium chlorite. Combination of these chemicals provides active chlorine dioxide, more soluble than sodium hypochlorite (NaOCl) in water and has about 2.5 times greater oxidizing capacity than hypochlorous acid ($HOCl_2$) (Inatsu et al. 2005). The commercial preparation of acidifie sodium chlorite (200 ppm) has higher effectiveness to destroy *Salmonella* and *E. coli* O157:H7 than sodium hypochlorite and chlorine dioxide (Ruiz-Cruz et al. 2007). Stopforth et al. (2008) reported that acidifie sodium chlorite resulted in reduction by 3 logs to 3.8 logs of *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* inoculated onto leafy greens. Recently, Allende et al. (2009) reported a reduction of more than 3 logs after washing of fresh-cut cilantro with

1 g L^{-1} of acidifie sodium chlorite. When lower concentrations of this compound were used (0.25 and 0.5 g L^{-1}), microbial counts were reduced by approximately 2 logs. Moreover, Ching-Hsing (2009) reported that soaking alfalfa in acidifie sodium chlorite at the concentration of 800 ppm for 45 minutes could eliminate 99.9% to 99.99% of pathogens (e.g., *Salmonella*). Although fresh-cut carrots treated with acidifie sodium chlorite showed the lowest growth rate of aerobic bacteria, compared to other sanitizers, during the storage period, a negative impact on organoleptic quality of shredded carrots occurred when it was used within the approved concentration range (Ruiz-Cruz et al. 2006).

Ozone

Ozone (O_3) is an effective treatment for disinfection of drinking water where it decomposes spontaneously to nontoxic products. In 2001, gaseous and aqueous ozone was approved by the US FDA for application as an antimicrobial agent to foods (FDA 2001). Corona discharge method is the most popular type of ozone generator for most industrial uses. The unit usually works by means of a corona discharge tube. It is cost-effective and does not require an oxygen source other than the ambient air (Figure 10.4).

The ambient air is pulled into the inlet of the generator and passed through air fil ter to prevent dust and insect contamination. A powerful fan accelerates air to the unit and a high voltage corona converts oxygen (O_2) in the air to ozone (O_3), which can be used for washing fresh-cut vegetables. The system also produces nitrogen oxides as a by-products. Use of an oxygen concentrator can increase ozone production and reduce the risk of nitric acid formation by removing the water

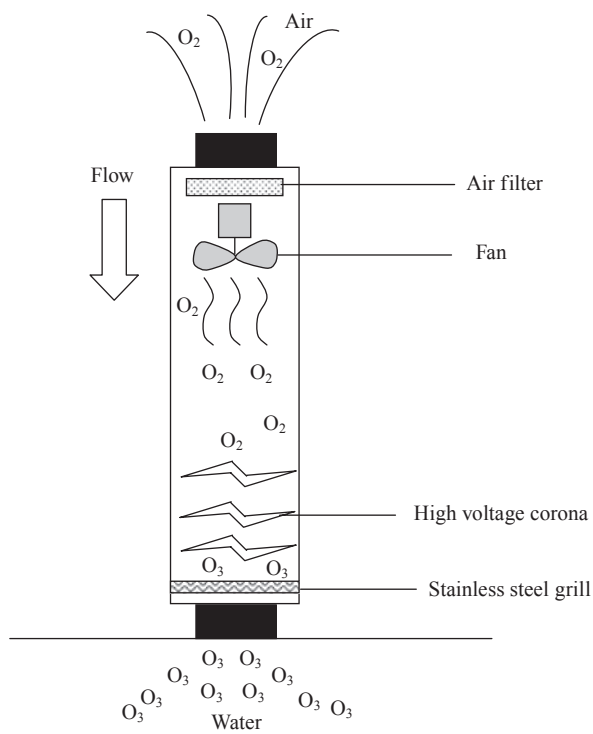

Figure 10.4 A schematic of an ozone generator.

vapor and most of the nitrogen (Becker et al. 2005).

Ozone rapidly reacts with intracellular enzymes, nucleic material, and components of envelope, spore coats, or viral capsids of microorganisms. It also decomposes rapidly without traces from oxidation and does not produce any toxic halogenated compounds. O_3 decomposes impulsively during water treatment through mechanisms involving the generation of hydroxyl free radicals ($^{\bullet}OH$). The $^{\bullet}OH$ radicals are the principal reactive oxidizing agents and are highly effective for inhibition of bacteria and virus (Kim et al. 2003). Ozone is 25, 2,500, and 5,000 times more effective in disinfection than hypochlorous acid, hypochlorite, and chloramines, respectively (Irtwange 2006). Ozone will oxidize organic chemicals into safer elements, e.g., breaking down ammonia and cyanide into nitrogen and water. In all reactions, the main byproduct after oxidation is oxygen.

O_3 has been applied to fresh-cut vegetables for sanitation to reduce microbial populations and extend the shelf life (Selma et al. 2006; Hassenberg et al. 2007). Selma et al. (2007) reported that washing shredded lettuce with ozone (1.6 ppm and 2.2 ppm) for 1 minute decreased *S. sonnei* in water by 3.7 logs and 5.6 logs, respectively. They also illustrated that application of O_3 for 60 minutes in fresh-cut onion, escarole, carrot, and spinach reduced total microbial count by 5.9 logs. Furthermore, turbidity of wash water was reduced significantl by O_3 treatment. The use of O_3 would require less frequent changing of water and lower sanitizer doses (Selma et al. 2008). Olmez and Akbas (2009) studied the optimization of ozone treatment for fresh-cut green leaf lettuce on *L. monocytogenes* counts and the overall visual quality of lettuce. Ozone treatment was found to be better than the chlorine and organic acid treatments. Klockow and Keener (2009) demonstrated that the whole spinach leaves inoculated with *E. coli* O157:H7 6460, treated in packaging with ozone generated in air and oxygen, showed the highest reduction of *E. coli* O157:H7 (3–5 logs) after 24 hours of storage.

However, ozone is a strong oxidizing agent; Kim et al. (2006) reported that above 5 ppm, ozonated water damaged the surface texture of the lettuce leaves. Koseki and Isobe (2006) observed a rapid onset of browning on iceberg lettuce treated with 10 ppm ozonated water whereas treatments with 3 ppm and 5 ppm ozonated water caused changes in the a^* value similar to the distilled water treatment. Moreover, ozone damages the vitamin B_{12}-binding protein by oxidizing the SH-groups (Dominy and Heath 1985). Ozone also causes lipid peroxidation. Ozonating of string beans for 20–25 minutes generated the product of lipid peroxidation (malondialdehyde), a loss of unsaturated fatty acids, and changes in membrane permeability (Alscher and Amthor 1988).

Another disadvantage of using ozone is its high instability, making difficul to predict how ozone reacts in the presence of organic matter (Cho et al. 2003). Although most materials are compatible with ozone at moderate concentrations of 1–3 ppm (Pascual et al. 2007), in the processing industry, it is important to keep the applied ozone levels as low as possible because it is corrosive to stainless steel, especially when the concentration is above 1 ppm. For ozone exposure in the working environment, the threshold limit value (TLV) for long-term (8 hours) and for short-term (15 minutes) exposures is 0.1 ppm and 0.3 ppm, respectively.

Peroxyacetic Acid

Peroxyacetic acid (PA), also referred to as peracetic acid, is an aqueous quaternary equilibrium mixture of acetic acid and hydrogen peroxide (Dell'Erbaa et al. 2007). It is a bright, colorless liquid with a piercing odor and a low pH (2.8). It can explode at temperatures higher than 110°C. Peroxyacetic acid is approved for addition into wash water

(Code of Federal Regulations 2000) and as a no-rinse food contact surface sanitizer. It has low foam characteristics and decomposes into acetic acid, water, and oxygen—all harmless residuals. It is a strong oxidizing agent and can be hazardous to handle at high concentrations but not at the level used in the industry. Being relatively tolerant to organic matter, it is exceptionally effective against biofilms Peroxyacetic acid has a broad spectrum of bactericidal activity over a broad pH range of up to pH 7.5, but varies in effectiveness against yeasts and molds. However, this compound losses its effectiveness in the presence of some metals. This compound is corrosive to brass, copper, mild steel, and galvanized steel, especially at high temperature. Like ozone and chlorine dioxide, peroxyacetic acid is effective in destroying pathogens at lower concentrations than those required for chlorine.

Although the use of peroxyacetic acid in fresh-cut vegetables is allowed up to 80 ppm in wash water (Code of Federal Regulation 2007), many studies revealed that it is not enough to obtain appropriate reduction of microbial load in fresh-cut vegetables (Hilgren and Salverda 2000; Nascimento et al. 2003; Hellstrom et al. 2006). Population reductions for aerobic bacteria, coliforms, and yeasts and molds on fresh-cut celery, cabbage, and potatoes, treated with 80 ppm peroxyacetic acid were less than 1.5 logs. Moreover, only 1.7 logs reduction was obtained in the microbial load of fresh-cut cabbage by using 80 ppm peroxyacetic acid (Vandekinderen et al. 2007; Vandekinderen et al. 2009). Ruiz-Cruz et al. (2007) also found only about 1 log reduction in the *E. coli* O157:H7 and *L. monocytogenes* counts in shredded carrot with 40 ppm of peroxyacetic acid. Conversely, Beuchat et al. (2004) reported that the use of 80 ppm peroxyacetic acid reduced *L. monocytogenes* by 4–5 logs in iceberg and romaine lettuce. In addition, peroxyacetic acid showed more than 2 logs reduction of *Salmonella* sp. in bell pepper and cucumber (Yuk et al. 2006). Addition of octanoic acid to peroxyacetic acid solutions increased effica y in destroying yeasts and molds in fresh-cut vegetable process water but had little effect on bacterial population reductions in fresh-cut vegetables (Hilgren and Salverda 2000).

Electrolyzed Water (EW)

Electrolyzed water (EW), also known as electrolyzed oxidizing water, is conventionally generated by electrolysis of 0.1% sodium chloride solution to produce an electrolyzed basic aqueous solution at the cathode and an electrolyzed acidic solution at the anode (known as acidic electrolyzed water, AEW) (Kim et al. 2000). Negatively charged ions, such as hydroxide ions and chloride ions in the salt solution, move to the anode to give up electrons and become oxygen gas, chlorine gas, hypochlorite ion, hypochlorous acid, and hydrochloric acid, while positively charged ions such as hydrogen ions and sodium ions move to the cathode to take up electrons and become hydrogen gas and sodium hydroxide (Hsu 2003) (Figure 10.5).

AEW has been reported to have a strong bactericidal activity against foodborne pathogens (Izumi 1999) and has pH 2.1–4.5; however, basic EW has a pH of above 11.5 and has not been reported to have any sanitizing properties. Huang et al. (2008) also reported the application of electrolyzed water in the food industry. Currently, two types of EW as acidic electrolyzed water (pH: 2.1–4.5) and neutral electrolyzed water (pH: 7.5–8.5) are of interest.

Biocontrol Agents

Biocontrol agents used in fresh-cut vegetables are antagonistic organisms, known as biopreservatives, and natural antimicrobial substances (Table 10.6).

Microorganisms such as lactic acid bacteria are used as biopreservative agents in foods to inhibit the growth of other undesirable microorganisms. Lactic acid bacteria are also considered as food grade microorganisms and

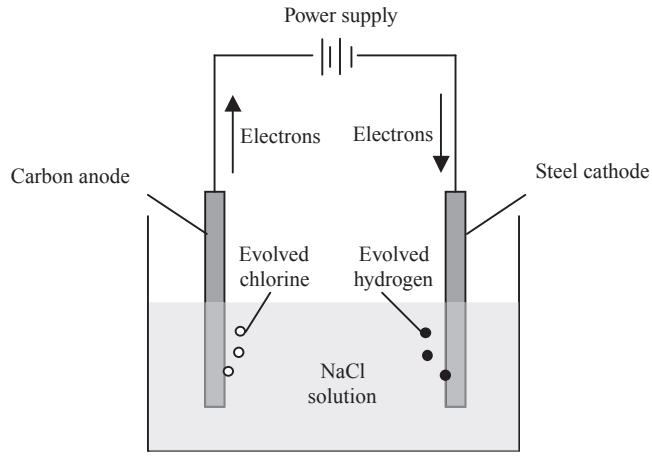

Figure 10.5 A schematic diagram of electrolyzed water generation.

generally recognized as safe (GRAS) by the US FDA. Lactic acid bacteria produce antimicrobial metabolites such as lactic and acetic acids, hydrogen peroxide, and enzymes including lysozyme. Some strains of lactic acid bacteria also produce bacteriocins (Breidt and Fleming 1997). Bacteriocins are described as natural antimicrobial substances.

Table 10.6 The biocontrol agents used in fresh-cut vegetables

Biocontrol agents	Effectiveness against pathogens
Biopreservatives	
Lactic acid bacteria	*Listeria monocytogenes*, *Salmonella typhimurium*, *Staphylococcus aureus*, coliforms, enterococci, *Escherichia coli*
Bacteriophage	*Listeria monocytogenes*, *Salmonella*, *Campylobacter jejuni*, *Salmonella oranienburg*
Natural antimicrobial compounds	
Bacteriocins	*Listeria monocytogenes*, *Bacillus cereus*, *Bacillus weihenstephanensis*, *Enterococcus faecalis*
Natural plant extracts (basil oil, acetic acid, ethanol, pyruvates)	*Salmonella* sp., *Listeria monocytogenes*
Whey permeate	Normal flor microorganisms

There is also interest in using bacteriophages as biopreservative in foods. In 2007, the US FDA approved a Listeria-specifi bacteriophage preparation, "Listex P100," for food preservation on ready-to-eat meat and deli products (FDA 2007). Phages have been successfully used for controlling the growth of pathogens such as *L. monocytogenes*, *Salmonella*, and *Campylobacter jejuni* (Rees and Dodd 2006). Pao et al. (2004) carried out trials to assess the potential of phages for controlling of *Salmonella* in experimentally contaminated broccoli with promising results. Kocharunchitt et al. (2009) recently reported the use of phages to control *S. oranienburg* in alfalfa. They revealed an approximately 1 log reduction of viable *Salmonella* achieved 3 hours after phage application.

Bacteriocins

Among antimicrobial compounds, bacteriocins are a heterogeneous group of antibacterial peptides and proteins with different molecular weight and composition. Bacteriocins are divided into three main groups. Class I, or antibiotics; Class II, which comprises heat-stable non-modifie peptides and two peptide bacteriocins; and Class III, which are large and heat labile peptides depending

on the microbial species and chemical properties (Cleveland et al. 2001). However, nisin is the only bacteriocin produced by *Lactococcus lactis*, which is generally recognized as safe (GRAS) as a direct human food ingredient (FDA 1988). Bacteriocins are considered to be safe because they are degraded by the proteases in the gastrointestinal tract, and the direct application of bacteriocins to fresh-cut lettuce has been tested (Cleveland et al. 2001).

Several studies have been carried out on the effect of bacteriocins against *L. monocytogenes* in ready-to-eat Caesar salad and fresh alfalfa sprouts, soybean sprouts, mung bean sprouts, green asparagus, cabbage, broccoli, and fresh-cut lettuce (Bari et al. 2005; Molinos et al. 2005; Allende et al. 2007). Recently, Randazzo et al. (2009) reported the use of bacteriocin RUC9 produced by a wild strain of *Lac. lactis* in iceberg lettuce. The bacteriocin reduced the *L. monocytogenes* viable count of 2.7 logs in 7 days of storage at 4°C. Bacteriocin can be also used in combination with other food additives. It can be used with pediocin, sodium lactate, citric acid, phytic acid, potassium sorbate, and ethylenediaminetetraacetic acid (EDTA) to inhibit *L. monocytogenes* in fresh-cut vegetables (Bari et al. 2005).

Enterocin AS-48 is another bacteriocin that has been recently investigated. Enterocin AS-48 is a broad-spectrum cyclic antimicrobial peptide produced by *Enterococcus faecalis*. Washing green asparagus, alfalfa, and soybean sprouts with this compound in combination with some preservatives such as potassium permanganate, acetic acid, citric acid, sodium propionate, and potassium sorbate reduced the growth and regrowth of *L. monocytogenes*, *B. cereus*, and *B. weihenstephanensis* to below detectable level (Molinos et al. 2008).

Natural Plant Extracts

Addition of plant-derived compounds, such as acetic acid, ethanol, and pyruvates, in fresh-cut mixed lettuce and cabbage not only inhibited the growth of *L. monocytogenes* and *B. cereu*s, but also reduced the total count of the products by 2 logs (Dawson et al. 1999). Essential oil is also used for inhibition of spoilage and pathogenic microorganisms. Washing lettuce with basil oil (0.1–1.0% v/v) was as efficien as washing with 125 ppm chlorine (Wan et al. 1998).

Grapefruit seed extract is also of interest because it possesses antimicrobial properties due to high amount of phenolic compounds (Hegger et al. 2002). Xu et al. (2007) applied grapefruit seed extract to reduce the growth of *Salmonella* sp. and *L. monocytogenes* in fresh-cut cucumber and lettuce. The use of grapefruit seed extract either alone or in combination with nisin and citric acid has been successful in inhibiting the growth of pathogens without effect on sensory quality of the products. In recent research, Martin-Diana et al. (2008) found that green tea extract can be used as a preservative treatment for fresh-cut lettuce with better prevention of ascorbic acid and carotenoid loss.

Physical Preservation Techniques for Fresh-Cut Vegetables

There are many physical methods that have been researched to reduce the microbial load in fresh-cut vegetables, including modifie atmosphere packaging (MAP), UV light, irradiation, high pressure processing, and ultrasonics. Among these techniques, MAP has been widely used commercially.

Modified Atmosphere Packaging

Modifie atmosphere packaging (MAP) is an effective tool used in the fresh-cut industry to extend shelf life by altering the gases in the package to produce a composition different from that of air (Al-Ati and Joseph 2002). Decreasing oxygen (O_2) while simultaneously increasing carbon dioxide (CO_2) can slow the rate of respiration of fresh-cut

vegetables. Consequently, senescence is delayed, thus extending the storage life of fresh-cut vegetables. MAP can be classifie as passively MAP and actively MAP. In passively MAP the package is sealed under normal air conditions, whereas in the actively MAP the package is flushe with a gas mixture before closing. After sealing, the gas composition is not further controlled and the composition unavoidably changes due to produce respiration and gas permeability of package film (Sivertsvik et al. 2002).

There is about 21% O_2 in air. As the concentration of O_2 inside the package falls below about 10%, respiration starts to slow and continues until O_2 level reaches approximately 2–4% for most produce. When O_2 is lower than 2–4% (depending on product and temperature), fermentative metabolism replaces normal aerobic metabolism, resulting in the production of off-fl vors, off-odors, and undesirable volatiles such as ethanol and acetaldehyde. Simultaneously as CO_2 increases above the 0.03% found in air, a suppression of respiration results for some commodities. In addition, elevated CO_2 suppresses plant tissue sensitivity to the effects of ethylene. Using MAP also reduces the growth of spoilage microorganisms, extending the shelf life compared to normal air environment, and slows the growth of pathogenic bacteria (Rosnes et al. 2003). For those products that can tolerate high concentrations of CO_2, suppression of the growth of many bacteria and fungi results at $>$10% CO_2.

Accumulation of water inside the package is a problem of MAP. This condition enhances condensation on the fil and on the package contents. The presence of water may promote the development of spoilage and also block O_2 diffusion into the tissues and through the film causing fermentation (Cameron et al. 1995). Thus, selecting packaging film that match the oxygen movement through the fil to the respiration rate of the product being packaged plays an important role in developing MAP. Packaging material of fil should be carefully considered to provide appropriate oxygen and carbon dioxide transmission of the products. Moreover, fluctuatin temperatures encountered during postharvest handling can have negative impacts on the quality of products in MAP due to the danger of reaching injurious levels of O_2 or CO_2 (Tano et al. 1999). It is also possible for O_2 and CO_2 levels to become inadequate to control microbial growth and development or even to favor microbial proliferation when the temperature increases.

UV Light

Ultraviolet (UV) light is a type of nonionizing radiation with wavelength from 100 nm to 400 nm, which is usually classifie into three types: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm). UV-C radiation at 254 nm has the highest germicidal action (Bintis et al. 2000). UV destroys microorganisms by directly damaging DNA and indirectly inducing resistance mechanisms in vegetables against pathogens. Exposure to UV also induces the synthesis of health-promoting compounds such as anthocyanins and stilbenoids in plants (Cantos et al. 2001). Moreover, this technique is relatively inexpensive and easy to use.

Many studies reveal the appropriate results from the use of UV light to reduce microbial load in fresh-cut vegetables. Erkan et al. (2001) reported a reduction of microbial activity and deterioration of zucchini slices after exposure to UV-C. Allende and Artes (2003) also found that the use of UV-C decreased the growth of psychrotrophic bacteria, coliform, and yeast of "Lollo Rosso" lettuce (*Lactuca sativa*) and "Red Oak Leaf" lettuce without adversely affecting sensory quality. UV-C radiation seemed to stimulate the growth of lactic acid bacteria, probably due to reduced growth of competitive flora and the use of two-sided UV-C is effective in reducing the natural microflor and extending the shelf life of lettuce (Allende et al. 2006). The UV-C treatment not only reduced

deterioration of peppers, but treated peppers also had firme texture and contained lower carotenoid content. Moreover, UV-C treatments reduced chilling injury (Vicente et al. 2005). Gomez-Lopez et al. (2005) reported that log reductions of 0.54 and 0.46 for aerobic psychrotrophic count were achieved after flashin MP cabbage and lettuce with UV-C, respectively. For the destruction of pathogen, Yaun et al. (2004) illustrated that ultraviolet energy at a wavelength of 253.7 nm (UV-C) reduced 3.3 logs and 2.2 logs in tomatoes and 2.79 logs and 2.65 logs in green leaf lettuce for *E. coli* O157:H7 and of *Salmonella* sp., respectively.

However, high UV doses can cause damage to the treated tissue. Allende and Artes (2003) found that the application of UV-C increased the respiration rate of lettuce. Furthermore, there are some interfering factors in UV effica y on water disinfection, including turbidity, suspended solids, and absorbing compounds. For this reason, the combination use of O_3 and UV process has been developed (Selma et al. 2006; Selma et al. 2007). The turbidity of wash water was reduced allowing less frequent change of water and the use of much lower sanitizer doses (Selma et al. 2008). Additionally, the combined treatments with hot air and UV-C were applied to minimally processed broccoli (*Brassica oleracea* L.) floret (Lemoine et al. 2008). Treatment at 48°C combined with a UV-C dose of 8 kJm^{-2} delayed postharvest senescence of minimally processed broccoli stored at 20°C.

Irradiation

Low-dose ionizing radiation has been considered to extend the shelf life of fresh-cut vegetables. Hagenmaier and Baker (1997) reported that irradiation at a mean dosage of 0.19 kGy of commercially prepared fresh-cut lettuce resulted in 3 logs and 2 logs reduction of total plate, and yeast and mold counts, respectively, after 8 days of storage. Lopez et al. (2005) studied the irradiation of fresh-cut celery and cabbage with 1 kGy. They found a reduction of 4.7 logs and 3.8 logs for total plate and Enterobacteriaceae counts respectively in celery; and a decrease of 3.8 logs and 3.6 logs in cabbage for total plate and Enterobacteriaceae counts, respectively. Irradiation also reduced the number of *Salmonella* in alfalfa sprout (Rajkowski and Thayer 2000) and *E. coli* in fresh-cut celery (Lu et al. 2005). In addition, irradiation improved some qualities of fresh-cut vegetables. Lu et al. (2005) reported that polyphenol oxidase and respiration rate of irradiated fresh-cut celery were much inhibited and lower than those of nonirradiated. The vitamin C, soluble solids, total sugars, and sensory quality of irradiated celery were also better than those of nonirradiated. Fan (2005) revealed that irradiation increased the phenolic content and antioxidant capacity of romaine and iceberg lettuce, but some adverse visual quality changes were encountered. The irradiated broccoli was also highly accepted by the panelists with scores of 5 and above (Gomes et al. 2008).

High Pressure Processing

High pressure processing (HPP) is a nonthermal advanced food processing technology. HPP provides several benefits minimal heat damage problems; freshness; and retention of fl vor and vitamins. Moreover, the use of very high hydrostatic pressure (up to 700 MPa) results in the destruction of foodborne microorganisms and enzymes involved in food spoilage (Bayindirli et al. 2006). Neetoo and Chen (2008, 2009) revealed that pressurization of alfalfa seed eliminated the risk of *E. coli* O157:H7 infections associated with consumption of raw alfalfa sprouts. Pressurization at 500 MPa and 600 MPa reduced the number of *E. coli* O157:H7 by 3.5 logs and 5.7 logs, respectively, with the germination rate of 91%, which was 4% lower than that of the untreated seeds.

Nevertheless, HPP can sometimes affect the qualities of fresh-cut vegetables, because

the tissue of vegetables is tender and can be easily damaged. Opatova et al. (2003) reported that although in treating cut cabbage and carrot, the application of 500 MPa led to total microbial inactivation, it caused changes in appearance and texture during two-week storage. On the other hand, Xu et al. (2003) showed that in high pressure treated vegetables, pathogenic microorganisms were inactivated and the treatment had little negative effect on nutritional and sensory characteristics. Moreover, Xu and Han (2006) illustrated that the texture and tissue of fresh-cut carrot treated with 400 MPa for 20 minutes or 500 MPa for 5 minutes were not damaged, which was similar to the results obtained by Xu (2005) for fresh-cut tomatoes.

Ultrasonic

Ultrasound technology is a nondestructive, fast, and reliable technique used in the food industry for extending shelf life (Mizrach 2008). Power ultrasound, 20–100 kHz, has a potential application to fresh produce decontamination. To ensure the inactivation of the most resistant microorganisms, high-power ultrasound is required as single treatment but the effect on food quality may be negative. The use of ultrasonication in combination with chlorine showed a reduction of 2.7 logs of *S. typhimurium* in iceberg lettuce, which was higher than using ultrasound alone, because it helped the release of microorganisms from difficul access locations in the vegetables (Seymour et al. 2002). However, Abreu et al. (2005) reported that the effect of a combination of ultrasonic and chlorine on yeast and molds in shredded carrots was similar to treatment with chlorine alone.

Conclusion and Future Trend

The safety of fresh-cut vegetables is a big concern in spite of the rising demand for this type of vegetables. Research is needed to develop or use new chemical treatments, such as bacteriocin and neutral electrolyzed water, and physical technology, such as ultrasonication and high pressure processing, to produce nutritive, high-sensory quality, and safe fresh-cut vegetables. The technology for removal of microorganisms is not cost-effective, resulting in the use of chemicals such as chlorine which is relatively known and cheaper. However, as discussed, there are limitations to the use of chlorine. Thus, it is important that further work continues in the development and testing of new techniques such as high pressure processing, UV treatments, and electrolyzed water.

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Chapter 11

Principles of Vegetable Canning

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Introduction

Botanically diverse vegetables are seasonal, regional, and highly perishable commodities due to high moisture (>80%). Traditional preservation techniques such as freezing, canning, and drying are aimed at inhibiting chemical, enzymatic, and microbial changes to minimize spoilage and extend the shelf life of fresh vegetables. The origin of canning dates back to the eighteenth century when Nicholas Appert, regarded as the "Father of canning," practiced heating sealed containers of foods (from which air has been removed) in boiling water as a means of preservation. Later, Louis Pasteur showed the relationship between temperature and microbial inactivation. In the early twentieth century, scientists in the United States established the foundations for commercial operations and developed retort process for canning. In the United States, the popularity of canned vegetables is second only to fresh vegetables and forms an integral part of vegetable production and utilization. Many new forms and varieties of canned vegetables, such as organic and low sodium, tailored to market needs are beginning to emerge to attract interest in this category. However, the canning industry is challenged by the perception of being producers of cheap commodities, and environmental concerns due to high water use and disposal of tin cans, etc. In this chapter we discuss the consumption, thermal processing principles, processing, and quality including nutritional quality aspects of vegetable canning.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Consumption of Canned Vegetables

As has been mentioned elsewhere in this book, consumption of vegetables that are low in calories, fat, and sugar, but high in fibe and important minerals and vitamins is recommended to minimize the risk of chronic diseases. Canned vegetables are peeled, cut, heat-processed, and ready-to-use products. If unopened, canned vegetables do not require refrigerated storage. The canning process thus enables safe and affordable vegetables. In the United States the average per capita use of fresh, canned, and frozen vegetables (excluding potatoes) during 2000 to 2008 was approximately 59%, 33%, and 7%, respectively (USDA, 2009). Figure 11.1 shows the trend in canned vegetable use in the United States. Canned tomatoes were the most consumed vegetables (in 2008, 67.2 lb), followed by sweet corn (6.8 lb), snap beans (3.3 lb), and carrots (1.6 lb).

Vegetable Canning

Low-Acid Food and the Microorganism of Concern

Microorganisms grow well around neutral pH of 7.0, but below pH 4.0 few (exceptions, yeast and mold) can grow. Most vegetables have pH >4.6 and are considered low-acid foods (Table 11.1). As a result, vegetables

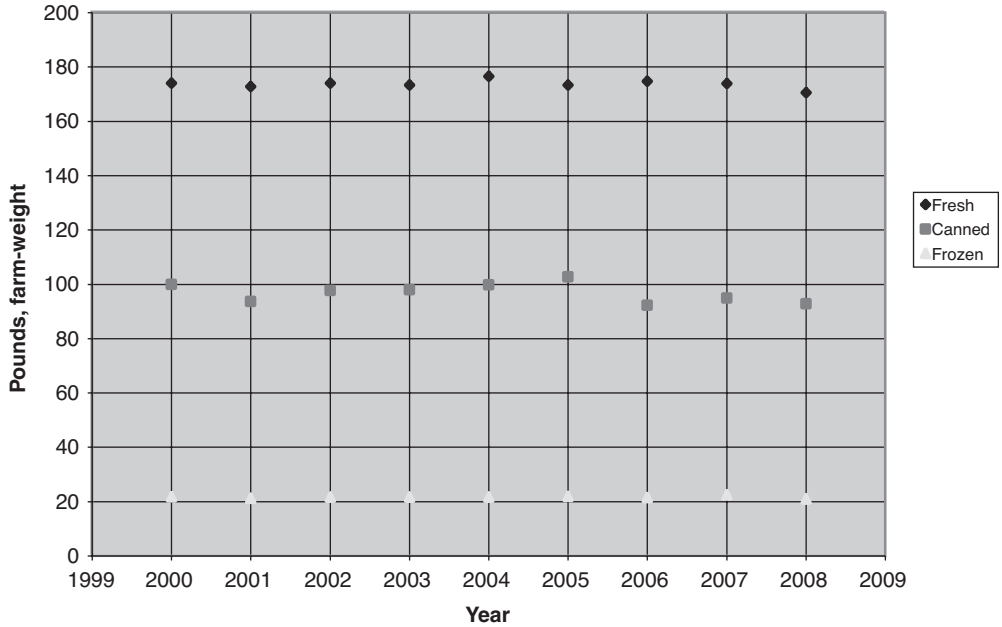

Figure 11.1 US per capita use of commercially produced fresh and processed vegetables.

Table 11.1 pH values of selected vegetables

Vegetable	pH
Artichokes	5.6
Canned	5.7–6.0
Asparagus	4.0–6.0
Canned	5.2–5.3
Beans	5.7–6.2
String	4.6
Lima	6.5
Kidney	5.4–6.0
Beets	4.0–5.6
Broccoli	5.2–6.0
Brussels sprouts	6.0–6.3
Cabbage	5.2–6.0
Carrots	4.9–5.2
Caulifl wer	5.6
Celery	5.7–6.0
Corn	6.0–7.5
Mushroom (cooked)	6.2
Onion	5.3–5.8
Peas	5.8–7.0
Pepper	5.15
Pumpkin	4.8-5.2
Sauerkraut	3.4–3.6
Spinach	5.5–6.8
Tomatoes (whole)	4.2–4.9
Canned	3.5–4.7

Source: http://www.fda.gov/food/foodsafety, Accessed on October 14, 2009.

are good candidates for growth of spoilage and pathogenic organisms. Canning of vegetables therefore requires special thermal processing considerations. The chief microorganism of concern in canned vegetables is *Clostridium botulinum* (*C. botulinum*), an anaerobic, Gram-positive, spore-forming microorganism that produces a deadly neurotoxin (botulism is a lethal paralytic illness) and can grow in low-salt and low-acid environment. This microorganism is inhibited by heating above 121°C. The toxin produced by *C. botulinum* is destroyed by heating to 85°C for at least 5 minutes, but the botulinum spores are heat stable and can be inactivated only by heating to 121°C under pressure of 15–20 lb/in^2 for at least 20 minutes. Low storage temperature (4°C) and high acid conditions (pH <4.5) inhibit growth of *C. botulinum* (Sobel et al. 2004). Unfortunately we cannot acidify vegetables before canning as it has a negative effect on the color of green vegetables.

Commercial Sterility

The term sterility signifie total destruction of all microorganisms within a medium. However, "commercial sterility" is often used in the context of canned or aseptically processed products to indicate that microorganisms related to food spoilage and public health concerns have been destroyed. According to the Food and Drug Administration's (FDA) code of federal regulations (21 CFR 11.3), "commercial sterility" of thermally processed food in hermitically sealed container means the conditions achieved:

(i) by the application of heat which renders the food free of:
   (a) microorganisms capable of reproducing in the food under normal nonrefrigerated conditions of storage and distribution; and
   (b) viable microorganisms (including spores) of public health significance or

(ii) by the control of water activity and application of heat, which render the food free of microorganisms capable of reproducing in the food under normal nonrefrigerated conditions of storage and distribution.

The FDA regulations further emphasize that in the case of low-acid foods such as vegetables which have pH values above 4.6, a "validated temperature-time" of heating established by qualifie persons having "expert knowledge of thermal processing requirements" be followed. The spores of putrefactive anaerobe 3679 (PA 3679) which are nontoxic but more heat resistant than the spores of *C. botulinum* are used as the test organism to evaluate "commercial sterility" (Pflu and Esselen 1979).

Thermal Process Considerations

Thermal treatment is the most common process in the food industry to enable microbiologically safe food. The appropriate heating temperature and holding time for processing of foods in hermetically sealed cans is aimed at destroying microorganisms that cause spoilage and foodborne illness. Minimum safe sterilization process was firs introduced in 1920 (Bigelow et al. 1920). Since then, the food industry has confidentl produced safe canned food for our use. The sterilization process takes into consideration the microbiological characteristics of the product and the storage requirements after the process. A heat-resistant microorganism is selected and its kinetics of inactivation is determined in the product to be processed. While high heat can kill microorganisms, in most cases it also has an adverse effect on the overall quality of the product. Most of the nutrients and nutraceutical compounds would be affected by high processing temperatures. Consumers are concerned with the quality and nutritive value of products and this has been a driving force for optimization of processing conditions, such as heating temperature and time, to balance safety and quality aspects of canning.

Thermal Death Time Curve

The thermal death time (TDT) corresponds to the inactivation of microorganisms at a given heating schedule; the inactivated microorganisms should not show growth in a subculture media. It is necessary to understand the decimal reduction time, generally recognized as D value, of microbial destruction before determining TDT. The D value is the time required to reduce the population of the microorganism by 90%. As shown in Figure 11.2, the number of microorganisms reduced from 10^5 to 10^4 CFU/ml (CFU is colony forming unit), and hence it represents 1D, or 1 decimal reduction in microbial population. Similarly, a 3D value represents a microbial reduction from 10^5 to 10^2 CFU/ml. The time required for microbial destruction at a lethal temperature can be given by:

$$t = D \log(N_o/N_t) \qquad (11.1)$$

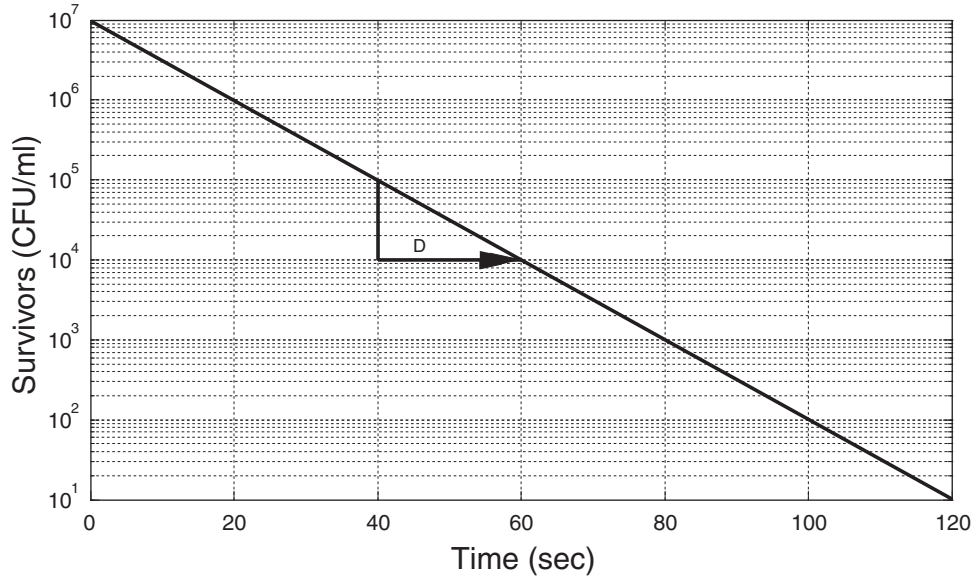

Figure 11.2 D value shown on a survivor curve for a constant lethal temperature.

where D is the decimal reduction time, N_o is initial microbial population, and N_t is population at time t. The total time required for a stated reduction in microbial (vegetative cells and spores) population is expressed as thermal death time. Thermal death time might be expressed as multiples of D values. Processing of low-acid foods should have a margin of safety and this is accomplished by having a thermal death time of 12D, also known as "12D" process, where D value represents for *C. botulinum.* A typical thermal death time curve is shown in Figure 11.3.

Thermal death time can be expressed by:

$$\log\left(D_{T_2}/D_{T_1}\right) = \left(-1/z\right)(T_2 - T_1) \tag{11.2}$$

where T is temperature and z is temperature range required to change D tenfolds.

The slope of the TDT curve is $-1/z$ where z relates to the effect of temperature on the destruction time. A z value of 10°C, as shown in Figure 11.3, shows that for a temperature increase of 10°C, the reduction in time is tenfold. Hence, highly temperature-sensitive microorganisms will have lower z values. Thermal death time is given by F value, which is specifi for particular organism and temperature. F value is usually represented with z value as superscript and temperature as subscript. For example, if a microorganism has a z value of 10°C and at a reference temperature of 121°C, then F value can be represented as F_{121}^{10}. D value for the most resistant spore of *C. botulinum* is about 0.21 minutes at the reference temperature of 121°C. A 12D process for this microorganism would be 12×0.21 minutes or 2.52 minutes at 121°C. For example, if a can contains one spore of *C. botulinum*, then using a D value of 0.21 minutes and time 2.52 minutes, we can calculate the number of survivors using equation (11.1), which is:

$$2.52 = 0.21 \log(1/N_t) \tag{11.3}$$

or $N_t = 10^{-12}$, and this means that there is probability of survival of one *C. botulinum* in 10^{12}; this is also referred to as "botulinum cook."

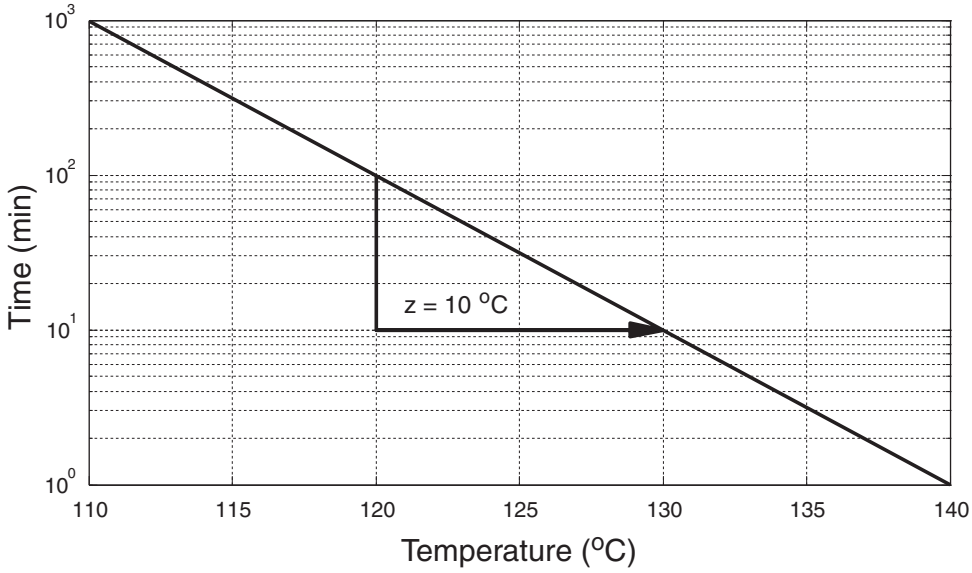

Figure 11.3 A typical thermal death time (TDT) curve.

Heat Transfer

The unsteady state heat transfer is the key mechanism during thermal processing of cans. The temperature inside the cans varies with position and time. Determining the time-temperature profil using basic theory of heat transfer provides insight into the thermal processing of canned food. Mathematical description of the problem requires initial temperature condition of the product inside the can, outer surface boundary conditions, and thermo-physical properties of the product. There are two modes of heat transfer that occur during heating of a can: (1) conduction and (2) convection. The outer surface of the can experiences heating from different media such as steam, water, and air, or combination of any two media. Heat is transferred from the media to the surface of the can through convection. The heat transfer from the container wall into the product depends on the product type. Conduction is the main mode of heat transfer if the product is solid or semi-solid. However, if the product is a mixture of solid and liquid, then the heat transfer is governed by a combination of conduction and convection.

An example of the heat transfer in conduction-heated product is presented in Figure 11.4, which represents a can of cylindrical shape. Since the can is cylindrical, a representative temperature profil will be at the cross section along the longitudinal axis. This cross section will be rectangular in shape with width and length equal to diameter and height of the can, respectively. This rectangle is symmetric at its longitudinal axis and hence half of this rectangle can be modeled to get temperature profile Even though the can is three-dimensional, the problem is now simplifie to a 2D axisymmetric problem, since the can is symmetrical on both sides of the central axis.

The heat transfer equation for axisymmetric case can be written as:

$$\left[\frac{1}{r}\frac{\partial}{\partial r}\left(k(T)r\frac{\partial T}{\partial r}\right)+k(T)\frac{\partial^2 T}{\partial z^2}\right] = \rho C_p(T)\frac{\partial T}{\partial t} \qquad (11.4)$$

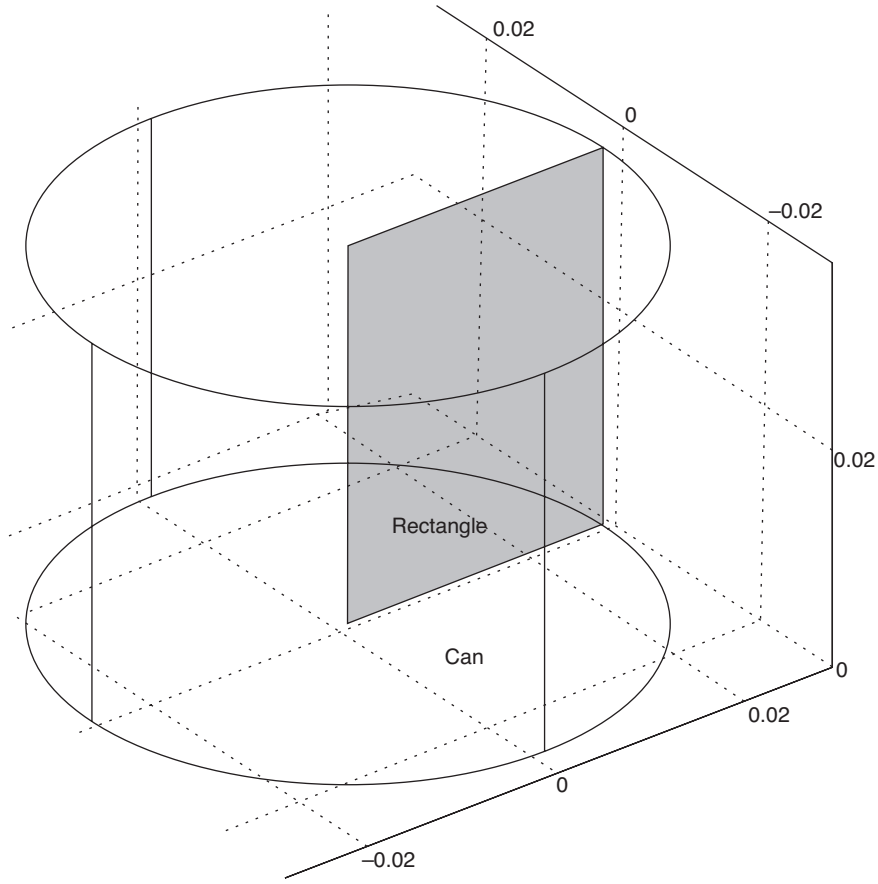

Figure 11.4 Three-dimensional picture of a can (202×214) and half cross-sectional profile (rectangle).

where k is thermal conductivity of food material, ρ is density, and C_p is specifi heat. r and z are dimensionless radius and height of the can, respectively. Here thermal conductivity and specifi heat are modeled as a function of temperature. A constant value of thermal parameters can also be provided in a similar way. The typical governing boundary conditions are used in this example. Axisymmetry boundary condition is given by equations (11.5) and (11.6).

$$\frac{\partial T}{\partial r}(0, z, t) = 0 \tag{11.5}$$

$$\frac{\partial T}{\partial z}(r, 0, t) = 0 \tag{11.6}$$

Initial condition of the product can be provided as given in equation (11.7):

$$T(r, z, 0) = T_i \tag{11.7}$$

Convective boundary condition at the surface of the can:

$$-k(T)\frac{\partial T}{\partial r}(R, z, t) = h(-T(R, z, t) + T_\infty) \tag{11.8}$$

$$-k(T)\frac{\partial T}{\partial z}(r, H, t) = h(-T(r, H, t) + T_\infty) \tag{11.9}$$

Using steam as heating medium with high heat transfer coefficien (h), the heat transfer

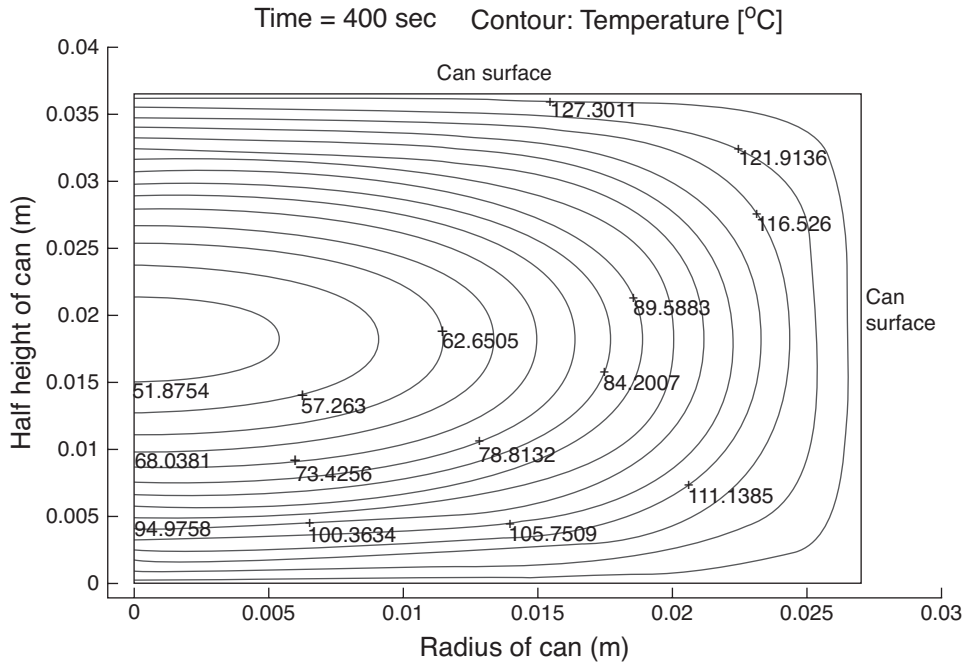

Figure 11.5 Solution of the heat transfer problem described by equation (11.4).

to the surface of can is rapid. Solution to the partial differential equation (11.4) can be found in standard textbooks (Carslaw and Jaeger 1986; Ozisik 1993). Numerical method such as finit difference or finit element can also be used to solve the transient heat conduction problem. The solution to the above example is shown in Figure 11.5. The solution is provided for earlier time in the process to show the clarity of temperature profile The temperature at various points inside a can is plotted in Figure 11.6. The slowest heating point is at the center of the can. A thermocouple is placed at the center of the can to monitor the temperature during thermal process. However, if the above-mentioned model is used to predict the temperature, it will most likely have inaccurate temperature prediction. This is because the effect of thermocouple is neglected in the model. Hence, in order to compare the results of experimental data with the predicted data, error due to thermocouple and position of thermocouple should be considered.

Lethal Rate

The general method for the lethal rate introduced by Bigelow et al. (1920) forms the basis for modern thermal process calculations. In order to calculate the process time for a product, thermal death time (F) should be known at all temperatures at which the product has been exposed. Equation (11.2) for the thermal death time relating to temperature can be written in the form of F notation as

$$\log\left(F_r/F\right) = \left(1/z\right)(T - T_r) \qquad (11.10)$$

which can be expressed as:

$$F_r/F = 10^{\left(1/z\right)(T-T_r)} \qquad (11.11)$$

Thermal death time F_r is calculated at a reference temperature T_r. The ratio F_r/F is called

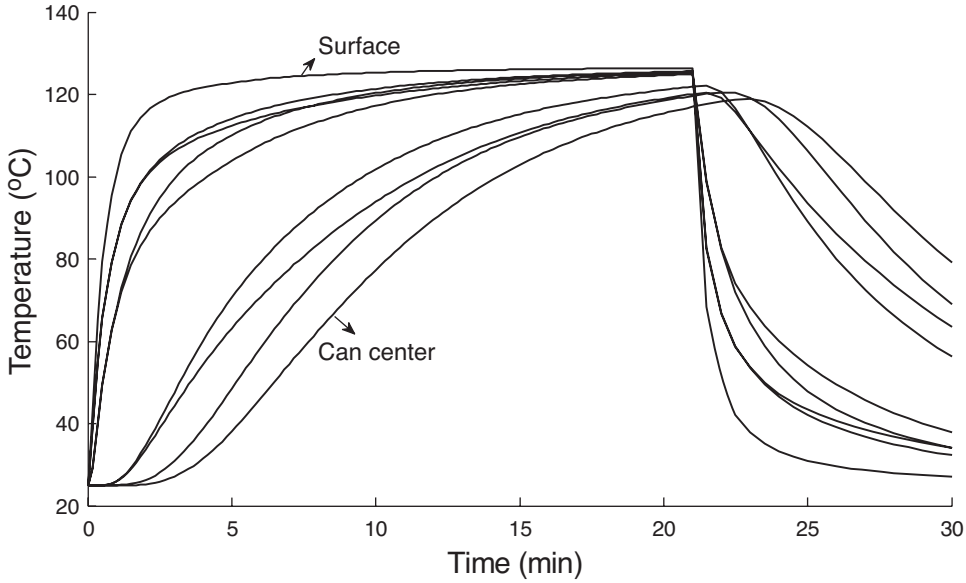

Figure 11.6 Temperature at various points inside a can heated by conduction.

lethal rate and is expressed as L (Ball 1923).

$$L = 10^{\left(1/z\right)(T-T_r)} \tag{11.12}$$

L is calculated at each temperature T, and lethal rate can be plotted against time as shown in Figure 11.7. The total area under the lethal rate curve can be obtained by

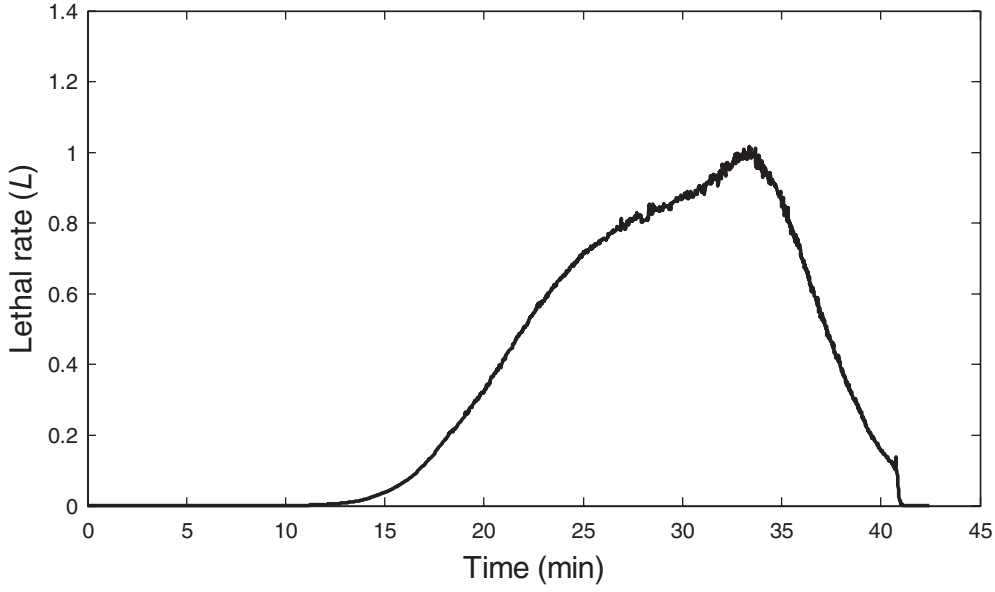

Figure 11.7 Lethal rate curve as calculated using equation (11.12).

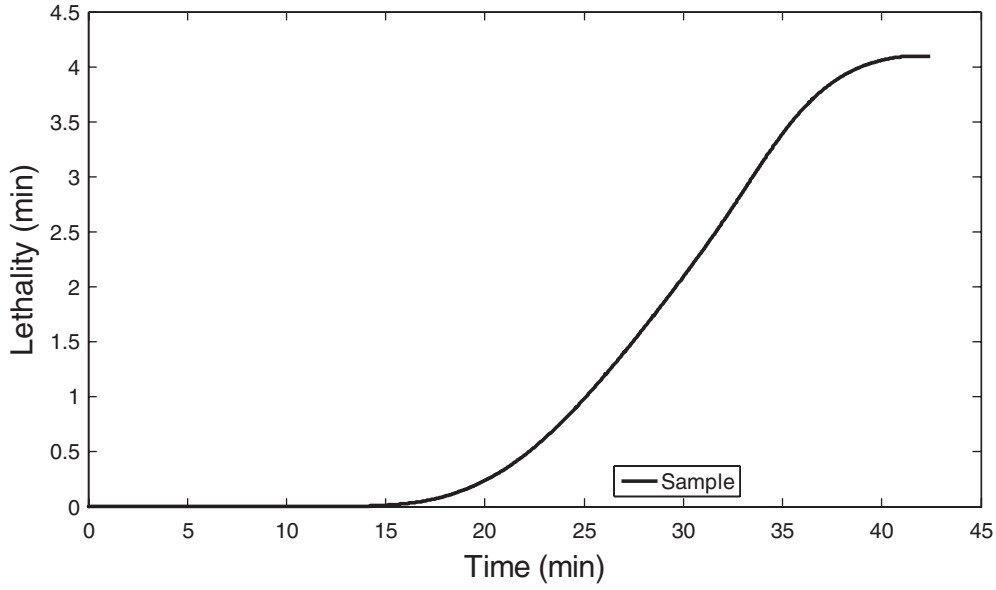

Figure 11.8 Lethality plot, lethality value calculated using equation (11.13).

integrating the curve over the time-temperature history and is referred to as lethality (F) (Patashnik 1953). F can be expressed as:

$$F = \int_0^t 10^{\left(1/z\right)(T-T_r)} \qquad (11.13)$$

where t is the total process time. An example plot of lethality versus time is shown in Figure 11.8. The process lethality calculated based on equation (11.13) must match the anticipated lethality for the specifi product in order to determine the process time.

Formula Method

The formula method (Ball 1923) was developed because of the deficien y of general method to determine process time indirectly. The formula method uses heat penetration data in parametric form to determine process time. This method is faster than the general method and can be used to study the effect of process variables. The equation is derived from the heat penetration curve.

$$B = f_h \log\left(j_h I_h / g\right) \qquad (11.14)$$

B is the process time and can be calculated by using the values of: (1) f_h, slope of the heating line; (2) j_h, the lag factor $(T_r - T_{pih})/(T_r - T_{ih})$; (3) I_h, initial temperature difference $(T_r - T_{ih})$; (4) g_c, retort temperature (T_r) minus cold spot temperature at the end of heating $(T_r - T)$. T_{ih} is the initial product temperature, T_{pih} is pseudo-initial product temperature, and T_r is retort temperature. The term g in equation (11.14) is evaluated based on a relationship with f_h/U.

$$U = F_o F^z_{121.1} \qquad (11.15)$$

where

$$F^z_{121.1} = 10^{(121.1 - T_r)/z} \qquad (11.16)$$

$F^z_{121.1}$ is number of minutes at the retort temperature and it is equivalent to 1 minute at 121.1°C.

Kinetics

Thermal destruction kinetics is important in order to characterize the thermal process for a specifi product. Kinetics can be define as the study of rate of reaction which varies with several factors such as moisture, pH, temperature, concentration, and other processing factors. The reaction rate equation is given as:

$$-\frac{dC}{dt} = kC^n \tag{11.17}$$

where C is concentration of the compound, n is reaction order, and k is rate constant (min^{-1}). The relationship between k and temperature is generally modeled by the Arrhenius Equation:

$$k = k_r e^{\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \tag{11.18}$$

where E_a is activation energy (J/g-mol), k_r is rate constant at reference temperature T_r, and R is gas constant (J/g-mole K). The use of a reference temperature T_r ensures that the correlation between K_r and E_a is not infinit . T_r can be set to average value of temperature range used in experiments (Van Boekel 1996). Alternatively, the value of T_r can be optimized by using inverse problem to get a best estimate of T_r (Schwaab and Pinto 2007).

Most reactions in food, such as nutrient retention, quality factors, and microorganism destruction follow a firs order reaction kinetics. Hence, for a firs order (n = 1) reaction, equation (11.17) can be:

$$C/C_o = e^{-k_r \beta} \tag{11.19}$$

where β is the time temperature history and is the integrated value of temperature *T(t)* over the entire time domain.

$$\beta = \int_0^t e^{\frac{-E_a}{R}\left(\frac{1}{T(t)}-\frac{1}{T_r}\right)} dt \tag{11.20}$$

Retention can be calculated for any product by using equation (11.19) provided that the kinetic parameters for particular compound (k_r and E_a) are known. For microorganism inactivation, similar expression can be used with the parameters D and z, where D can be represented by the following equation:

$$D = D_o 10^{\left((T_o - T)/z\right)} \tag{11.21}$$

Various techniques are available for evaluation of thermal destruction kinetics of microorganisms. Traditional use of isothermal method for kinetic parameter evaluation is a regular practice in the industry. The ln (C) is plotted versus time at different isothermal temperatures. Rate constant k can be obtained from this plot as a slope of the lines. The ln(k) can be plotted against *1/T* to obtain activation energy (slope of the line), E_a. However, if the plot of ln (C) versus time is not a straight line, then it can be considered *n*th-order reaction. In case of *n*th-order reaction, $[C^{1-n}/(1-n)]$ can be considered with time and minimization of sum of squares will provide the order of reaction n. Some researchers have shown that the use of nonisothermal method instead of the traditional method (isothermal or 2-step regression) to evaluate the kinetic degradation parameters produces more reliable results as nonisothermal method is close to the real processing time of product (Dolan 2003; Peleg and Normand 2004; Valdramidis et al. 2008). The nonisothermal method or 1-step nonlinear regression can be performed on equation (11.19) to estimate kinetic parameters k_r and E_a using time-temperature history of the product. Nonisothermal method is usually suited for low-moisture products where uniform temperature cannot be achieved instantly.

Inoculated Pack

The validation of the process schedule and parameters derived mathematically is done through the inoculation pack tests. The product under consideration is inoculated with a certain number of heat-resistant microorganisms (such as PA 3679). The product is then processed under normal operating conditions for several combinations of time and

temperature that have been formulated using calculation methods discussed earlier in this chapter. After processing, the inoculated pack is incubated at a certain temperature that is favorable for the growth of inoculated microorganism. Inoculated pack is checked routinely for signs of microbial growth. The minimum time and temperature combination for an inoculated dose without any positive growth should be selected for the process schedule. This process time and temperature should correspond closely to the calculated process schedule.

Canning Process

Unit Operations

The typical unit operations in a canning plant are as below.

Washing

Field-harvested vegetables can contain soil, foreign materials, etc. Thorough washing removes soil and foreign materials, reduces the load of spoilage bacteria, and aids in sanitation. Cold water is used as it prevents leaching and protects the texture of vegetables. As bacterial population will increase in the wash water, its level is monitored.

Size Grading

Sorting is necessary to enable uniform product size. Different types of sorters such as revolving or vibrating type, or automatic sorters that sort the product based on their size or color can be used.

Peeling/Cutting

There are different types of peelers used for peeling fruits and vegetables. Mechanical peelers include steam peelers and abrasive peelers. Lye (caustic soda solution) peelers are used for peeling certain vegetables.

Blanching

Blanching is an important operation for vegetables in which air, water, or steam can be used to heat the product to about 88–99°C. As mentioned in the other chapters of this book, blanching is performed to: (1) inactivate enzymes responsible for quality degradation such as texture and color changes; (2) remove air from the raw vegetables which results in better packing inside the can and reduces chances of corrosion by reducing excess oxygen from the headspace; (3) prevent browning in certain products; (4) help to preheat the product before sealing; and (5) soften the food and make it easier to fil in containers. For blanching, the product can either be placed in hot water or be conveyed through belt and exposed to hot water or steam. Blanching of vegetable soybean at 100°C for 90 seconds reduced the initial lipoxygenase activity by 99% (Mozzoni et al. 2009). However, the blanching operation produces the major portion of the effluent in a canning plant. The use of microwave for blanching has potential to improve this situation.

Filling/Weighing

Prepared vegetables are placed into cans by means of a depositor. A depositor adds a predetermined quantity of products in each can followed by the addition of brine (NaCl and/or $CaCl_2$). The can is not completely filled leaving about 1 inch of headspace is important. Lower headspace can cause the ends of can to bulge and may also cause understerilization.

Exhausting and Vacuum Closing

Exhausting is a key step to maintain vacuum. In this process, fille cans are passed through an exhaust box containing water at about 90°C so as to bring the temperature of the center of the can to about 71°C. The exhausting expands products and expels trapped air and

gases. Vacuum closing helps to retain the container shape and prevents distortion during retorting; it maintains the concave position of the can and helps in reducing oxygen inside the can. Low level of oxygen prevents discoloration that might happen due to oxidation of fats or vitamins; it also reduces internal corrosion of the can. High-speed vacuum sealers draw the vacuum out of the headspace of can. The firs step in this process is to clinch the lid on the can without an air tight seal. Then the machine applies vacuum to remove air from the headspace of the container and then it is finall sealed with the second press rollers to get a double air tight seam.

Retort Process

Low-acid products (pH >4.6) are processed in retorts. Temperature inside a retort is usually 110–135°C, and depending on the type of retort, heating media can be water, steam, or steam with air. After the thermal treatment is completed, cans are cooled down to 30–40°C. At this point, cans are taken out of retort, labeled, and stored at room temperature. The room temperature should not exceed 30°C as it increases the chances of growth of thermophilic bacteria. Vegetable soybean (pH 6.5) can be processed with brine 150 g/L NaCl and 2.9 g/L $CaCl_2$ in a 6.83 cm diameter by 8.26 cm height can for 9 minutes at 121°C to achieve a lethality of 4 minutes. This treatment is enough to achieve a 12 log reduction (Mozzoni et al. 2009). Table 11.2 gives the typical temperature and time required for canning of selected vegetables.

Retort/Sterilizers

Different types of retort are based on batch or continuous operation. Further categorization of retorts is based on the use of heating media such as water, steam, and steam/air. Some of the commercially available retorts are discussed in this section.

Table 11.2 Temperature-time for canning of selected vegetables

Vegetables	Can size	Fill weight (ounces)	Fill weight (grams)	Initial temperature °F	Retort time (minutes) 240°F	Retort time (minutes) 250°F
Asparagus	300 × 407	9.7	275	70	26	15
	603 × 700	68	1928	70	43	25
Beets	303 × 406	11.7	332	140	36	25
	603 × 700	75	2126	140	45	31
Carrots (sliced)	303 × 406	11.6	329	140	30	20
	603 × 700	77	2183	140	37	23
Corn (whole kernel)	303 × 406	12	340	140	46	22
	603 × 700	76	2155	140	76	37
Corn creamed	303 × 406			140	95	72
	603 × 700			140	260	215
Green beans	303 × 406	10	284	120	20	11
	603 × 700	76	2155	120	30	19
Lima beans	303 × 406	9	255	120	37	17
	603 × 700	65	1843	120	63	20
Peas	303 × 406	11	312	140	35	17
	603 × 700	76	2155	140	52	23
Potatoes (whole)	300 × 407	10.5	298	50	39	27
	603 × 700	80	2268	140	50	32
Pumpkin	300 × 407			140	69	57
	603 × 700			140	240	210
Spinach	300 × 407	11.7	332	140	61	45
	603 × 700	66	1871	140	71	48

Source: Adapted from Downing (1996).

Static Retort: A static retort does not provide agitation to the can and they normally operate at 115.6°C to 121.1°C (240°F to 250°F). The cans are kept inside the retort and the retort is sealed. Pressure is build up in the retort for cooking after venting the air with steam. There is continuous supply of steam during the duration of cook. Vertical steam retort is a good example of static retort. Some retorts also use steam and air combination to achieve uniform temperature distribution. Water spray retorts circulate the stored water through pumps and spray it on cans. The water is then circulated through the heat exchanger where it is heated again by the steam. Cascading water fl w retorts use continuous fl w of heated water throughout the retort to maintain uniform temperature distribution.

Rotary Cookers: Rotating action or agitation to the can provides a better rate of heat transfer to the product inside the can and hence significantl reduces process time. Cans inside the retort can be rotated at a certain speed depending on the type of product. There are three phases of can rotation: (1) Fixed reel travel—cans are carried on a central axis for a distance of about 220 degrees around the periphery of the shell of retort; (2) Free rotation—cans roll freely on their central axis on a spiral tees at the lower portion of the shell for a distance of about 100 degrees; and (3) Transitional phase—this is the transition phase for the cans from free rotation to the fi ed reel travel (Downing 1996).

Continuous retorts: In this type of retort, cans are carried from one end of the retort to the other end along the surface of the retort. Sometimes agitation is also provided to improve heat transfer rate by inducing forced convection in the product inside the can. This system has advantages over the static or batch type systems in terms of time and energy. Steriflamm process is a continuous cooker and utilizes direct flam (1093.3°C, or 2000°F) on rolling cans (80 rpm) for predetermined time (Ramaswamy and Marcotte 2006). Cans are packaged under high vacuum and are brought up to an initial temperature of 100°C/212°F before processing with flame This system is suitable for processing small cans.

Hydrostatic pressure sterilizers: This is also a continuous type retort system in which steam pressure is maintained by the water pressure. There are four chambers in hydrostatic cookers, a come-up leg, sterilizing chamber, a hydrostatic come-down leg, and a cooling system. It uses large columns of water as a feed system for cans inside the high pressure steam chamber of the cooker. Cans are placed horizontally on a moving chain which carries cans through the legs into the sterilization chamber. Processing time is determined by the chain speed and the temperature of the chamber. This system is suitable for large volume productions and it can also handle various sizes of cans and jars. The major advantages of such a system include savings in floo space, high volume operation, and reduction in steam and water cost.

Metal Containers

Usually, the dimension of a can is expressed with two numbers with three digits each. The firs digit represents whole inch while the other two digits represent fractional unit in sixteenth of an inch. The firs three-digit number is the diameter of the can whereas the second three-digit number is can height. For example, a can with dimension 202×214 would have a diameter of 2 2/16 inch and height 2 14/16 inch. There are several types of containers available which can be used in place of cans. Plastic pouches and trays have gained importance in the industry because of convenience, cost, and environmental considerations.

Quality of Canned Vegetables

Sensory Quality and Standards for Canned Vegetables

Besides safety, the quality of canned vegetables in terms of color, texture, and fl vor

is important to consumers. The quality of canned vegetables starts with proper selection of raw material (variety, maturity, composition, etc.) to be processed. Further, proper postharvest handling and storage are important to maintain sensory qualities. Most often, the canning plants are situated closer to growing locations so as to facilitate canning of freshly harvested produce without loss of quality. Processors typically contract growers for supplying specifie quality raw materials for canning. In many instances they would specify the exact variety, Brix, tenderness, maturity and size, color, defects, etc., that they would allow in their canned products.

The canned vegetables are evaluated for color, uniformity of size and shape, absence of defects, texture, character, and, for some canned vegetables like snap beans, clarity of the liquor. While evaluating a canned vegetable, record is kept for container size, code, net weight, vacuum (inches), headspace (inches), drained weight, and drained weight/put-in weight ratio.

The USDA's Agriculture Marketing Service has published a commodity specificatio for canned vegetables (USDA 2009) giving details of grades, labeling, packaging, Universal Product Code (UPC), etc. For example, USDA Grade A or "Fancy" canned vegetables signify vegetables that are carefully picked for color, tenderness, and freedom from blemishes. The USDA Grade B is of excellent quality but not quite as well selected for color and tenderness as Grade A. The Grade C vegetables are not as uniform in color and fl vor as Grades A and B. These products can be used in soups, stews, casseroles, etc., where appearance is not critical. The US FDA's Code of Federal Regulation (CFR) 21: Part 155 gives specifi requirements for canned vegetables in terms of minimum fil weight (90% of the water capacity of the container), minimum drained weight (should not be less than 50% of the net weight), acceptable quality level (AQL), etc.

Nutritional Quality

A comparative nutritional profil of selected raw and canned vegetables per 100 grams is given in Table 11.3. As expected, the canning process has an effect on vitamin C (42–90%

Table 11.3 Comparative selected nutritional values of some raw and corresponding canned vegetables

	Tomato		Sweet corn		Green snap beans	
Nutrients/100 grams	Raw	Canned NDB-11885	Raw NDB-11167	Canned NDB-11172	Raw NDB-11052	Canned NDB-11056
Calories	16	17	86	81	31	23
% Moisture	94.78	94.28	76.05	76.71	90.32	93.29
Total fat (g)	0.19	0.13	1.35	0.93	0.22	0.11
Protein (g)	1.16	0.78	3.27	2.64	1.83	1.18
Total carbohydrate (g)	3.18	4	18.7	18.8	6.97	4.41
Dietary fibe (g)	0.9	1	2	1.9	2.7	2.3
Sugar (g)	NA	2.38	6.26	3.04	3.26	0.78
Vitamin A (IU)	1496	117	187	45	690	353
Vitamin C (mg)	16	9.3	7	0.7	12.2	4.3
Niacin (mg)	0.593	0.712	1.77	0.375	0.734	0.202
Calcium (mg)	5	31	2	5	37	28
Iron (mg)	0.47	0.97	0.52	0.72	1.03	0.87
Potassium (mg)	212	188	270	135	211	111

Source: USDA: http://www.nal/usda.gov/fnic/foodcomposition (accessed on October 2, 2009).

loss) and vitamin A (49–92% loss). In case of niacin the data shows about 80% loss in canned sweet corn and green beans but about 20% gain in canned tomatoes. The loss in potassium is 12–50%. The fibe content of canned vegetables is close to the raw. The major nutrients (carbohydrates, fat, and protein) and calorie values are also comparable to the corresponding raw vegetables.

Rickman et al.'s (2007) review of nutritional data of fresh and processed fruits and vegetables showed that depending on commodity, freezing and canning processes preserve nutrient value. They indicated that although the initial thermal treatment can cause loss of water-soluble and oxygen-labile nutrients such as vitamin C and the B vitamins, these nutrients are relatively stable in canned vegetables during storage due to absence of oxygen.

Spoilage of Canned Vegetables

In spite of thermal processing to destroy microorganisms, canned vegetables undergo microbial spoilage as a result of faulty can sealing, underprocessing, inadequate cooling, contamination, etc. These products with a pH >4.6 can be spoiled by thermophilic fla sour microorganisms (e.g., B. Coagulans), sulfid spoilers (clostridium nigrificans) and/or gaseous spoilers. Mesophilic spoilers include putrefactive anaerobe (especially, PA 3679) (Jay et al. 2005).

In canned vegetables, visual signs of any dent, off-odor, leakage, mold, etc., should be of concern and defective cans of vegetables should never be taste tested. Defects like hard swell (can ends are swollen hard to be readily depressed indicative of gas formed in the can) are not acceptable and such containers should be properly disposed off. The other terminology for defective cans is "flip per" (one end of the can is slightly bulged) and "springer" (cans with faulty double seam).

Conclusion

Canned vegetables can be a source of safe, nutritive, and shelf-stable vegetables throughout the year. This chapter provides an overview of the important aspects of vegetable canning in terms of pH, microbiological, and thermal process considerations. The appropriate selection of temperature and holding time for canning a vegetable is critical to ensure public safety. The vegetable canning industry is strictly controlled through various regulations to prevent defective products from reaching the consumers.

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Chapter 12

Refrigeration and Freezing Preservation of Vegetables

Kasiviswanathan Muthukumarappan and Brijesh Tiwari

Introduction

The utilization of fresh vegetables is somewhat limited due to seasonality, perishability, and regional nature of production. Poor postharvest handling and storage cause decay, shriveling, and loss of quality of fresh vegetables and other horticultural commodities (Alvarez and Trystram 1995). Effective processing can preserve quality and extend the use of vegetables beyond the production cycle (Wu et al. 2004). Refrigeration and freezing preservation of vegetables have economic importance for unprocessed and processed products (Campañone et al. 2002). In all modes of processing, the objective is to minimize and inhibit chemical and biochemical reactions, microbial growth, water evaporation, respiration, etc., that affect quality and shelf life (Campañone et al. 2002).

Freezing of fruits and vegetables is generally considered superior to canning and drying for retention of sensory and nutritive qualities (Fennema 1977). Freezing has been successfully employed for the long-term preservation of vegetables. In general, the process involves lowering the product temperature in the range of $-18^{\circ}C$ to $-25^{\circ}C$. During freezing, most of the water changes into ice, which greatly reduces microbial and enzymatic activities; the respiration is also reduced. Nutrients, such as ascorbic acid, can be protected in frozen products; however, there could be losses during the prefreezing and preconsumption periods (Fennema 1993). Prior to freezing, products undergo a pretreatment to minimize quality loss. For example, most frozen vegetables are blanched prior to freezing. In this chapter we review the important developments related to refrigeration and freezing preservation of vegetables.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Freezing of Vegetables

In China, ice cellars were used to preserve foods as early as 1000 BC (Archer 2004). Freezing preservation of foods has been employed since the 1800s. Low-temperature postharvest storage is used widely to extend the shelf life of horticultural produce. Refrigerated storage of vegetables allows the preservation of their quality after harvest, because low temperatures decrease the speed of cell metabolism and delay plant senescence in general and fruit ripening in particular (McGlasson et al. 1979; Sevillano et al. 2009). The frozen and chilled convenience-food market is growing annually by 3.5% and is projected to grow further (Gormley et al. 2003). This is primarily due to lifestyle changes and less time available for meal preparations at home (Creed and Reeve 1998).

Freezing is a simple method of preservation that preserves vegetables over long periods of time while maintaining many of their

fresh-like qualities (Prochaska et al. 2000). However, while freezing helps to preserve by retarding enzymatic reactions, senescence, and microbial growth, it does not fully stop these reactions (Bahceci et al. 2005). The result can be the development of off-odors, off-colors, off-fl vors, changes in texture, and nutrient loss. Blanching, which involves mild heating of products for short periods of time, is usually included as a prefreezing step. As also highlighted elsewhere in this book, the advantages of blanching include inactivation of enzymes, reduction of microbial load, removal of gases from the plant tissue, shrinkage of the product to facilitate packaging, fix ation of texture and color, and cleaning of the surface of the vegetable (Bahceci et al. 2005). Typically, blanching is done by treating the vegetables with steam or hot water for 1–10 minutes at 75–95°C; the time/temperature of blanching would vary according to the vegetable to be processed (Lund 2000). The temperature and the time employed reduce the viable microorganisms on vegetables (Archer 2004).

Industrial production of frozen vegetables involves blanching, before blast-freezing or individual quick freezing (IQF), to reduce microbial load and inactivate enzymes responsible for unwanted textural changes during frozen storage (Lin and Brewer 2005). Several studies considered the effects of freezing on nutrient levels (Howard et al. 1999; Korus et al. 2002; Lisiewska et al. 2002). Favell (1998) reported changes in ascorbic acid due to freezing for a range of vegetables. He observed negligible losses in carrots but 20% and 30% losses in broccoli and green peas, respectively. Abdel-Kader (1990) reported 25% ascorbic acid loss in peeled potatoes after blanching for 2 minutes at 100°C prior to freezing. During frozen storage of green leafy vegetables, vitamin C losses can be as high as 60–70% (Lisiewska and Kmiecik 1997).

In comparison to canned products, frozen products contained slightly higher levels of β-carotene on a wet weight basis (Howard et al. 1999; Scott and Eldridge 2005). Ismail and Lee (2004) showed 12–26% loss of polyphenols in fi e species of cooked cruciferous vegetables. Nicoli et al. (1997) indicated that the overall antioxidative properties are maintained in frozen products.

Besides inhibition of metabolic processes and microorganisms, freezing can lead to irreversible changes in the physical properties and quality (Jeremiah 1998; Góral and Kluza 2009). Huarte-Mendicoa et al. (1997) reported significan increase in the nitrate level during industrial freezing in broccoli. However, Some reports indicate decrease in the nitrate level during freezing and frozen storage of spinach (Jaworska 2005) and parsley (Lisiewska and Kmiecik 1997). Leszczynska et al. (2009) reported that boiling of previously frozen-stored (for 4 months) vegetables reduced the level of nitrate compared to corresponding fresh vegetables by 36% in Brussels sprouts, 76% in curly kale, 84% in white caulifl wer, 88% in green caulifl wer, and 91% in broccoli. Further, in vegetables frozen prior to boiling there was 24% (curly kale), 85% (broccoli, green caulifl wer), and 76% (white caulifl wer) less nitrate than the fresh boiled vegetables.

Freeze-chilling involves freezing and frozen storage followed by thawing and chilled storage. It has an advantage over chilling as it allows bulk preparation of frozen products followed by controlled batch release of thawed product into the chilled chain.

Ulla and Merete (1999) showed that the degradation of vitamin C of cooked floret was more rapid when the raw broccoli heads were stored at 10°C instead of 1°C or 5°C, which was also in accordance with earlier investigations (Eheart and Odland 1972).

Puupponen-Pimiä et al. (2003) observed a pronounced decrease in the antioxidant activity during the refrigerated storage of broccoli. Rodriguez-Amaya (1993) found loss of color of carrots, which was a direct reflectio of carotenoid destruction during chilled storage. In addition, Park (1987) showed that carotene

content of carrot was affected by freezing and subsequent thawing. Leja et al. (2001) reported good stability of total polyphenols in broccoli during 7-day storage at 5±1°C. According to Sarkar and Phan (1979), the total phenolics of carrots stored at 3±1°C and ~90% relative humidity increased steadily with storage time. Talcott et al. (2005) reported that free gallic acid was unaffected by hot water treatment, but its concentration decreased after storage at 5°C for 8 days.

Frozen vegetables including potatoes form a significan proportion of the market in terms of frozen food consumption. Since freezing does not improve product quality, the quality of frozen vegetables depends on the quality of fresh materials used for freezing (Galindo et al. 2007). Gomez and Sjoholm (2004) illustrated tolerance of carrots to freezing by the metabolic response to low-temperature stress in both acclimated and nonacclimated carrot slices held at −5°C temperature overnight. Figure 12.1a shows a piece of nonacclimated carrot tissue that has been extensively damaged by freezing. In contrast, Figure. 12.1b shows much more intact tissue of the cold-acclimated samples frozen under the same conditions.

Although vegetables such as carrots are usually frozen quickly to produce small ice crystals, these ice crystals may grow larger over time through recrystallization. Recrystallization occurs when temperature gradients form within the product during freezing or thawing, or when the temperature fluctuate during storage or transportation (Griffit and Ewart 1995; Breton et al. 2000). Recrystallization in frozen foods can result in membrane damage, thus reducing water-holding capacity (high drip loss), and associated loss of nutrients (Fletcher et al. 1999; Breton et al. 2000).

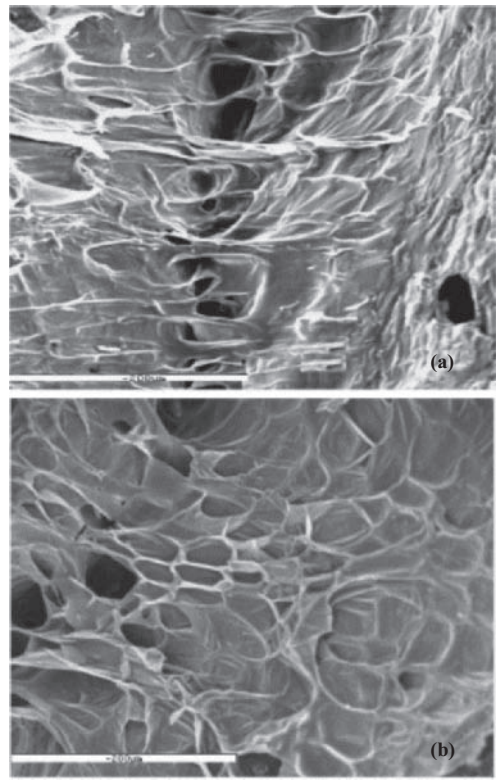


Figure 12.1 Conventional scanning electron micrographs showing parenchyma of frozen carrots. Carrot slices from (a) non-acclimated and (b) cold-acclimated field-grown carrot tap roots were covered with plastic foil and frozen at −5°C overnight. (From Gómez and Sjöholm (2004).)

Freezing Equipment

The type of freezing equipment for a product depends on factors such as type, size, and shape of raw material; finishe product quality; production rate; space availability; investment; and cooling medium. The freezing equipment can be grouped as follows:

1. Direct contact with cold surface: Here, the product (either packed or unpacked) will be in direct contact with a metal surface during the freezing process. This group includes plate freezer and scraped surface freezer.
2. Air as cooling medium: Here, air at very low temperature is used for freezing the food products. Still air freezers, air blast tunnel, belt freezer, spray freezer, fluidize

bed freezer, and impingement freezers fall under this category.

3. Liquids as coolants: Here, very low-temperature liquids are used for freezing the products. The liquids may be sprayed on the product or the products may be immersed in the liquids. This group includes immersion-type and cryogenic freezers.

The following discussion describes the important features of the freezers mentioned above. The data on convective heat transfer coefficient and freezing times given (Table 12.1) can be used to select the equipment.

Direct Contact Freezers Using Cold Surface

Plate Freezers

In plate freezers, the metal wall of the plate separates the cooling medium and the product. In freezing of packaged food products, the packaging fil also acts as a separation layer and adds its own resistance to heat transfer. Plate freezers can be double plate or multiplate arrangements. The plates are hollow in construction and the cooling medium is either arranged in coils or is floodin the hollow plate. Plates in the plate freezer are arranged in an insulated cabinet. Heat transfer between the plates and the product is mainly by conduction. As shown in Figure 12.2a, in double plate freezer the freezing proceeds from both sides of the product. Air pockets or air fil between the plates and food packages offer resistance to heat transfer. In order to avoid this, in multiplate configurations plates are subjected to a pressure of less than one bar (Figure 12.2c). This will create better contact between the plates and the food packets and eliminate any air pockets or air fil between them. But care should be taken to prevent damage and collapse of packages when pressure is used. Generally, spacers are provided to prevent this problem. In case of loosely packed foods, stagnant air fil inside the packet offers resistance to heat transfer. Plate arrangement in multiplate freezer can be horizontal, as shown in Figure 12.2c, or vertical, as shown in Figure 12.2b. Horizontal plates are mainly used for products of regular size and rectangular shape. Vertical plate arrangement is used for unpacked, deformable foods such as fis and meat products. Liquid and semisolid foods can also be frozen in vertical plate freezers.

Table 12.1 Typical convective heat transfer coefficients and freezing times for different freezing systems

Method of freezing	Convective heat transfer coefficient (W/ m^2 K)	Freezing time at −18°C (minutes)	Food
Still air	6–9	180–4320	Meat carcass
Blast (5 m/s)	25–30	15–20	Unpacked peas
Blast (3 m/s)	18	—	—
Spiral belt	25	12–19	Hamburgers, fis finger
Fluidized bed	90–140	3–4	Unpacked peas
		15	Fish finger
Plate	100	75	25 kg blocks of fis
		25	1 kg carton vegetables
Scraped surface	—	0.3–0.5	Ice cream
Immersion (Freon)	500	10–15	170 g card cans of orange juice
		0.5	Peas
		4–5	Beef burgers, fis finger
Cryogenic	1500	0.9	454 g of cake
		2–5	Hamburgers, seafood
		0.5–6	Fruits and vegetables

Source: Fellows 2000.

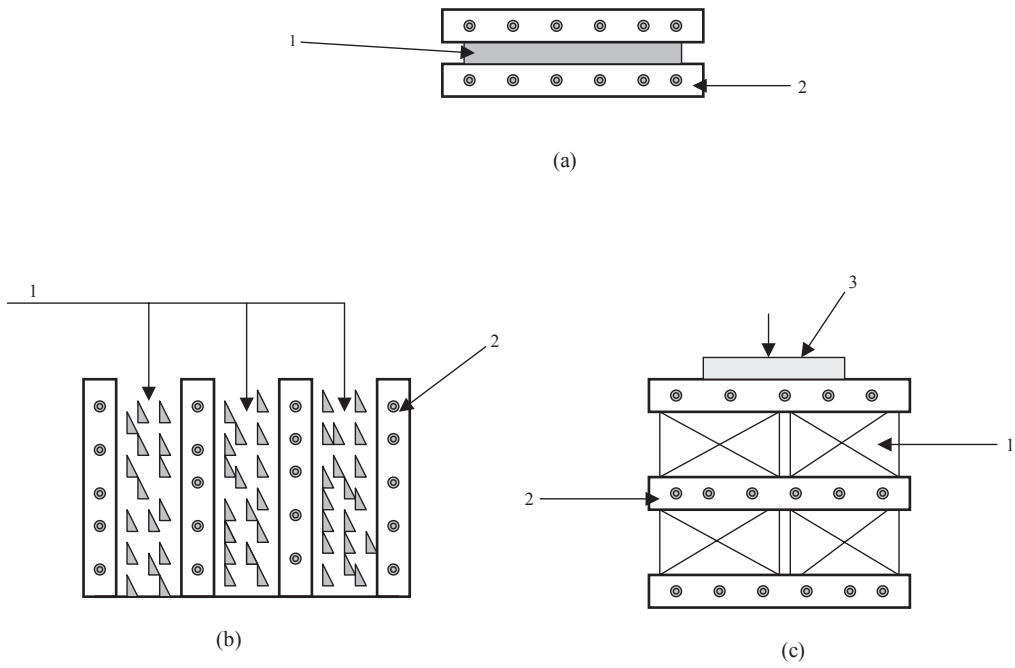


Figure 12.2 Plate freezers: (a) Double plate, (b) vertical plate, and (c) horizontal plate with press.

The number of plates (there can be up to 20 plates) would depend on the capacity of the system. Flat packaged foods, ice cream, whole fish meat pieces, and packaged vegetables are some of the products frozen in plate systems. Plate freezers are compact, require less floo and headspace, and enable a high freezing rate. The throughput for the unit volume of the freezer is high when compared to air blast freezers.

Scraped Surface Freezer

This type of freezer is mainly used for liquid and semisolid foods with or without particulates. It consists of two concentric cylinders, the outer one being insulated to prevent heat gain from the surroundings. Cooling medium fl ws in the annular space between the two cylinders whereas the food is contained in the inner cylinder. A scraper rotates inside the inner cylinder and scraps the frozen product layer from the freezer surface. This keeps the metal surface clean and gives high heat transfer coefficients Scraped surface freezers can be operated in batch mode or continuous mode. The product is frozen very fast, and fast freezing gives large number of small ice crystals in the product. This type of freezer is extensively used in the ice cream manufacturing industry.

Freezers Using Air as Cooling Medium

Still Air Freezers

Still air freezers are similar to cold stores. They are relatively large in size and serve the purpose of freezing as well as the storage of the product. The refrigerant coils are generally located at one side of the room. Air fl ws in the room at very low velocities. The convective heat transfer coefficient are very

low and freezing requires longer time. Slow freezing may lead to damage of the quality of the product due to formation of large ice crystals. Weight loss of the product, especially unwrapped products, will be more as the product is in contact with the air for a long time.

Air Blast Tunnel

Air blast tunnel freezer consists of an insulated tunnel in which the cooling air is circulated by fans or blowers. The product to be frozen is placed on trolleys, hooks, or conveyors, and passed through the tunnel. In batch mode (Figure 12.3a) the product trolleys are kept inside the tunnel for the required residence time and removed before taking a fresh batch. The air fl w arrangement can be horizontal or vertical in relation to the product. In continuous systems, as shown in Figure 12.3b, the product trolleys enter the tunnel at one end and come out at the other end after a given residence time.

A continuous moving conveyor can also be used in these systems. Continuous systems can have co-current or counter-current air fl w arrangements. As compared to co-current fl w, counter-current fl w arrangement would give better heat transfer rates and a high temperature difference between the product and the cooling air. The temperature of air used in these systems can be −30 °C to −40°C and air velocities can be 3–6 m/s. The residence time of the product in the freezer depends on the type and size of the product, temperature, and velocity of air. Air blast

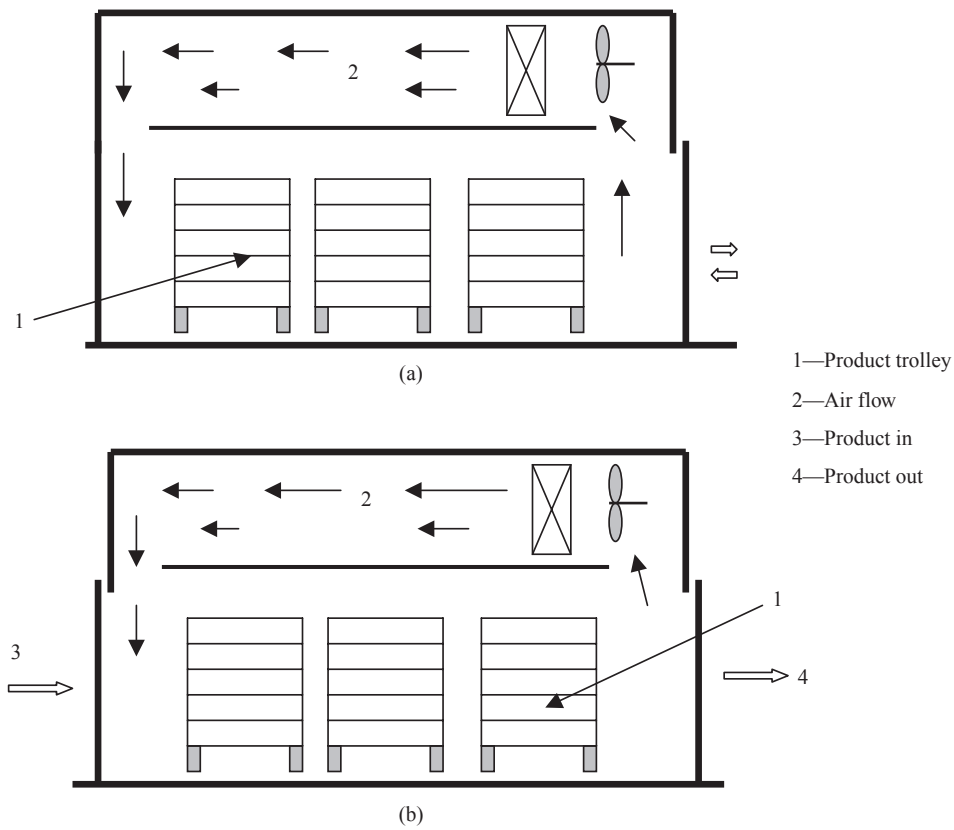


Figure 12.3 Air blast freezers: (a) batch type, (b) continuous type.

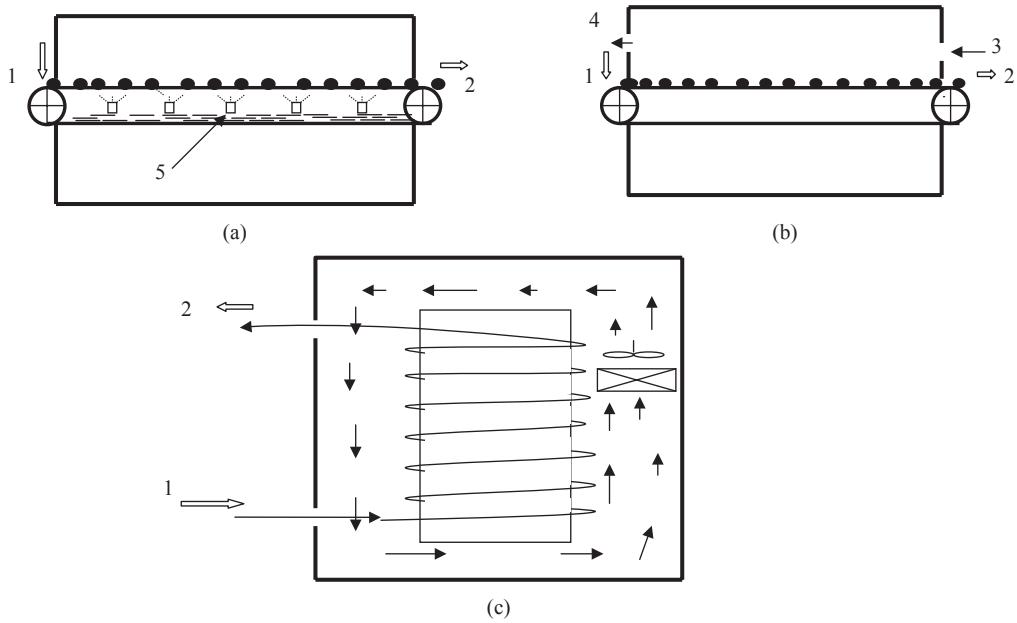
freezers are simple and easy to operate and a wide range of product shapes and sizes can be frozen. However low efficiencies poor heat transfer coefficients nonuniform distribution of air, and substantial moisture evaporation, especially from unwrapped foods, are some disadvantages with these systems.

Belt Freezer

Belt freezers consist of a continuous stainless steel or plastic belt moving in an insulated room. Belt freezers can be straight belt type (Figures 12.4a and 12.4b) or spiral belt type (Figure 12.4c). Products either in solid or liquid form can be frozen in this type of freezer. In case of solid foods, perforated belts are generally used and air can be forced upward through the belt. The upward movement of air can partially lift the product, giving high heat transfer rates and free fl wability to the frozen product. Air velocities in the range of 1–6 m/s are generally used in these systems. The product is loaded at one end of the room and is either scraped from the belt surface at the other end or pops up due to the brittle nature of the frozen product. Heat transfer in these systems can be convection and conduction. When high capacities and quick freezing are required, cryogenic gas spray can be used from the top. In spiral belt freezer, a continuous conveyor belt moves around a cylindrical drum giving up to 50 rounds. These systems require higher headspace when compared to straight belt systems. Air fl w can be upward or downward through the spirals. As it accommodates a long conveyor belt, this arrangement gives longer product residence times. This type of arrangement is well suited for products requiring longer freezing times, packaged products, and bigger products.

Fluidized Bed Freezer

It consists of a perforated metal plate on which a bed of particles rests. Cold air at high



1—Product in, 2—Product out, 3—Air in, 4—Air out, 5—Liquid coolant spray

Figure 12.4 Belt freezers: (a) liquid spray, (b) air cooling, and (c) spiral belt.

velocities is forced through the perforated plate. At low air velocities the air merely percolates through the bed, but as the air velocity is increased, the pressure drop across the bed increases and when it equals the ratio of weight of the bed and area of the bed, incipient fluidizatio occurs. At this point, the entire bed of the particles is physically lifted from the bottom plate. The particles start vibrating around themselves. This reduces the resistance in the boundary layers and gives very high heat transfer coefficients Air used as cooling medium is generally at -40^{o}C and velocity of the air depends on the product size, density, and fluidizatio characteristics. The heat transfer in fluidize beds is by convection between the product and the cooling air, and conduction between the adjacent particles as well as between the particles and the support plate. Automatic discharge of the product from the bed can be achieved by providing vibrations or making the support plate slightly inclined. The residence time of the product in the bed depends on the feed rate and volume of the bed, and is controlled by overfl w weir/plate. Fluidized bed freezer can also be used for packaged foods but the packing fil offers its own resistance to heat transfer. The bed to particle heat transfer mechanisms for small and large particles are well described, and two to three times increase in heat transfer coefficient is reported when compared to forced air convection (Sheen and Whitney 1990). Over and above a certain heat transfer coefficient the internal resistance of the product becomes the limiting factor and will not help achieve reduced freezing time. Hence, it is recommended to derive the upper limit of convective heat transfer coefficien for different food products in fluidize beds. Fluidized bed freezer works on the IQF concept and the particles are frozen as individual particles giving free fl wing characteristic to the product. The moisture loss in fluidize beds can be about 2%. The products frozen include diced carrot, peas, corn kernels, small onions, and diced fruits and vegetables.

Impingement Freezer

In a conventional air blast freezer using cold air, the stagnant boundary layer of air surrounding the product offers high resistance to heat transfer. Due to poor convective heat transfer coefficient freezing rates are low and large ice crystals will be formed, leading to poor quality of the product. Impingement freezer is a type of blast tunnel freezer in which cold air at very high velocity is impinged against the food from top or bottom or from both directions. The impingement disrupts the boundary layer of air surrounding the product, thereby eliminating the boundary layer resistance to heat transfer. This technique is being used in freezing bakery products, candy cooling, and on-board freezing of fis fillet (Salvadori and Mascheroni 2002). Foods that do not contain surface particles and toppings, chicken, meat, and bread dough are frozen in this type of freezer. Nozzles used in impingement freezers have a great influenc on the air fl w and may be single hole, orifices or jet tubes. Impingement freezers require low processing times, give higher throughput, and lead to low weight loss of the product as freezing is completed in lesser time.

Freezers Using Liquids as Cooling Media

Immersion Type

In this system, glycol or brine, water-solute mixtures such as sugar alcohol, and propylene glycol-water mixtures are used as coolants. Generally, packaged products are frozen in immersion systems. Freezing is fast due to direct contact and very low temperatures of the freezing medium. Liquid foods can also be frozen in these systems, in which case the belt conveyor used has long corrugations and the product is placed in the corrugations. The coolant is sprayed from the bottom of the belt. There is no direct contact of the food and the cooling medium. Alternatively,

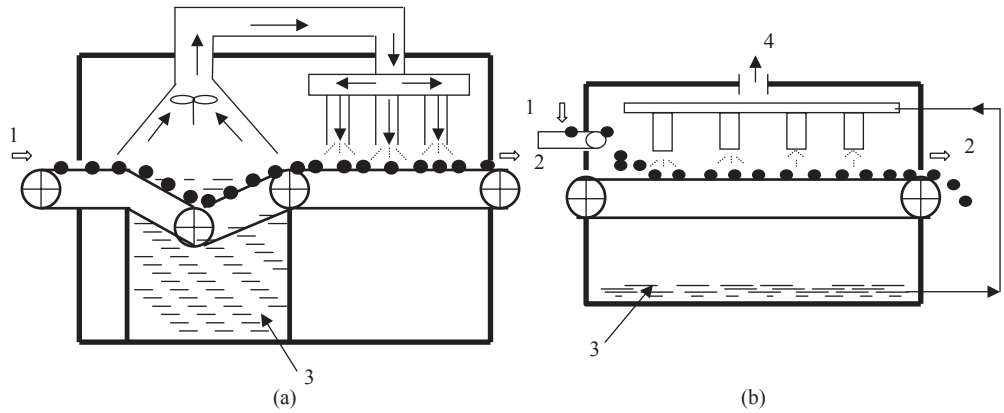
the corrugated belt can be arranged to pass through a bath of freezing medium giving immersion-type arrangement. However, the top of the corrugation is above the coolant surface and thereby prevents direct contact of product with the coolant. These systems are nowadays not commonly used.

Cryogenic Freezers

Cryogenic freezing came into existence in the 1960s with the introduction of cryogens such as liquid nitrogen and carbon dioxide. Cryogenic liquids have very low boiling points. The boiling points of liquid nitrogen and liquid carbon dioxide are −196°C and −79°C, respectively. Cryogens are colorless, odorless, and chemically inert. They give very large temperature differences and high heat transfer rates. Enthalpy of liquid nitrogen and liquid carbon dioxide are 228.7 kJ/kg and 310.3 kJ/kg, respectively.

Cryogenic freezer consists of an insulated chamber in which a metallic perforated belt moves continuously. The belt is loaded with the product at one end and at the other end the frozen product is unloaded. The entire belt length can be subdivided into precooling, spray or immersion, and equilibrating sections. The precooling section helps in reducing the product temperature close to −70°C. This helps in preventing freeze cracking damage to the product when it is exposed to direct contact of the cooling medium in subsequent immersion or spray section. In the immersion/spray section the product comes in contact with liquid nitrogen, giving a product temperature of the order of −190°C. Attaining such a low temperature is possible because the evaporating liquid nitrogen gives very high convective heat transfer coefficients

In case of liquid CO_2, when high pressure liquid is released to the atmosphere, it forms vapor and dry ice in almost equal proportions. Conversion of liquid CO_2 to vapor requires some time for sublimation and hence spray of coolant is done close to entrance of the freezer. Figure 12.5a and 12.5b show the immersion and spray types of cryogenic freezers. The latest modificatio to cryogenic freezers is cryomechanical freezers which combine the advantages of both cryogenic and mechanical freezers. The product is firs immersed in liquid cryogen and then moved to mechanical section that can be spiral, tunnel, belt, or spray freezer. The vapors generated in cryogenic section can be used in the mechanical section and the fina temperature is reached in this section. Combining cryogenic and mechanical systems gives reduced



1—Product in, 2—Product out, 3—Cooling medium, 4—Vapors out

Figure 12.5 Cryogenic freezers: (a) immersion type, (b) spray type.

freezing time, reduced product weight loss, high throughput, improved product quality, and improved efficien y (Agnelli and Mascheroni 2001).

Effect of Freezing on Quality

As discussed before, during freezing most of the water changes into ice, retarding microbial and enzymatic activities. Oxidation and respiration are also minimized. Slow freezing may cause structural impairment due to the formation of large ice crystals. It may also result in higher enzyme and microbial activities as well as increased oxidation rates, resulting from increased solute concentration and the insolubility of oxygen in ice (Rastogi et al. 2007). Slow freezing rate does not stop the physical and biochemical reactions that govern the deterioration of foods (George 1993). Rapid freezing using cryogens induces cracking because of two effects: the initial decrease of volume due to cooling and the subsequent increase in volume due to freezing (Kalichevsky et al. 1995). Slow freezing of cellular tissues from fruits and vegetables can lead to large extracellular ice crystals, an increased concentration of solutes, and therefore to cell dehydration and death through osmotic plasmolysis and membrane damage. Upon thawing, extracellular ice does not reenter the cells and may cause extensive drip and texture softening (Cheftel et al. 2000). The reduction in freezing point under pressure causes super cooling upon pressure release and promotes rapid ice nucleation and growth throughout the sample, producing small ice crystals, rather than an ice front moving through the sample. Generally, thawing occurs more slowly than freezing, potentially allowing further damage to the sample. High pressure-induced thawing reduces the loss of the water-holding capacity and improves color and fl vor preservation in fruit. Benet et al. (2004) provided an extensive terminology for freezing and thawing processes including pressure-shift thawing.

Texture in frozen fruits and vegetables is considered to be an important component of product quality (Roy et al. 2001). Pectic polysaccharides, which are abundantly found in the primary wall and the middle-lamella between cells, are primarily responsible for most of the texture of fruits and vegetables. Because of consumer demand for the firm crisp, and succulent texture of raw vegetables, considerable amount of research has been directed toward modifying processing techniques to retain more of the textural quality of fresh products (Bourne 1989). Substantial depolymerization and destruction of cell wall pectins during processing of frozen carrots severely affected the firmnes and textural quality. Studies show that tissue exposure to high temperature for a few seconds showed greater retention of postfreezing firm ness. While rapid freezing rates retain better texture and high degree of cellular integrity, considerable softening and structural damage were seen at slower rates. A study by Roy et al. (2001) showed that the high temperature short time (HTST) blanching followed by rapid freezing at –4.5°C/minute can be recommended as the optimum thermal processing conditions for improvement of textural quality in frozen carrots.

High Pressure-Assisted Freezing

Freezing has many advantages for extending the shelf life and quality of vegetables and their products. However, this technique has a risk of damage to the food caused by the formation of ice crystals (Fuchigami et al. 1997; Otero et al. 1998; Norton et al. 2009). This mainly occurs due to slow freezing which may cause extensive structural damage to the vegetable tissues by puncturing cell walls due to the formation of larger ice crystals. The size and location of ice crystals formed during freezing depend on the rate and fina temperature of the process, and affect important quality parameters such as exudate, texture, and color of the frozen products (Norton et al.

Table 12.2 Some examples of the application of high pressure-assisted freezing in vegetables

Vegetable and its product	Processing conditions	Findings	Reference
Eggplant		High-pressure-assisted freezing resulted in lower quality damage in comparison with conventional air-freezing techniques.	Otero et al. (1998)
Chinese cabbage (midribs)	100–700 MPa	Texture of samples frozen at 200 MPa, 340 MPa, and 400 MPa was comparatively intact in relation to samples frozen at 100 MPa and 700 MPa. Release of pectin and histological damage in midribs frozen at 200 MPa and 340 MPa were less than midribs frozen at 100 MPa and 700 MPa.	Fuchigami et al. (1998)
Broccoli	180–210 MPa, −16°C to −20°C	The protein content decreased after the high-pressure treatments. Peroxidase and polyphenoloxidase enzymes could not be inactivated. After 30 days of frozen storage at −20°C, the f avor of broccoli was not acceptable to consumers, but the texture remained quite firm The vacuole membrane was destroyed and an internal disorganized cell was observed after pressure shift freezing treatment.	Prestamo et al. (2004)
Potato	210–300 MPa	In the pressure range 210–240 MPa, a metastable ice I modificatio area was observed, as the nucleation of ice (I) crystals in the thermodynamically stable region of ice (III) was reached. A significan degree of supercooling was obtained before freezing the tissue water to ice (III). Phase transition and freezing times for the different freezing paths were compared for processes such as freezing at atmospheric pressure, pressure-assisted freezing, and pressure-shift freezing.	Schluter et al. (2004)
Carrot	100–700 MPa	Textural properties of carrots pressurized at 200–400 MPa at −20°C were found to be more acceptable; pectin release and histological damage were also lower in samples frozen at 100 MPa and 700 MPa.	Fuchigami et al. (1997, 1998)
Potato cubes	400 MPa	Pressure-shift freezing resulted in increased crystallization rates compared to conventional freezing at -30°C. Reduction in drip loss. Water uptake and texture values were improved.	Koch et al. (1996)

Source: Rastogi et al. 2007.

2009). Table 12.2 shows some of the applications of high pressure-assisted freezing in vegetables.

High pressure-assisted freezing has many advantages, mainly relating to the extension of keeping quality (Cheftel 1995), changing the physical and functional properties of food systems (Cheftel 1992), and exploiting the anomalous phase transitions of water under extreme pressures, e.g., lowering of freezing point with increasing pressures (Kalichevsky et al. 1995). The thermodynamic properties of water, such as the freezing point, viscosity, and diffusion coefficients are significantl influence by the application of high pressure. Under high pressure, water remains in a liquid

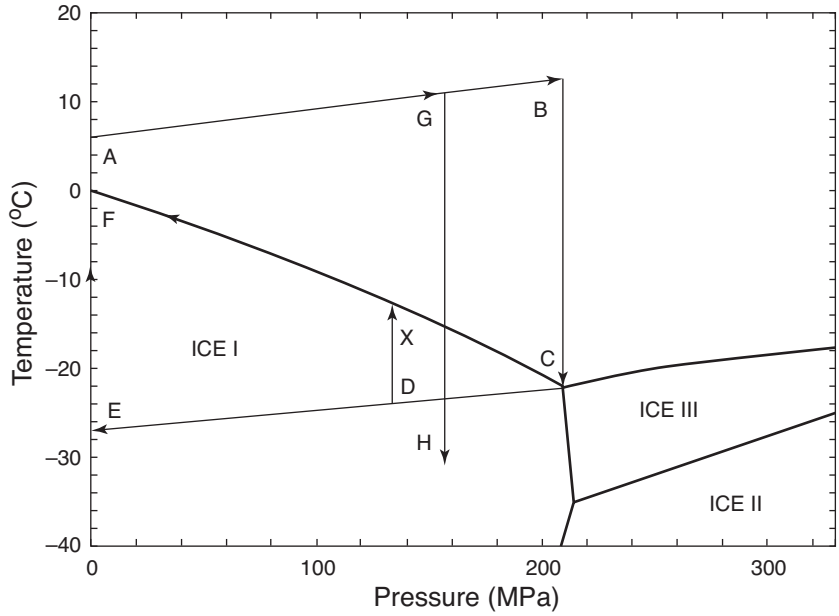
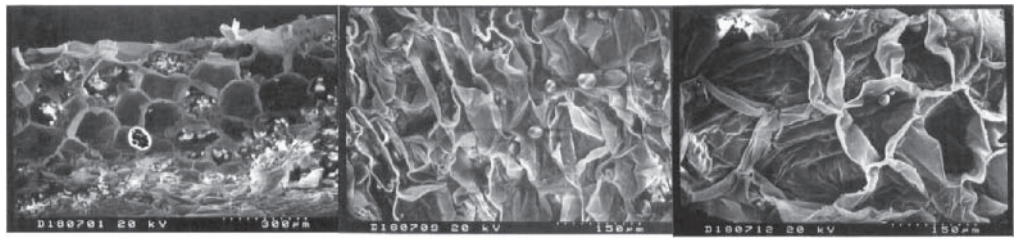


Figure 12.6 Phase diagram of water, with pathways followed during HPSF and PAF freezing processes. ABCEF: rapid release HPSF; ABCDXF: slow release HPSF; AGH: PAF. (From Norton et al. (2009).)

state below 0°C, with a reduction in its freezing point to a minimum of −22°C at 207.5 MPa (Bridgman 1912). Therefore, by observing the influenc of pressure on the phase diagram of water, various pathways of changing the physical state of food can be followed by manipulating ambient temperature and/or pressure. Figure 12.6 shows the phase diagrams of two types of high pressure freezing processes, namely, high pressure-assisted freezing (PAF) and high pressure shift freezing (HPSF) (Otero and Sanz 2000; Norton et al. 2009). In the former process, phase transitions occur under constant pressure, higher than atmospheric pressure, and as the latent heat of crystallization is reduced when pressure increases, reductions in phase transition times can be achieved. On the other hand, releasing the pressure once the temperature of the food reduces to the modifie freezing point results in a high supercooling effect and the ice nucleation rate is greatly increased. The main advantage of HPSF is that the initial formation of ice is instantaneous and homogeneous throughout the whole volume of the product. Therefore, HPSF can be useful to freeze foods with large dimensions where the effects of freeze cracking caused by thermal gradients can become pronounced (Martino et al. 1998).

Koch et al. (1996) observed improved rehydration and textural properties of potato cubes during pressure-shift freezing (400 MPa) compared with conventional freezing (0.1 MPa, −30°C), subsequent frozen storage (−18°C), or pressure treatment (400 MPa) at +15°C. Pressure-shift freezing resulted in increased crystallization rates compared to conventional freezing, reduction in drip loss, increase in water uptake during rehydration, and improved texture. Figure 12.7a–c shows the scanning electron microscope image of untreated, conventionally frozen, and pressure-assisted frozen potato cubes, respectively. In these figures the preservation of cell structure during pressure-assisted freezing (Figure 12.7c) compared to conventional freezing (Figure 12.7b) is seen. Michiko et al. (1998)



(a) (b) (c)

Figure 12.7 Scanning electron microscopy photograph of (a) untreated, (b) conventionally frozen (freezer, 0.1 MPa, −30oC, 1 h), and (c) pressure-assisted frozen (400 MPa, 20 minutes) potato tissue. (From Koch et al. (1996).)

studied the effect of high pressure freezing (100 MPa and 700 MPa) on the texture and microstructure of Chinese cabbage. They observed a significan difference between the texture of raw and pressured-treated Chinese cabbages. Raw midribs were firme compared to nonfrozen samples pressurized at 200–400 MPa. PAF at 100 MPa and 700 MPa was found to induce excessive softness to the midribs. Similarly, Michiko et al. (1997) reported the histological changes in carrots frozen using high pressure-assisted freezing and observed that when raw carrots were frozen at 50 MPa, –15°C; 100 MPa, –15°C; 150 MPa, –25°C; 200 MPa, –28°C, they were extremely damaged due to volume expansion by the formation of ice. Conversely, carrots pressurized at 100 MPa, –10°C (between liquid phase and ice) and 200 MPa at –20°C (liquid phase) were not damaged because they were frozen rapidly during pressure reduction. These results of high pressure freezing of vegetables showed that the conditions at which ice crystals are formed before depressurization have critical impact on the fina texture (LeBail et al. 2002). Table 12.3 lists some of the advantages of pressure-assisted freezing.

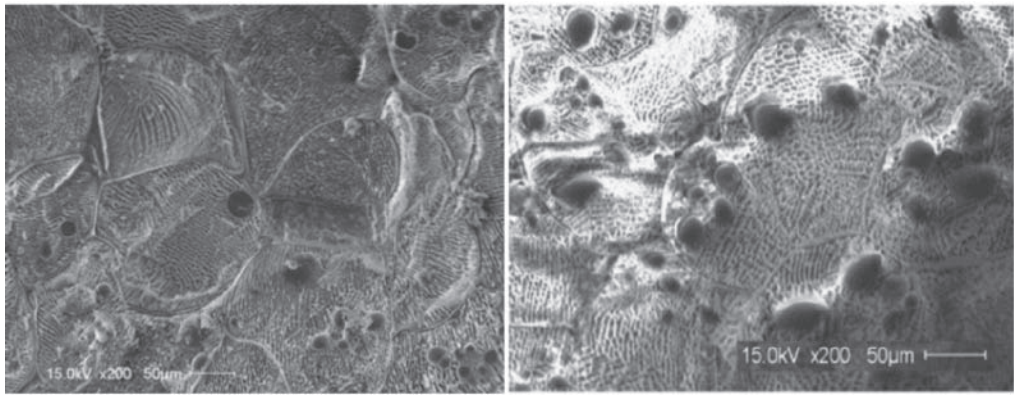
Table 12.3 Advantages of pressure-assisted freezing

1. Enables food processing at ambient or lower temperatures.
2. Enables instant transmittance of pressure throughout the system, irrespective of size and geometry, thereby making size reduction optional.
3. Ensures microbial inhibition without use of heat and chemical preservatives/additives.
4. Can be used to create ingredients with novel functional properties.

Source: Rastogi et al. 2007.

Ultrasound-Assisted Freezing

Application of power ultrasound in freezing is currently under investigation. Power ultrasound has proven to be extremely useful in crystallization processes. It serves a number of roles in the initiation of seeding and subsequent crystal formation and growth (Mason et al. 1996). Power ultrasound has been applied to accelerate the ice nucleation of many chemical processes (Fennema 1982). In freezing, this would lead to small ice crystals and reduce the time between the onset of crystallization and the complete formation of ice, thus reducing damages to cellular structure. Unlike nucleating agents (e.g., silver iodide), the power ultrasound used for nucleation does not require direct contact with the products. Thus, it is unlikely to face legislative issues (Acton and Morris 1992). Power ultrasound has proved to be very useful in controlling crystallization processes since sonication can enhance both the nucleation rate and crystal growth rate by producing fresh and/or more nucleation sites (Sun and Li 2003).



(a) (b)

Figure 12.8 Cryo-SEM micrograph for potato tissue by immersion freezing showing disruption of cells and separation of cells (a), as compared with Cryo-SEM micrograph for potato tissue by ultrasonically assisted immersion freezing under power of 15.85 W showing much better preserved microstructure (b). (From Sun and Li (2003).)

Crystallization and nucleation in freezing process are mainly due to the cavitations which consist of the formation, growth, and collapse of cavitating bubbles in liquids. The cavitation bubbles can act as nuclei for crystal growth, and/or the nuclei already present would be fragmented into smaller ones caused by the strong forces originating from the collapse of cavitation bubbles (Mason 1998; Simal et al. 1998; Li and Sun 2002). Therefore, power ultrasound has been recently studied in assisting and/or accelerating various freezing processes (Zheng and Sun 2006). Research to date shows that power ultrasound can accelerate the freezing process of many fresh vegetables mainly through its ability to enhance the heat and mass transfer process; ultrasound is reported to improve convective heat transfer coefficien (Sastry et al. 1989; Marybeth and Sastry 1990).

Power ultrasound is reported to enhance the freezing rate during immersion freezing of potato slices (Li and Sun 2002). Power ultrasound-assisted freezing is also reported to be able to improve the quality of the frozen product (Sun and Li 2003). Cryogenic scanning electron microscope photos indicate that plant tissues of ultrasound-assisted frozen potatoes exhibit a better cellular structure, as less extracellular void and cell disruption/breakage appears, than those without acoustic treatment, as shown in Figure 12.8. The changes in microstructure are mainly attributed to the increase in freezing rate induced by power ultrasound (Li and Sun 2002; Sun and Li 2003; Zheng and Sun 2006). However, freezing rate by ultrasound-assisted freezing is influence by various factors including processing time, ultrasound power level, and pulse time (Sun and Li 2003). Ultrasound-assisted freezing could be easily incorporated into the existing refrigeration and freezing equipments such as immersion freezer, plate freezer, chest freezer, and scraped surface freezer. In immersion freezing, power ultrasound can be applied through the refrigerant, with the mechanical vibrations generated either by ultrasonic probes directly positioned inside the refrigerant or transducers mounted to the walls of the refrigerant tank (Fellows 2000; Zheng and Sun 2006). In plate freezer, the ultrasound transducers can be directly welded underneath the contact surface. This arrangement also brings some additional benefi since heat generated by the transducer can be carried away by the

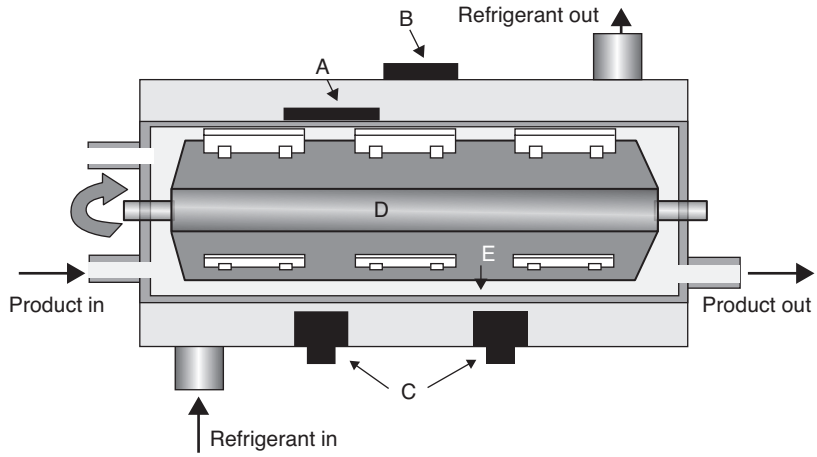


Figure 12.9 Scraped surface freezer with ultrasonic transducer (From Zheng and Sun (2006).)

refrigerant. The ultrasonic device can be attached to the scraped surface freezer at several locations, as suggested by Zheng and Sun (2006) (Figure 12.9). The most preferable place will be on the external surface of the freezer barrel (A). Transducers may also be mounted on the outside surface of the freezer (B); transducers can also be sealed through the outer wall of the freezer jacket and directly attached to the inner wall (C), the rotating shaft (D), or via a vibrating plate positioned in the bulk of the liquid (E).

Dehydrofreezing

Dehydrofreezing is one of newly developed food freezing techniques in which fresh or minimally processed vegetables and their products are dehydrated to an appropriate moisture level prior to freezing (Robbers et al. 1997; Spiazzi et al. 1998). Dehydrofreezing provides a promising way to preserve fruits and vegetables by removing part of the water from food materials prior to freezing (Biswal et al. 1991; Robbers et al. 1997). A reduction in moisture content would reduce the amount of water to be frozen, thus lowering refrigeration load during freezing. In addition, dehydrofrozen products could lower the cost of packaging, distribution, and storage, and maintain product quality comparable to conventional products (Biswal et al. 1991). The dehydration treatment not only reduces the amount of water to be frozen but also makes cell structures less susceptible to breakdown by changing cell turgor pressure (Li and Sun 2002; Wu et al. 2009). As a consequence, the damage to plant cells caused by ice crystal formation and the post-thawing quality degradation such as color change, softening, and loss of fl vor and nutritional substances may be alleviated. Various dehydrofrozen products have been reported to be organoleptically acceptable (Biswal et al. 1991; Lazarides and Mavroudis 1995).

For frozen vegetables, except freezing rate and exudate, sensory characteristics and texture would be the important factors influ encing their acceptability by consumers (Li and Sun 2002). Biswal et al. (1991) studied the hardness, taste, and overall acceptability of dehydrofrozen green beans. They reported that osmotically dehydrated frozen green beans were as good and equally acceptable as conventionally frozen green beans. Wu et al. (2009) studied the application of vacuum-dehydrofreezing technique for long-term storage of fresh-cut eggplant. They

reported that the freezing time of the dehydrated samples was shortened and the rate of immersion freezing was higher than that of the air freezing, and they observed improvement in the surface color and texture after the dehydration-freezing-rehydration treatment compared to the nondehydrated samples. Similarly improvement in the physical properties of radish during dehydrofreezing, thawing, and rehydration was observed by Shizuka et al. (2008). Dermesonlouoglou et al. (2007) reported that osmodehydrofreezing shows improved quality and functional characteristics of tomato slices for prolonged storage of 12 months compared to conventionally frozen sliced tomatoes.

Future Trends in Freezing of Vegetables

The current challenges of the frozen vegetables industry pertain to production efficien y and high product quality. The growth of the frozen foods industry would mostly be influ enced by socioeconomic changes and technological developments. The successful application of freezing of vegetables would enable round-the-year availability of seasonal vegetables. Future growth and developments in frozen vegetable industry will depend on the availability of proper equipment suitable for continuous processing. Application of novel processing techniques such as ultrasound and high pressure-assisted freezing to produce better-quality frozen vegetables with extended shelf life will help the frozen vegetable industry. Consequently, in recent years, greater advancement in freezing and refrigeration is mainly characterized by the advancement in material handling, application of novel techniques to enhance freezing rate, and greater control over quality. The future commercial application of novel processing techniques such as high pressure and power ultrasound-assisted freezing will depend on the development of adequate industrial equipment that is easy to operate and economically viable.

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Chapter 13

Drying of Vegetables: Principles and Dryer Design

Jasim Ahmed

Introduction

Drying is one of the oldest, most common, and most diverse food processing methods. The most common method of drying in many developing countries is open air drying, which can be done in direct sunlight or under shaded conditions. Sunlight heats food effectively by driving out moisture, but direct sunlight and heat can affect thermally-sensitive vitamins and pigments significantl . In mechanical drying, water is removed from the food materials through heat, and to do this the latent heat of vaporization is supplied. Phase change and production of a solid phase as end product are essential features of the drying process.

Drying is an energy-intensive process accounting for 10–25% of the total energy used in the manufacturing process worldwide (Mujumdar and Passos 2000). The wide variety of dehydrated foods available in the market (snacks, dry mixes and soups, dried vegetables, etc.) and the concern for quality and energy conservation emphasize the need for understanding drying processes (Krokida et al. 2003).

Drying of foods is required for many reasons: reducing bulk, easy handling and transportation, preservation and storage, shelf-life extension, desired size, and free-fl wing properties. The microorganisms which cause food spoilage and decay are unable to grow and multiply in the dried food and many of the enzymes, which promote undesirable changes in the chemical composition of the food, cannot function without water (Earle 1993).

Drying is a complex process involving simultaneous heat and mass transfer requiring precise process control. Drying behavior of food materials depends on the composition and moisture content of the food material to be dried, its thickness and geometry, airfl w rate, and relative humidity. Although the process is mainly physical in nature, it can result in desirable and undesirable physical and biochemical changes. The common physical changes observed in dried food materials are shrinkage, puffing crystallization, agglomeration, and change in glass transition temperature. In many cases, improper drying may lead to irreversible damage to product quality and hence a nonsaleable product.

A wide range of dried vegetables (potato, carrot, broccoli, caulifl wer, green pea, spinach) is available in the market in whole, sliced, or ground form. Reduction in moisture during drying of high-moisture materials, like vegetables, induces changes in shape, density, and porosity. Product quality plays a major role in food drying operation. Upon rehydration, dried vegetables should exhibit desirable sensory and nutritional quality. Numerous processing techniques have been practiced

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for drying of vegetables. However, it should be noted that water should be removed in such a way that dehydrated products can easily be rehydrated to regain their structure. No single dryer can be used for all or even several of the vegetables. It is, therefore, essential to revert to the fundamentals of heat, mass, and momentum transfer, coupled with the knowledge of the material properties, when attempting to select a drying process or dryer. This chapter deals with basic fundamentals, mathematical modeling, and dryer design pertaining to vegetable drying. The common drying terminology and concepts related to vegetables are presented in Table 13.1

State of Water in Vegetables

Water in vegetables is present mainly in two forms: free (or unbound) and bound. Free water behaves as pure water, and bound water, which is physically or chemically bound to food materials, exhibits vapor pressure lower than that of pure water at the same temperature (Figure 13.1). Free water is the firs fraction of moisture adherent to the food surface to be removed. Water remains in the pores and the capillaries. Bound water may exist in different forms: unfreezeable, immobile, monolayer, etc. A fraction of bound water is loosely adsorbed to food

Table 13.1 Common terminology related to vegetable drying operations

Terminology	Definitio
Dry bulb temperature	It is the temperature measured using a standard mercury-in-glass thermometer.
Wet bulb temperature	It is the temperature reached by a water surface, such as that registered by a thermometer bulb surrounded by a wet wick, when exposed to air passing over it.
Humidity of air	Mass of vapor carried out by a unit mass of vapor-free gas.
Relative humidity	Ratio of partial pressure of the vapor to the vapor pressure of the liquid at the gas temperature.
Psychrometric chart	A graph of the absolute air humidity (y-axis) as a function of temperature (x-axis) at varying degrees of saturation.
Equilibrium Relative Humidity (ERH)	It is the relative humidity when the movement of moisture from a material to the environment (and vice versa) has equalized.
Moisture content (weight basis)	It measures the amount of moisture as a fraction of the total weight of wet material.
Moisture content (dry basis)	It measures amount of moisture as fraction of the bone-dry material.
Bound moisture	Liquid physically and/or chemically bound to solid matrix so as to exert a vapor pressure lower than that of pure liquid at the same temperature
Free moisture	Moisture content in excess of the equilibrium moisture content (hence free to be removed) at given air humidity and temperature.
Unbound moisture	Moisture in solid which exerts vapor pressure equal to that of pure liquid at the same temperature.
Equilibrium moisture content (EMC)	It is the moisture content at which the material is neither gaining nor losing moisture; this, however, is a dynamic equilibrium and changes with relative humidity and temperature.
Water activity (a_w)	The vapor pressure of water of a sample divided by saturation vapor pressure of pure water at the same temperature. Water activity is measured as ERH of the atmosphere in contact with the product at constant temperature where a_w = ERH/100.
Constant rate period	Under constant drying conditions, the drying period when evaporation rate per unit drying area is constant (when surface moisture is removed).
Falling rate period	The drying period (under constant drying conditions) during which the rate falls continuously in time.
Porosity	Porosity is the ratio between the volume of air present in the sample and the overall volume.
Shrinkage	Represents a relative or reduced dimensional change of volume, area, or thickness.

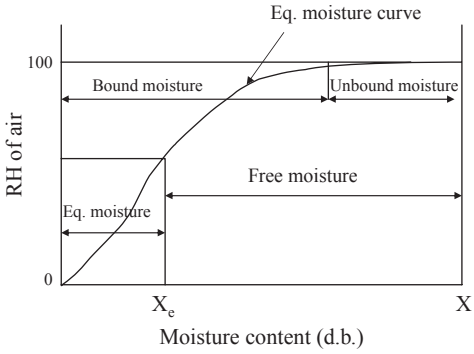

Figure 13.1 Different types of moisture present in food.

materials while higher energy requirement is necessary to remove water trapped in colloidal gels.

Moisture Representations

Moisture content in food materials can be expressed on either a wet (MC_{wb}) or dry (MC_{db}) basis (fraction or percentage basis). These can be mathematically expressed as:

$$MC_{wb} = \frac{mass\ of\ water}{mass\ of\ wet\ food} = \frac{mass\ of\ water}{mass\ of\ water + mass\ of\ bone\ dry\ food} = \frac{X_w}{X_w + X_{bdf}} \quad (13.1)$$

$$MC_{db} = \frac{mass\ of\ water}{mass\ of\ bonedry\ food} = \frac{X_w}{X_{bdf}} \quad (13.2)$$

The moisture content on wet or dry basis can be converted into another form by the following equations:

$$MC_{wb} = \frac{MC_{db}}{100 + MC_{db}} \times 100 \quad (13.3)$$

$$MC_{db} = \frac{MC_{wb}}{100 - MC_{wb}} \times 100 \quad (13.4)$$

Equilibrium Moisture Content

The equilibrium moisture content (EMC) is an important property of food products, which influence several aspects of drying and storage. The moisture content of a wet food material in equilibrium with air of definit humidity and temperature is define as the equilibrium moisture content (EMC). In the drying process, EMC represents the moisture content of the product which is approached at the completion of the process. It determines the minimum moisture content to which food can be dried under a given set of drying conditions.

A moisture sorption isotherm (MSI) describes the relationship between the water activity and the EMC for a food product. An isotherm obtained by exposing the dry solid to air of increasing humidity gives the adsorption isotherm (Figure 13.2), whereas the one obtained by exposing the wet solid material to air of decreasing humidity is known as the desorption isotherm. Apparently, the latter is of interest in drying since the moisture content of the solids gradually decreases. Most drying materials exhibit "hysteresis" where each of the two isotherms follows a different path. MSIs of biological materials are nonlinear, generally sigmoidal in shape, and have been classifie as type II isotherms by Brunauer (1945). Some isotherms are of type III that behave parabolically or exponentially, and certain food isotherms have an intermediate

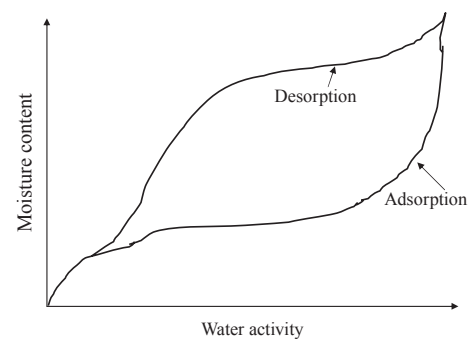

Figure 13.2 Typical moisture sorption isotherm.

Table 13.2 Commonly used mathematical models for MSI of vegetables

Model	Equation
GAB	$X_e = \frac{X_m.C.a_w}{(1-k.a_w)(1+(C-1).k.a_w)}$
BET	$X_e = \frac{X_m.C.a_w}{(1-a_w)(1+(C-1).a_w)}$
Henderson	$X_e = 0.01[\frac{-\log(1-a_w)}{10^f}]^{\frac{1}{n}}$
Caurie	$X_e = \exp\left[a_w \ln(v) - \frac{1}{4.5X_s}\right]$
Smith	$X_e = B + A.\log(1-a_w)$
Oswin	$X_e = A\left[\frac{a_w}{1-a_w}\right]^B$
Halsey	$X_e = \left[\frac{A}{\ln(1/a_w)}\right]^{1/B}$
Iglesias and Chirife	$X_e = A + B\left[\frac{a_w}{(1-a_w)}\right]$

shape between types II and III (Iglesias and Chirife 1981).

A large number of mathematical models (about 200) have been proposed in the literature for the sorption isotherms of food materials. Some of these equations have theoretical or half-theoretical backgrounds, others are simply empirical and the fittin abilities of those equations vary with the group of foods—some are suitable for one group of vegetables whereas others may be suitable for another group of vegetables. Some common models used for sorption isotherm of vegetables are presented in Table 13.2.

The EMC of foods (X_e) can be described by mathematical models having two or more parameters (Van den Berg 1984). However, models having more than three parameters are too complicated for straightforward interpretation or use. The GAB (Guggenheim-Anderson-deBoer) equation has been suggested as the most versatile sorption model available in the literature and has been applied successfully to various dehydrated vegetables (Boquet et al. 1978; Rahman 2009). It is based on the BET (Brunauer-Emmett-Teller) theory and involves three coefficient (X_m, C_o, and K_o) which have physical signifi cance, two of them being functions of temperature. The GAB equation parameters for some vegetables are presented in Table 13.3

Drying Principles

The basic objective of drying lies in moisture removal, where the internal water of a hygroscopic material moves in the form of liquid, vapor, or both to the surface of the material and finall evaporates with supply of heat. The process of drying is a complex operation involving transient transfer of heat and mass along with several rate processes. The fundamental driving force for drying is the chemical potential of the water present in the food material. The water moves from inside of the material where chemical potential is higher towards the outer surface where potential is low.

In most cases, drying is accomplished by vaporizing the water that is present in the food, and to do this the latent heat of vaporization must be supplied (Earle 1993). The heat may be supplied by convection, conduction, and radiation, or volumetrically by placing the wet material in a microwave or radio frequency electromagnetic fiel (Mujumdar 2007). In this chapter, dielectric drying has been excluded since the mechanism of drying is different. Most of the heat in thermal drying operations is supplied at the surfaces of the drying material (except dielectric heating) so that the heat must diffuse into the solid primarily by conduction. The liquid must pass through the boundary of the material until it is transported away by air or the carrier gas. In adiabatic drying, diffusion may occur in solid or gas phase, but often drying rates are controlled by heat transfer coefficient than by mass transfer coefficient (McCabe et al. 2001). Transport of moisture within the solid food may occur by various mechanisms including: liquid diffusion, vapor diffusion, surface diffusion, hydrostatic pressure differences, and combinations of these.

Vegetables contain a high amount of mostly loosely bound or free water. During

Table 13.3 Parameters of the GAB equation for adsorption isotherm of vegetables

Vegetable	Temperature (°C)	X_m	K	C	References
Potato	15	4.6668	0.8834	10.8705	Liendo-Cardenas et al. (2000)
Potato fla es	20	4.4390	0.9013	8.1940	Liendo-Cardenas et al. (2000)
	30	3.7041	0.9542	6.1770	Liendo-Cardenas et al. (2000)
Sweet potato	15	9.6500	0.8193	4.1401	Liendo-Cardenas et al. (2000)
Sweet potato fla es	20	8.8536	0.8607	3.5802	Liendo-Cardenas et al. (2000)
	30	6.1452	0.9592	3.8233	Liendo-Cardenas et al. (2000)
Carrot	30	4.4	1.146	4.377	Rahman (2009)
	45	8.3	1.074	0.978	Rahman (2009)
Fig	30	5.1	1.129	4.733	Rahman (2009)
Okra	45	5.4	1.121	2.690	Rahman (2009)
Red bell pepper (untreated)	30	0.075	1.021	12.533	Vega-Galvez et al. (2008)
Red bell pepper (with salt and $CaCl_2$ treatment)	30	0.061	1.092	2.850	Vega-Galvez et al. (2008)
Red pepper	40	7.41	0.793	29.3	Kim et al. (1991)
Tomato	30	16.6	0.83	31.4	Timmerman et al. (2001)
Pumpkin	25	0.099	0.975	6.247	Mayor and Sereno (2004)
Onion	20	7.54	0.96	2.72	Samaniego-Esguerra et al. (1991)
	30	7.39	0.97	2.29	Samaniego-Esguerra et al. (1991)
Green beans	20	7.34	0.94	2.58	Samaniego-Esguerra et al. (1991)
	30	6.99	0.95	2.28	Samaniego-Esguerra et al. (1991)

X_m, monolayer moisture content; C, constant related to heat of sorption of the firs layer; K factor, related to heat of sorption of the multilayer.

mechanical drying, moisture evaporation of vegetables is very rapid, and in some cases (green leafy vegetables: coriander leaves, spinach, mint leaves) the drying is completed within an hour or two. Shrinkage and bulk density of dried vegetables are two important parameters which are related to the drying method and the conditions during drying, and are good indicators of the quality of the end product.

Heat and Mass Transfer during Drying

Both heat and mass transfers occur when a wet food material comes in contact with hot air (Figure 13.3). Heat fl ws from the medium (hot air) to the food surface, which results in moisture being driven out from inside the food material to the surface and finall evaporating to the medium. Heat must be transferred to equal the heat of vaporization. All three of the mechanisms by which heat is transferred—conduction, convection, and radiation—are important in drying. The relative importance of these mechanisms varies from one drying process to another and, generally, one mode of heat transfer predominates to such an extent that it governs the overall process.

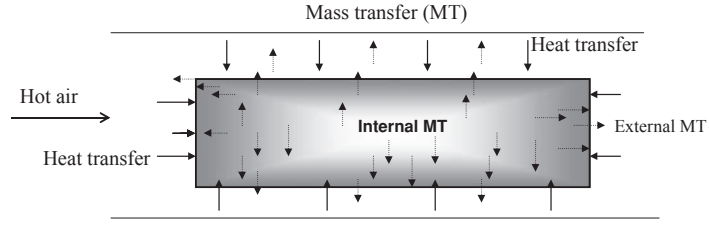

Figure 13.3 Heat and mass transfer (MT) in a food slab during hot air drying.

In heat transfer, heat energy is transferred under the driving force provided by a temperature difference, and the rate of heat transfer is proportional to the potential temperature difference and to the properties of the transfer system characterized by the heat-transfer coefficient

In air drying, the rate of heat transfer is given by:

$$q = h\,A(T_a - T) \tag{13.5}$$

where q is the rate of heat transfer (W), h is the surface heat-transfer coefficien (W/m^2. ^{0}C), A is the area (m^2) through which heat fl w is taking place, T_a is the air temperature (°C), and T is the temperature (°C) of the material surface which is drying.

As drying proceeds, the character of the heat transfer situation changes. Dry material begins to concentrate in the surface layers and conduction must take place through these dry surface layers which are poor heat conductors so that heat is transferred to the drying region progressively more slowly.

While air fl ws over a moist food surface, water is transferred from the surface to the air. The equations governing the rate of mass transfer are similar to those for heat transfer. Mass is transferred under the driving force provided by a partial pressure or concentration difference. The rate of mass transfer is proportional to the potential (pressure or concentration) difference and to the properties of the transfer system characterized by a mass-transfer coefficien and represented as:

$$\frac{dX}{dt} = k'_g A \Delta H \tag{13.6}$$

where X is the mass (kg) being transferred, t is the time (h), A is the area (m^2) through which the transfer is taking place, k'_g is the mass-transfer coefficien in kg-moles/(m^2.s), and ΔH is the humidity difference (mass of vapor per unit mass of vapor free gas).

The mass transfer coefficien can be determined in similar fashion as heat transfer coefficien by using dimensionless number. The Nusselt number (Nu) in mass transfer is analogous to Sherwood number (Sh) and can be represented as:

$$Sh = \frac{k_g D}{D_{wm}} \tag{13.7}$$

where D is the diameter, k_g is the mass transfer coefficien (kg mol/m^2 h), and D_{wm} is the diffusivity expressed in kg-mole/(m s).

Similarly, the equivalent of Prandlt number (Pr) in mass transfer is the Schmidt number (Sc) as shown below:

$$Sc = \frac{\mu}{\rho\, D_m} = \frac{\mu}{M_a D_{wm}} \tag{13.8}$$

where μ is the viscosity (Pa s), ρ is the density (kg/m^3), D_m is the mass diffusivity (m^2/s) or D_{wm} (kg mole/(m s). For drying operation, M_a of air = 29 kg/kg mole and D_m for water in air = 2.2×10^{-5} m^2/s.

The mass transfer coefficien for carrot cubes was estimated by Gornicki and Kaleta (2007) using Sherwood number (Sh) from the following dimensionless equation, as suggested by Schlunder (1977), and found to be less than 0.015 ms^{-1}.

$$Sh = 2 + \frac{0.66 Sc^{0.5} Gr_m^{0.25}}{2.5^{0.25}} \left(1 + \frac{1.74 \times 10^{-4} Sc^{0.33} Gr_m^{0.5}}{2.5^{0.5}}\right)^{0.25} \tag{13.9}$$

where Gr stands for Grashof number, which is a dimensionless number.

The application of mass-transfer equation is not so simple since the movement of moisture changes during drying. At the start, the moisture is transferred from the surface of the material, and afterward, to an increasing extent, from inside the food to the surface, and finall to the air. Thus, the firs phase of drying occurs from the moist surface to the ambient air and gradually the process becomes diffusion-controlled.

Drying Curves

Drying of vegetables is a process unique to the specifi product and drying system under consideration. Products containing moisture behave differently on drying, according to their moisture content. Consider the drying of a wet food material under constant psychrometric conditions (temperature, humidity, air velocity, and direction of fl w remain constant) (Figure 13.4). In the most general cases, after an initial period of adjustment, the dry-basis moisture content (X_o) decreases linearly with time (t) following the start of the evaporation. At the beginning, free water moves to the surface which is easily removed by vaporization. This is followed by a nonlinear decrease in X with t until, after a prolong time, the solid reaches its EMC, X_e, and drying stops. Water is held by forces whose intensity ranges from the very weak forces, retaining surface moisture, to very strong chemical bonds (Earle 1993).

Drying of vegetables generally occurs in two stages, each characterized by different drying rates. A drying process can be well represented by a diagram based on material moisture content and drying time, the drying rate and drying time, and the material temperature and drying time. The drying rate is define as the amount of moisture removed from the dried food material in unit time per unit of drying surface, which is the derivative of total moisture content (X) versus time (t), i.e., $\left(\frac{dX}{dt}\right)$. There are three different periods observed while drying rate is plotted as function of drying time and moisture content (Figures 13.5a and 13.5b):

(i) Preheating period (A-B; drying rate is almost zero): This part is observed while wet food material is exposed to hot air; initially only a minor change in moisture content occurs. This happens because all the heat provided in the drying air is used to heat up the material to the drying temperature.

(ii) Constant rate period (B-C; drying rate is constant in time): During this time period, the mass of water starts to evaporate from the surface in equal intervals of time. The drying rate remains constant for certain time period, which is often referred to as the constant rate period; during this period, material temperature is constant as well.

(iii) Falling rate period (C-D; drying rate decreases over time): As the drying progresses, it takes more time for internal

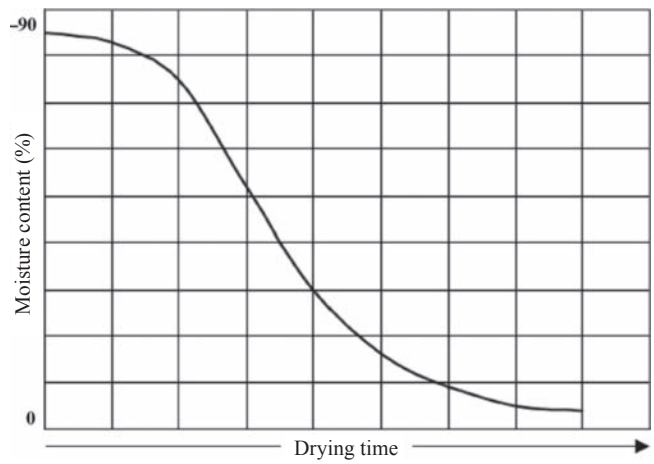

Figure 13.4 Typical drying curve for vegetable.

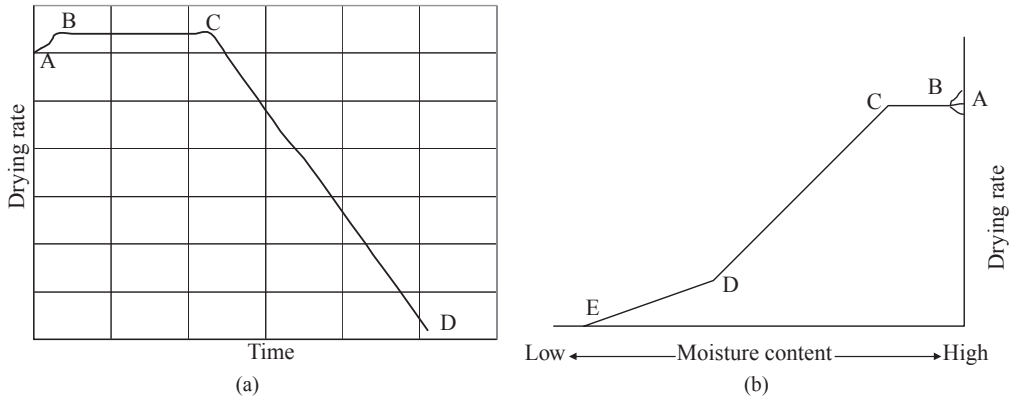

Figure 13.5 Typical drying rate curves for vegetables, with respect to time (a) and moisture content (b).

moisture to move to the surface, and evaporation of water is no longer constant in time. As a result, drying rate will decline and some of the heat from the drying air will heat up the material. There may be more than one falling rate period (DE in Figure 13.5b) due to structural changes in the food product during drying.

The average moisture content at which the rate of drying changes from constant rate period to the falling rate period is termed as critical moisture content (X_c). The change from constant drying rate to a slower rate occurs at different moisture contents for different foods. However, for many foods, the change from constant drying rate occurs at a moisture content, in equilibrium with air, of 58–65% relative humidity, i.e., at a_w = 0.58–0.65 (Earle 1993). If the initial moisture content of the food material is below the critical value, there will be no constant rate period. The value of critical moisture content depends on material thickness, rate of drying, and resistance to heat and mass transfer within the food material (McCabe et al. 2001).

The constant drying rate (R_c) can be calculated from the following expression wherein the predicted transfer coefficient are used:

$$R_c = \frac{\dot{m}_v}{A} = \frac{h_y(T - T_i)}{\lambda_i} \qquad (13.10)$$

where m_v is rate of evaporation (kg water/h), A is drying area (m^2), h_y is heat transfer coefficien (W/m^2°C), T is hot air temperature (°C), T_i is interface temperature (°C), and λ_i is latent heat at temperature T_i (J/kg).

A constant rate drying period appears due to continuous supply of water at the surface from the inside of the material. The rate of evaporation becomes equal to the incoming water, and the gas-liquid interface and wet food material are at the wet bulb temperature (McCabe et al. 2001). As drying proceeds, the surface water is supplied by inner cellular moisture and the material shrinks. Sometimes rapid drying produces hard texture of the shrunken material. The effect is known as case-hardening. Case-hardening is a common problem in dried vegetables, which affects physical and sensory properties of food.

Moisture distribution in porous food material during the falling rate period is governed by a complex network. The moisture fl ws by capillary action and surface diffusion. The pore sizes at surface of the food material vary widely. During water removal by vaporization, a meniscus is formed across each pore

which balances capillary forces by the interfacial tension between water and the food material. The strength of the capillary force is a function of pore cross section. Small pores generate higher capillary force and, therefore, pull more water compared to larger pores.

Drying of vegetables predominantly follows a falling rate profile Mass transfer during this period is caused by liquid diffusion or capillary fl w. The liquid diffusion is frequently used to describe drying behavior in the falling rate period of vegetables.

Most vegetables, under the experimental conditions, do not show any constant drying rate period and entire drying takes place in falling rate period, suggesting that diffusion is the most dominant mechanism governing moisture movement.

A critically important aspect of drying technology is mathematical modeling of the drying processes. The objective is to allow process engineers to decide the most suitable operating conditions and further to fabricate the drying equipment and drying chamber according to their requirements (Strumillo and Kudra 1986). Table 13.4 shows in-layer drying models used for different vegetables.

Moisture Diffusivity in Vegetables

In food drying, diffusion transport mechanism has a significan role, especially during the falling rate period, which is controlled by the mechanism of liquid and vapor diffusion. This behavior indicates an internal mass transfer-type drying with moisture diffusion as the controlling step. The water diffusion coefficien reflectin the whole complexity of water transport is referred to as an effective coefficient Generally, it is difficul to predict the effective mass diffusion coefficien values

Table 13.4 Thin-layer drying models used for vegetables

Model	Equation	References with specifi vegetable
Lewis	$MR = \exp(-kt)$	Yaldiz and Ertekin (2001), Kabganian et al. (2002): echinacia root
Page	$MR = \exp(-kt^n)$	Ahmed et al. (2001): coriander leaves, green beans; Yaldiz and Ertekin (2001), Gupta et al. (2002): red chili
Modifie Page	$MR = \exp[(-kt)^n]$	Vega et al. (2007): Red bell pepper; Mwithiga and Olwal (2005): kale
Henderson & Pabis	$MR = a.\exp(-kt)$	Ahmed (1997): Turnip & radish; Srinivasakannan and Balasubramanian (2009): green pepper
Modifie Henderson & Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	
Simplifie Fick's diffusion	$MR = a\exp(-kt) + c$	
Logarithmic	$MR = a\exp[-c(t/L^2)]$	Lee and Kim (2009): white radish; Akpinar and Bicer (2008): green pepper
Two term	$MR = a\exp(-k_o t) + b\exp(-k_1 t)$	
Two term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Figiel and Kita (2008): walnut kernels; Guine and Fernandez (2006): chestnut
Verma and others	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Doymaz (2007a): pumpkin slice
Diffusion approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	
Wang & Singh	$MR = 1 + at + bt^2$	Wu et al. (2007): eggplant drying; Miranda et al. (2009): Aloe Vera
Midilli–Kucuk equation	$MR = a\exp(-kt^n) + bt$	Karaaslan and Tuncer (2008): spinach

theoretically; therefore, experimental techniques based on sorption/desorption kinetics, moisture content distribution, or porosity have been used (Bialobrzewski and Markowski 2004). For vegetables with significantl high moisture content, like celery, it is often assumed that mass diffusion is determined by external conditions of mass transfer. The rate of moisture movement during drying is well described by effective diffusivity (D_{eff}) value. Fick's second law of diffusion is commonly used to describe moisture movement during drying as follows:

$$\frac{\partial X}{\partial t} = D_{eff}\frac{\partial^2 X}{\partial x^2} \tag{13.11}$$

The above equation is based on a few assumptions that: (i) there is symmetric mass transfer with respect to the center, (ii) the diffusion coefficien is independent of local moisture content, and (iii) the volume shrinkage is negligible.

Crank (1975) provided analytical solutions of equation (13.11) for various regular geometry (rectangular, cylindrical, and spherical) materials.

With the appropriate initial and boundary conditions:

$$t = 0, 0 < X < L, X = X_o$$

$$t > 0, X = 0, \frac{\partial X}{\partial t} = 0$$

$$t > 0, X = L, X = X_e$$

The solution of equation (13.11) for a slice at constant diffusivity is available in the literature.

$$MR = \frac{X - X_e}{X_o - X_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}$$

$$\exp\left[-(2n+1)^2\frac{\pi^2 D_{eff}t}{4L^2}\right] \tag{13.12}$$

where MR is the moisture ratio (dimensionless) and L is the half thickness of the slice for drying from either side or the thickness of the slice for drying from one side (m).

Equation (13.12) can be modifie for infi nite cylinder and sphere as:

$$MR = \sum_{n=1}^{\infty}\frac{4}{b^2}\exp[\frac{-b_n^2 D_{eff}t}{r_c^2}] \tag{13.13}$$

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[\frac{-n^2\pi^2 D_{eff}t}{r_c^2}\right] \tag{13.14}$$

where b_n, $n = 1, 2, 3 \ldots$ are constant and r_c is the radius of the cylinder and sphere.

For a longer drying time, while the Fick number, $D_{eff}t/r^2$, is greater than 0.1 or MR is less than 0.6, only the firs term of the series solution is used. The effective moisture diffusivity can be estimated from the slope of the linear plot of the logarithm of the moisture ratio ($\ln\frac{X-X_e}{X_o-X_e}$) against drying time using the following equation (Rizvi 1986):

$$D_{eff} = \frac{-slope(r^2)}{5.783} \tag{13.15}$$

The above equation was fitte adequately for potato, carrot core, and carrot cortex (Srikiatden and Roberts 2006). The effective diffusivity was determined from the slope of the plot of $\ln(MR)$ versus time. Approximate ranges of effective moisture diffusivity for selected vegetables are presented in Table 13.5.

The diffusivity in solids is a function of both temperature and moisture content. However, the material's internal structure (density, porosity) also plays an important role in the determination of the effective mass diffusion coefficient Bialobrzewski and Markowski (2004) observed that density in addition to moisture content and temperature significantl affected diffusivity of celery root, while the effects of porosity on the moisture diffusion coefficien were described by Saravacos and Kostaropoulos (1996). The sample size and air velocity had no significant effect on the effective moisture diffusivity of vegetables, which is expected in a diffusion-controlled process (Srikiatden and Roberts 2006). There is a significan variation

Table 13.5 Effective diffusivity for vegetables

Vegetable	Temperature (°C)	Deff ($m^2\ s^{-1}$)	References
Potato	40–70	$4.55 \times 10^{-10} - 12.7 \times 10^{-10}$	Srikiatden and Roberts (2006)
Onion		$2.514 \times 10^{-9} - 3.233 \times 10^{-9}$	Pathare and Sharma (2006)
Garlic		1.2910^{-10}–31.68×10^{-10}	Sharma et al. (2009)
Carrot (core)	40–70	$6.42 \times 10^{-10} - 23.4 \times 10^{-10}$	Srikiatden and Roberts (2006)
Carrot (cortex)	40–70	$6.68 \times 10^{-10} - 13.63 \times 10^{-10}$	Srikiatden & Roberts (2006)
Carrot (slice)	21–56	$5.58 \times 10^{-10} - 23.12 \times 10^{-10}$	Berruti et al. (2009)
Chempedak		$3.291 \times 10^{-10} - 4.534 \times 10^{-10}$	Chong et al. (2008)
Tomato		$3.910 \times 10^{-10} - 7.530 \times 10^{-10}$	Doymaz (2007b)
Red chili		$3.780 \times 10^{-9} - 7.100 \times 10^{-9}$	Kaleemullah and Kailappan (2006)
Paprika		$9.100 \times 10^{-9} - 1.000 \times 10{-}8$	Ramesh et al. (2001)
Lettuce		$6.030 \times 10^{-9} - 3.15 \times 10{-}8$	Lopez et al. (2000)
Green beans		$2.640 \times 10^{-9} - 5.710 \times 10^{-9}$	Doymaz (2005)
Caulifl wer		$6.030 \times 10^{-9} - 3.15 \times 10{-}8$	Lopez et al. (2000)
Mint		$7.040 \times 10{-}12$	Akpinar (2006)
Parsley		$4.530 \times 10{-}12$	Akpinar (2006)
Basil		$6.440 \times 10{-}12$	Akpinar (2006)
Fig		$3.17 \times 10^{-10} - 16.2 \times 10^{-10}$	Xanthopoulos et al. (2009)
Red bell pepper		$3.2 \times 10^{-9} - 11.2 \times 10^{-9}$	Vega et al. (2007)
Mushroom		$3.932 \times 10^{-10} - 17.8 \times 10^{-10}$	da Silva et al. (2009)
Celery		$1.86 \times 10{-}11 - 24.53 \times 10{-}11$	Bialobrzewski and Markowski (2004)

of the estimated values of moisture diffusivity by different models as reported by various researchers. This can be attributed to the particular experimental and analysis methods used and the variation in composition and structure of the examined materials (Hassini et al. 2004).

Effects of temperature on diffusivity coefficien (D_{eff}) and activation energy (E_a) are generally described by the Arrhenius equation, as shown below (Henderson and Pabis 1961; Crisp and Woods 1994; Madamba et al. 1996):

$$D_{eff} = D_o \exp[-\frac{E_a}{RT}] \tag{13.16}$$

where D_{eff} is the diffusivity (m^2/s), D_o is the pre-exponential factor (1/s), E_a is the activation energy for the moisture diffusion (kJ/mol), R is the universal gas constant (kJ/mol K), and T is the absolute temperature (K).

The activation energy for vegetables (potato, carrot) was found to be in the range of 16 kJ/mol to 50 kJ/mol (Gupta et al. 2002; Srikiatden and Roberts 2006; Berruti et al. 2009).

Prediction of Drying Time

The total drying time is a sum of drying times in two succeeding periods: constant rate and falling rate period. The drying rate curve for food materials shows a constant rate starting from initial moisture content (X_o) to critical moisture content (X_c). The drying rate further decreases linearly before reaching zero (i.e., $X = 0$).

At constant rate:

$$\frac{-dX}{dt} = R_c \tag{13.17}$$

The expression for drying time at constant rate period is given below:

$$t_c = \frac{(X_o - X_c)}{R_c} \tag{13.18}$$

where t_c is the time taken for constant rate period (h). Different analytical expressions are obtained for the drying times t_f depending on the functional form of drying rate or the model used to describe the falling rate,

e.g., liquid diffusion, capillarity, evaporation-condensation. For some solids, a receding front model (wherein the evaporating surface recedes into the drying solid) yields a good agreement with experimental observations. The principal objective of all falling rate drying models is to allow reliable extrapolation of drying kinetic data over various operating conditions and product geometries. Details are available in any unit operation book.

The expression for drying time at falling rate period can be expressed as:

$$\frac{-dX}{dt} = \frac{R_c}{X_c}(X) \tag{13.19}$$

After integrating equation (13.18) for constant rate time (t_c) with the end of drying time (t), and the corresponding moisture content X_c with X, the following equation results:

$$t - t_c = \frac{X_c}{R_c} \ln \frac{X_c}{X} \tag{13.20}$$

After substituting t_c from the equation (13.18), the total time can be predicted as:

$$t = \frac{X_o - X_c}{R_c} + \frac{X_c}{R_c} \ln \frac{X_c}{X} \tag{13.21}$$

The above equation is valid for one falling rate period of drying where at $X = 0$ the drying rate is zero. For two falling rate periods, the drying time for each falling rate period is calculated separately and then the drying times for constant rate and the two falling rate periods are summed up to fin the total drying time (Toledo, 1991):

$$t = \frac{X_o - X_{c1}}{R_c} + \frac{X_{c1} - X_{r1}}{R_c} \ln \left[\frac{X_{c1} - X_{r1}}{X_{c2} - X_{r1}}\right] + \left[\frac{X_{c1} - X_{r1}}{X_{c2} - X_{r1}}\right] \left[\frac{X_{c2} - X_{r2}}{R_c}\right] \ln \left[\frac{X_{c2} - X_{r2}}{X - X_{r2}}\right] \tag{13.22}$$

where X_{c1}, X_{c2} and X_{r1}, X_{r2} are critical moisture content and residual moisture content for the firs and second falling rate periods, respectively. Residual moisture content is found by extending the falling rate curve to its intersection with the abscissa of the drying rate curve drawn as rate versus moisture content (Toledo 1991).

The equation for falling rate period can be derived from Fick's law of diffusion, and by ignoring the initial thermal transient and equation (13.12), it can be rewritten as:

$$MR = \frac{X - X_e}{X_o - X_e} = A' e^{-kt} \tag{13.23}$$

where k is a drying constant (h^{-1}), t is drying time (h), and A' is a constant.

The end of the constant rate period, when $X = X_c$ at the break point of drying rate curves, signifie that the water has ceased to behave as if it were at a free surface and that factors other than vapor-pressure differences are influencin the rate of drying. Thereafter the drying rate decreases and this is called the falling rate period of drying. The rate-controlling factors in the falling rate period are complex, depending upon diffusion through the food and the changing energy-binding pattern of the water molecules. Very little theoretical information is available for drying of foods in this region and experimental drying curves are the only adequate guide to design drying process in such cases.

Effect of Pretreatment on Drying

Product quality is becoming more and more important for dehydrated vegetables, which must retain quality attributes (color, texture) and nutritional quality after rehydration. Improvement of such qualities can be achieved by pretreatment before drying. Blanching is a very common practice for vegetables. It is carried out to inactivate natural enzymes in order to improve color, texture, and finall the overall acceptability of the product (Ahmed et al. 2001). Blanching of vegetables can be performed by exposing them to hot water or direct steam or by microwave for short time

period. Drying behavior of pretreated and control samples is alike although drying rate has been influence by pretreatment.

Shrinkage during Drying of Vegetables

Food materials are prone to undergo volumetric changes upon water loss which are expressed as shrinkage. Shrinkage during drying of vegetables occurs when the viscoelastic matrix contracts into the space previously occupied by the water removed from the cells (Aguilera 2003). Shrinkage of vegetables during drying has an impact on the quality of the dried product. If the extension of shrinkage during the drying process is controlled, quality of the dehydrated product may be improved. For this purpose, a good knowledge of shrinkage mechanism and the influenc of process variables on shrinkage is needed (Mayor and Sereno 2004).

Vegetables contain high initial moisture contents and experience alterations of their original form during the drying process due to significan shrinkage. When water is removed from the material, a pressure imbalance is produced between the inner portion of the material and the external pressure, generating contracting stresses that lead to material shrinkage or collapse, changes in shape, and occasionally cracking of the product (Mayor and Sereno 2004). Shrinkage of vegetables increases with the volume of water removed; since the more the water removed, the more contraction stresses are originated in the material. Shrinkage can be measured directly with a caliper or micrometer or by monitoring changes in related parameters such as porosity and density.

Recently, there have been many studies describing the shrinkage behavior of various vegetables in terms of prediction models (Mayor and Sereno 2004; Yadollahinia and Jahangiri 2009). Additionally, shrinkage affects the predictions of moisture and temperature profile obtained by drying models and should be taken into account in the mathematical simulation of the drying process. A good review on the subject and subsequently mathematical modeling is discussed elsewhere (Mayor and Sereno 2004). When porosity formation occurs during the drying process, it should be included in the model to take into account that phenomenon. This porosity formation can change with process conditions, and its inclusion in the model allows taking into account the influenc of process conditions on shrinkage. Shrinkage has been define as a relative or reduced dimensional change of volume, area, or thickness; volume shrinkage is often represented by:

$$S = \frac{V}{V_o} \tag{13.24}$$

where S is the shrinkage, V_0 is the initial volume (m^3), and V is the reduced volume (m^3).

Shrinkage of dried vegetables has been correlated with geometry of the materials. In their study of drying of carrot cubes, Gornicki and Kaleta (2007) correlated surface area of the dried solid to the initial surface area and the dried volume to the initial volume, considering that the dried body shrinks in three dimensions in the same degree, by the following equation:

$$\frac{A}{A_o} = \left(\frac{V}{V_o}\right)^{2/3} \tag{13.25}$$

where A_0 is the initial surface area (m^2) and A is the reduced area (m^2).

Some other researchers have correlated shrinkage with area or perimeter of the vegetables. Yadollahinia and Jahangiri (2009) reported that area and perimeter shrinkage of potato during drying was almost linearly related to its dimensionless moisture content and independent-from-air temperature when $X/X_o > 0.1$. Area shrinkage decreased as a function of moisture content as drying proceeded. It is believed that the changes in the area during initial drying were due to the elasticity of the cellular potato tissues and the structure was sufficientl elastic to shrink

into the space left by the evaporated moisture. At relatively lower moisture ratio (<0.1), the potato slice started to bend upwards and the area decreased more rapidly, resulting in an irregular shape of the slice. Air velocity showed no significan influenc on shrinkage at the studied temperature.

Again, shrinkage of vegetables can be correlated to moisture content by considering the shrinkage of tissue structure of the vegetable upon drying by the following linear relationship (Wang and Brennan 1995; Pabis 1999; Hatamipour and Mowla 2002, Mayor and Sereno 2004):

$$\frac{V}{V_o} = a\frac{X}{X_o} + 1 - a \qquad (13.26)$$

where a is dimensionless empirical constant.

Figure 13.6 illustrates shrinkage data of dried carrot cubes fitte above linear relationship adequately. Blanching has no marked effect on volumetric shrinkage data of carrot cubes (Gornicki and Kaleta 2007). It has been reasoned that biopolymers with common structural elements do not contract during blanching.

Shrinkage of food materials has a negative consequence on the quality of the dehydrated product. Changes in shape, loss of volume, and increased hardness cause, in most cases, a negative impression in the consumer. In addition, shrinkage has decreased the rehydration capability of the dried vegetables. Jayaraman et al. (1991) reported the inability of the plant tissue to fully rehydrate, and they attributed this fact to the dense and collapsed structure of the dried material with largely shrunken capillaries while studying drying of caulifl wer.

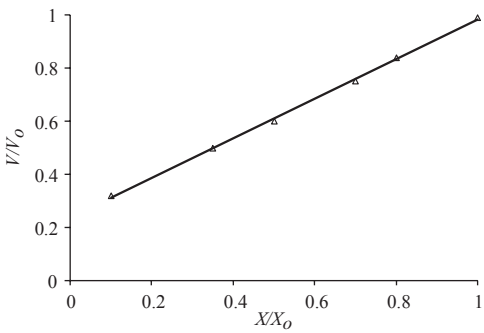

Figure 13.6 Fitting of shrinkage model for blanched carrot cubes. (Adapted from Gornicki and Kaleta (2007).)

Glass Transition and Drying of Vegetables

Glass transition is the most important property of amorphous materials, both practically and theoretically, since it involves a dramatic slowing down in the motion of chain segments that rarely can be observed in the static state (Ahmed 2009). The glass transition temperature (T_g) is define as the temperature below which the physical properties of amorphous materials change in a manner similar to those of a solid phase (glassy state), and above which amorphous materials behave like liquids (rubbery state). A material's molecular mobility becomes restricted in the glassy state (below T_g). Noncovalent bonds between polymer chains become weak compared to thermal motion above T_g, and the polymer becomes rubbery and exhibits elastic or plastic deformation without fracture. Above T_g, the specifi volume of the material increases to accommodate the increased motion of the wiggling chains. For materials, T_g is the midpoint of a temperature range in which they gradually become more viscous toward the lower range of temperature and liquid changes to solid in the higher range. A given sample does not have a unique value of T_g because the glass phase is not at equilibrium. The measured value of T_g will depend on the structure and molecular weight of the bio/polymer (crystalline or cross-linking, diluents, thermal history, and age), on the measurement method, and on the rate of heating or cooling.

The glass transition temperature of dried vegetables has significan importance for their storage and physical properties. In addition, there is an increasing consumer demand for processed products that keep more of their

original characteristics in such a way that preserving quality attributes of dehydrated food products is becoming of crucial importance. Quantifying the mobility changes induced by glass transition may be the route for the elucidation of the link between the process and product quality.

The extent of shrinkage and density of the dried product depend on the mobility of water in the material, which finall affects glass transition temperature. However, the mode of drying plays a major role in determination of the product's characteristics and consequently the glass transition phenomenon. In freeze drying operation, drying takes place below the T_g (glassy state) and the product exhibits minimum shrinkage but becomes porous in nature. On the contrary, hot air drying taking place above T_g (rubbery state) with significan amount of shrinkage and poor product quality (Ratti 2001). Limited researches have studied glass transition temperature of air-dried vegetables. Effect of water activity on T_g of freeze-dried onion and tomato is presented in Table 13.6.

Dryer Design

The design of a dryer is basically based on empirical knowledge, whereas modeling and simulation can improve the design performance and product quality. There are various types of dryers available commercially. Dryer design depends mostly on the particular needs of the enormous variety of food products which require drying. For example, a drying operation suitable for carrot is not applicable to green leafy vegetable. Drying processes and equipment may be categorized according to various criteria including the nature of material, the method of heat supply, and the mode of operation.

The selection of dryer as well as drying process is a complex operation; therefore, many factors are taken into account. The overall selection and design of a drying system for a particular vegetable is governed by a suitable combination of product quality, optimum drying parameters, and cost of the operation. A fl w diagram for dryer design consideration is shown in Figure 13.7. The factors that have direct influenc on the capacity of a drying system are: quantity and characteristics of the heating medium (commonly air) used for drying, thermophysical property of the material, and the drying time. In most cases,

Table 13.6 Glass transition temperatures for freeze-dried onion and tomato powders

	Glass transition temperature (°C)	
a_w	Onion*	Tomato†
0.07	–	28.39 ± 0.12
0.12	15.0 ± 2.3	26.50 ± 0.10
0.23	–	−0.79 ± 0.01
0.33	−11.0 ± 4.7	−3.23 ± 0.01
0.44	−21.1 ± 2.9	−18.27 ± 1.09
0.53	−26.1 ± 0.6	−27.94 ± 1.17
0.61	−46.6 ± 0.5	−37.20 ± 0.02
0.76	−68.8 ± 0.5	−60.87 ± 0.87
0.85	−87.5 ± 4.9	–

*Sti and Sereno 1994.
†Baroni et al. 2003.

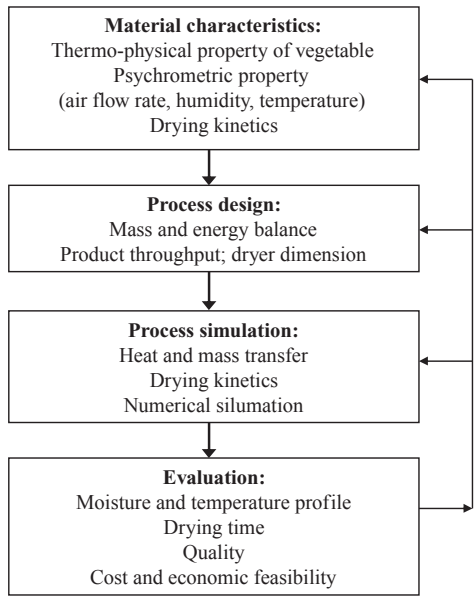

Figure 13.7 Important steps in designing a vegetable dryer.

thermophysical properties are taken from the published data.

The principle and design details of dryers are available in many books on food process design (Perry and Green 1997; Mujumdar 2007; Kudra and Mujumdar 2009). A brief overview of dryer design pertaining to vegetables is discussed in the following section.

Classification of Dryers

There is no simple way to classify dryers. Some dryers work in batch process, while the others work in continuous mode. Dryers under vacuum operate at reduced temperature and are effective for heat-sensitive food materials. Dryers can be classifie (or follow one of the categories) as shown below:

(i) Direct contact between the heating medium (hot air) and wet material (food).

(ii) Indirect contact where heat transfer takes place from an external medium, e.g., condensing steam.

(iii) Dryers are heated by dielectric or microwave energy.

A broad classificatio of dryers, as given by Kudra and Mujumdar (2009), is presented in Table 13.7.

Material Handling in Dryers

In adiabatic dryers the food materials are exposed to the gas (hot air) by different ways, which include:

(i) Hot air is blown across the surface of a bed or slab and the process is termed as cross-circulation drying.

(ii) Air is blown through a bed of coarse granular solids placed on a screen, which is known as through-circulation drying.

Table 13.7 Classification and selection of dryers

Criteria of selection	Dryer type
Mode of operation	• Batch • Continuous
Heat input type	• Convection, conduction, radiation • Electromagnetic field combination of heat transfer mode • Intermittent heat or continuous • Adiabatic or nonadiabati
State of material in dryer	• Stationary • Moving, agitated, or dispersed
Operating pressure	• Vacuum • Atmospheric
Drying medium	• Air • Superheated steam • Flue gas
Drying temperature	• Below boiling temperature • Above boiling temperature • Below freezing temperature
Relative motion between drying medium and drying solid	• Co-current • Counter-current
Number of stages	• Single • Multistage
Residence time	• Short (<1 minute) • Medium (1–60 minutes) • Long (>60 minutes)

Source: Adapted from Kudra and Mujumdar (2009).

(iii) Air is passed through the material at such a velocity that it can fluidiz the material, which is known as fluidize drying.

Calculation of Heat Duty

The basic components of a dryer consist of an airfl w control unit, a heating and heating control unit, an electrical fan, measurement sensors, and the drying chamber. The basic heat transfer equation for a dryer is similar to equation 13.5.

$$q = UA\bar{\Delta}\bar{T} \tag{13.27}$$

where U is the overall heat transfer coeffi cient (W/m^2°C) and A is the heat transfer area (m^2) for a particular dryer. For tray dryers and conveyor belt dryers, A is the area of the horizontal surface carrying the wet food materials.

The heat is required to accomplish the following steps:

(a) Heat the moist food to the vaporization temperature.
(b) Vaporize the liquid.
(c) Heat the solid food materials to their fina temperature.
(d) Heat the vapor to its fina temperature.

Commonly, the heat requirement for item (b) is the significan enough compared to other items. The rate of heat transfer (q) per mass of bone-dried solid X_{db} can be calculated from the following expression:

$$\frac{q}{X_{db}} = c_{ps}(T_{sb} - T_{sa}) + X_a c_{pL}(T_v - T_{sa}) + (X_a - X_b)\lambda + X_b c_{pL}(T_{sb} - T_v) + (X_a - X_b)c_{pv}(T_{va} - T_v) \tag{13.28}$$

where T_{sa} is the food temperature (°C), T_v is the vaporization temperature (°C), T_{sb} is the fina solid food temperature (°C), T_{va} is the fina vapor temperature (°C), and λ is the heat of vaporization (J/g).

Equipment and Process Design

For a process and dryer design for vegetables, the following points should be considered (Mujumdar 2007; Kudra and Mujumdar 2009):

- Dryer throughput; mode of feedstock production (batch/continuous).
- Physical, chemical, and biochemical properties of the wet vegetable as well as fina product specification
- Moisture content of the wet vegetable and finishe product.
- Drying kinetics and sorption isotherms.
- Operation should be hygienic (no contamination is allowed).
- Flexibility of operation (e.g., dryer design for potato should be usable for carrot).
- Easy to operate and automatic control.
- Process safety (fire- explosion-proof).
- Energy consumption and type of energy used (should be economical).
- Minimum cost and space.

The data related to design should be taken from the actual measurement, previous experience, or from literature. It is preferred to do a pilot plant trial before starting an industrial-scale dryer that could provide a chance to optimize the process parameters as well as desirable product quality. Pilot plant trial may improve design of the dryer or, sometimes, a designer could follow a different approach to obtain desirable product characteristics. Sometimes, drying of vegetables can take place in two different dryers to obtain better quality characteristics. The initial drying requires huge moisture evaporation while the second operation is slower. Thus, a combination of dryers could be beneficia from processing as well as quality points of view.

Quality Parameters and Process Design

The fina goal of a dryer design is to obtain desirable and quality vegetable products. Vegetables are very sensitive to quality changes resulting from drying at higher temperatures. The salability of dried vegetables depends upon the color and texture of the product. The drying parameters used for one vegetable may not be applicable to another vegetable due to different cellular structure, different pigments, and initial moisture content. A fast drying operation may lead to case-hardening of vegetable products where moisture is trapped inside the vegetable by a highly compact surface layer. The hot air drying causes structural changes in foods, due to case-hardening and tissue collapse, which influenc dry texture and inhibit rehydration (Karel 1975). Again, slow drying takes a long time to dry which affects the economics of the manufacturing unit by slowing down production and can raise a concern on food safety. In addition, such a drying regime allows ample time for chemical and enzymatic reactions that may affect nutrients such as vitamin C, degrade fl vor compounds, and alter color (Drouzas and Schubert 1996; Lin et al. 1998).

An optimum process design can maintain the quality of the product, in addition to proper drying.

Dryer Efficiencies

Energy efficien y and cost are practical concerns of the drying process. Generally, energy efficien y is a ratio of the minimum energy required to the energy actually consumed. However, due to the complex relationships of the food, the water, and the heating medium (air), a number of efficien y measures can be worked out, each appropriate to circumstances and therefore selectable to bring out special features important in the particular process (Earle 1993). Efficien y calculations are helpful during the performance evaluation of a dryer, while looking for improvements, and in making comparisons between the various classes of dryers.

Energy consumption of the convective air drying process was calculated as (Durance and Wang 2002):

$$Q = \frac{[(G \times 36750) + (P_1 + P_2)t]}{(W_1 - W_2)} \tag{13.29}$$

where Q is energy consumption per kg water removed (kJ/kg), G is natural gas consumption of process (m^3), 36750 kJ/m^3 natural gas, P_1 is power input of inlet air fan (kW), P_2 is power input of outlet air fan (kW), t is the process time (s), W_1 is initial weight (kg), and W_2 is the weight at end of drying (kg).

The efficien y of air dryers may decrease as the product dries due to product shrinkage that reduces air/product contact. The energy efficien y is found to be lower in the falling rate period; product temperature is also higher because evaporative cooling of the surface is reduced (Durance and Wang 2002). The average energy consumption during air drying of tomato is reportedly about 29,900 kJ/kg (Durance and Wang 2002). Actual cost savings will depend on the relative efficiencie of the dryer designs and heating medium. It is, however, recommended that the most effi cient strategy may be a combination of initial convection drying to remove the less strongly bound water of the constant rate period, followed by dielectric drying to accelerate the falling rate period (Owusu-Ansah 1991).

Conclusion

The drying principles, common terminology, and theoretical modeling used in drying of vegetables have been discussed in this chapter. The EMC and its role in sorption isotherm of dried vegetables are discussed. Recent developments in vegetable drying, heat and mass transfer, and drying time calculation provided in this chapter can help vegetable processors in drying vegetables. Shrinkage,

a real quality challenge in dried vegetables, has been discussed in detail, mentioning different types of shrinkage. The glass transition temperature (T_g) data for dried vegetables would enhance shelf life and food formulation. The design criteria and scale-up of dryers must be preceded with appropriate laboratory and/or pilot-scale experimentation. Considerations for quality of dried vegetables play a significan role in dryer design and selection. Product quality must be an essential part of any vegetable dryer calculation and specifica tion.

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Chapter 14

Drying Vegetables: New Technology, Equipment, and Examples

E. Özgül Evranuz

Introduction

Dehydration of food is not simply a process of water removal but also serves to preserve the structure, sensory characteristics, and the nutritional value of the starting material (Aguilera et al. 2003). The quality of dried vegetables is highly dependent on the type of dryer and the drying conditions as well as the composition and physical properties of the raw material. Quality degradations like shrinkage, decrease in rehydration capacity, and loss of taste, aroma, color, and nutritional value are the main problems to be solved during drying (Sablani 2006).

Conventionally, vegetables are sun or hot air dried. Sun drying is one of the most common drying methods for fruits and vegetables in the tropical and subtropical countries, because of abundant supply of sun energy without any cost. However, in sun drying, the rate of drying is highly dependent on the weather conditions and the end products are of acceptable rather than desired quality (Gallali et al. 2000; Murthy 2009).

Hot air drying is an energy-intensive process and thus must rely on cheap energy sources to be economical (Mujumdar and Huang 2007). In the traditional convection and conduction drying of heat-sensitive materials, there is an upper limit for the drying temperature above which sensory and nutritional quality of the food material decreases in varying amounts depending on the type of the material and time and temperature of drying. The novel thinking in the development of new vegetable drying technologies aims at using a low level of temperatures during drying and/or increasing the heat and mass flu es to obtain better-quality products (Kudra and Mujumdar 2002). The industrial acceptance or application of the new method is, however, dependent on whether it provides higher capacities, better energy efficien y, or lower investment and running costs as well as reduced environmental impact and greater safety in operation (Mujumdar 2007).

There are some recently published books (Kudra and Mujumdar 2002; Chen and Mujumdar 2008; Hui et al. 2008; Ratti 2009) and review papers (Nijhuis et al. 1998, Chou and Chua 2001; Vega-Mercado et al., 2001; Barbosa-Cánovas and Juliano 2004; Raghavan and Orsat 2007) devoted entirely to the traditional and new drying concepts and technologies. In this chapter, an overview of some of the innovative concepts that have been proposed in the scientifi literature and the selected application of these concepts with particular emphasis on vegetable drying will be provided.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Innovative Concepts of Drying

The innovative concept of drying can be described as a new method that provides modificatio of the operative conditions or adaptation of the scientifi developments that fin use in areas other than drying (ultrasound, microwave, RF, PEF, etc.) into conventional drying processes (Mujumdar 2007). The innovative concept of drying contributes to the dehydration process by decreasing the drying time, increasing the energy efficien y, or improving the quality. It is commodity-specific fl xible (a range of combinations can be done), advantageous, but not necessarily cost-effective (Mujumdar 2007; Mujumdar and Huang 2007). In the following sections a general description of some of the innovative concepts that have been reported in the recent scientifi literature is given.

Heat Pump-Assisted Drying

The idea of using heat pumps in drying is to recover both the sensible and the latent heat of vaporization of the hot moist air leaving the dryer and to provide continuous supply of dry air to the drying chamber (Islam and Mujumdar 2008). A heat pump-assisted dryer consists of an evaporator (cold heat exchanger), a compressor, a condenser (hot heat exchanger), and a fan to provide air movement, all enclosed in an insulated chamber (Perera and Rahman 1997). Heat pumps operate similar to refrigerators. Hot moist air from the drying chamber fl ws over the evaporator where the moisture condenses and drained from the dryer. The refrigerant that fl ws through the evaporator coils recovers the sensible and latent heat of condensation and releases it at the condenser to reheat the air within the dryer (Perera and Rahman 1997; Kudra and Mujumdar 2002; Islam and Mujumdar 2008). A heat pump-assisted dryer can advantageously be operated at low temperatures (10°C to 45°C) independent of outside ambient weather conditions or in modifie atmospheres, and is thus a potential alternative to conventional hot air drying of heat-sensitive materials (Perera and Rahman 1997; Chou and Chua 2001; Hawlader et al. 2006; Islam and Mujumdar 2008). Pastes and viscous liquids can also be handled in heat pump drying systems if the liquid or paste materials are frozen to solidify prior to insertion into the drying chamber for freeze-drying at atmospheric pressure (Alves-Filho 2002). Since a heat pump-assisted drier is operated in a closed cycle, higher energy efficiencie are attained albeit the long drying times compared to hot air drying systems (Queiroz et al. 2004; Lee and Kim 2009). Quality of the products dried in heat pump drying system is comparable to that obtained by freeze drying (Alves-Filho 2002; Hawlader et al. 2006). However, there is some concern about the microbial safety of heat pump-dried foods, especially if it is poorly designed and the water activity at the surface increases above the critical value of 0.6, thus promoting microbial growth (Perera and Rahman 1997).

Desiccant Drying

The method is proposed for drying at low or moderate temperatures to preserve the sensory and nutritive quality of the foods and increase the energy efficien y of the dryer (Nagaya et al. 2006; Djaeni et al. 2007). In desiccant or adsorption drying process, the material to be dried is either contacted with a moisture-adsorbent material for the desired adsorption-desorption to take place or the adsorbent is used to lower the humidity of the drying air. In the selection of a sorbent, the type of the product and its end use, sorption characteristics and the commercial availability of the sorbent, the effect of the sorbent/carrier on the material being dried, and the possible upstream and downstream processes are all important factors (Kudra and Mujumdar 2002). Some of the conventional adsorbents are silica gel, zeolite, and bentonites (Kudra and Mujumdar 2002). Rice

husks (Witinantakit et al. 2009) and hazelnut shells (Ak and Evranuz 2000) are reported as potential desiccants for drying paddy and hazelnut respectively. Nagaya et al. (2006) have shown that the air velocity control along with the temperature control provided six times faster drying rate compared to conventional desiccant-based drying wherein only the temperature was controlled. Witinantakit et al. (2009) have reported that initial moisture content of the sorbent had stronger effect than the volumetric mixing ratio in paddy drying using rice husks as adsorbent. Energy effi ciency can be increased by using multistage adsorption dryers (Djaeni et al. 2007; Djaeni et al. 2009). Drying with dehumidifie air has been successfully applied to mushrooms (Gürtaş Seyhan and Evranuz 2000; Nagaya et al. 2006), cabbage, eggplant, carrot, spinach (Nagaya et al. 2006), and tomato pulp (Goula and Adamopoulos 2005). Desiccant drying application has found wide use in solar drying systems (Thoruwa et al. 2000; Hodali and Bougard 2001). The use of adsorbents in fluidize bed drying at high or subfreezing temperatures under atmospheric or vacuum conditions has a high potential for reducing the drying time, and increasing the energy efficien y and quality of the end product (Lombraña and Villarán 1997; Tatemoto et al. 2007; Rahman and Mujumdar 2008a, 2008b).

Use of Electromagnetic Radiation Energy: Infrared, Microwave, Radio Frequency Radiations

Electromagnetic radiation is a fiel that propagates energy in the form of wave which is characterized by wave velocity, wavelength and frequency (Rosenthal 1992). The interaction of radiation with matter involves exchange of energy which is inversely proportional to its wavelength. At the high energy end of the spectrum, there are gamma rays with frequency of 10^{21} Hz and wavelength in the order of 10^{-13} m, and at the low energy end are radio waves of 10^{6} Hz frequency and wavelengths longer than 1 m (Rosenthal 1992).

The energy carried by electromagnetic radiation having wavelengths shorter than infrared (IR) radiation is high enough to induce electronic or chemical changes in the absorbing molecules, and thus absorbed energy does not cause heating in the product (Hoy 2005). However, at wavelengths in IR, microwave, and radio frequency range, the primary effect of incident radiation is heating (Piyasena et al. 2003; Orsat et al. 2007, 2008). The idea behind using electromagnetic radiation energy is thus to make use of this heating in drying processes to speed up the drying rate and to reduce the drying time. The amount of absorbed energy, and hence the degree of heating, varies from zero to complete absorption depending on the incident power and dose, electric fiel strength, and dielectric properties of foods to be heated (Orsat and Raghavan 2009). For each type of radiation there is a specifi piece of equipment available.

Infrared heating equipments are specifi cally designed electric lamps provided with filament or ceramic rods or gas-fire broilers that produce temperatures in the range of 620°C to 800°C (Rosenthal 1992). During IR heating the radiant energy from the heating element is transferred to the product surface without heating the surrounding air (Chua and Chou 2003). IR radiation, because of shorter wavelengths (0.75–100 μm), does not penetrate far into the food, but heat is produced at the surface of the food, creating a temperature gradient from the surface to the center. Heat transfer from the surface to the interior of the food is then by conduction. IR radiators can be used in combination with many type of dryers like tray (Sharma et al. 2005; Mihoubi et al. 2009; Nasiroglu and Kocabiyik 2009), tunnel (Reyes et al. 2008), vacuum (Mongpraneet et al. 2002), heat pump (Chua et al. 2004), and vacuum-freeze (Reyes et al. 2008) dryers.

Electromagnetic radiation in the frequency range from 300 GHz to 300 MHz is known as microwave radiation. In order not to interfere with the communication system, the microwave frequencies of 915 MHz, 2450 MHz, 5.8 GHz, and 24.124 GHz are allocated for domestic, industrial, scientific and medical applications (Piyasena et al. 2003). Microwaves are generated by a device known as magnetron and interact with the matter by way of dipolar rotation and ionic conduction (Orsat and Raghavan 2005). The penetration ability of the microwave radiation into the food is much deeper than IR radiation, so with microwaves "volumetric heating" is obtained (Erle 2005). The interaction of food with microwave radiation is dependent on water content. In addition, inorganic ions of salts dissolved in food also interact with the microwave. The major limitations in microwave drying application are occurrence of hot and cold spots due to nonuniform electrical fiel in the cavity and fast increase in product temperature as the water content is reduced (Erle 2005; Zhang et al. 2006). In order to overcome these drawbacks, the material to be dried should be in constant motion during microwave application so that all its parts get approximately the same dose of energy and/or low levels of microwave power density (Watts/grams of material) are to be used. Product temperature can also be controlled by controlling duty cycle (on/off periods for power) (Erle 2005; Orsat et al. 2007).

The radio frequency (RF) band of the electromagnetic radiation covers the longest wavelengths of electromagnetic spectrum in the frequency range from 300 kHz to 300 MHz, and similar to microwave radiation, RF radiation when absorbed generates volumetric heating in the material. RF heating is affected by the frequency, the square of the applied voltage, the dimensions of the product, and the dielectric loss factor of the material (Piyasena et al. 2003; Orsat and Raghavan 2009; Marra et al. 2009). RF energy can penetrate deeper into the material and generates more uniform heating compared to microwave energy, and hence is suitable for heating large particles (Piyasena et al. 2003; Marra et al. 2009). However, drying applications of RF energy are less common than microwave drying. Some of the food applications reported in the recent literature cover heating for meat processing or postbaking of cookies, crackers, postharvest disinfestations of fruits, microbial inactivation of liquids, blanching, and thawing (Vega-Mercado et al. 2001; Piyasena et al. 2003; Marra et al. 2009).

Superheated Steam or Low Pressure Superheated Steam Drying

The idea behind using superheated steam in drying is to increase the drying rate by increasing the mobility of water in the material to be dehydrated (Mujumdar and Huang 2007). This is accomplished by providing high steam temperature (higher than the inversion temperature) so that water in the material evaporates at the saturated boiling temperature at the operating pressure in the dryer, at a rate faster than that in hot air drying. Since the superheated steam is in direct contact with the material to be dried, there is no resistance to moisture diffusion to the steam and the drying rate in the constant rate period is controlled by the heat transfer only (Kudra and Mujumdar 2002; Mujumdar and Huang 2007; Devahastin and Suvarnakuta 2008). The drying system operates in a closed cycle and comprises of a heat treatment chamber, a compressor, a heat exchanger, and a blower (Chou and Chua 2001). Superheated steam drying provides higher energy efficien y accompanied by higher drying rates, eliminates the occurrence of oxidative spoilage reactions and helps decontaminate microorganisms, toxins, and spores due to its normally oxygen-free and high-temperature environment, and is environmentally friendly (Devahastin and Suvarnakuta 2008). However, superheated steam driers are more complex than hot air

dryers; there is a need for some additional devices for proper working of the system and additional steps before feeding the material into the dryer; the prevailing temperatures in the dryer may not be suitable for the material to be dried; and, finall , unless the steam is needed elsewhere in the process, the energy-related advantages are irrelevant (Kudra and Mujumdar 2002). In superheated steam drying, the drying rate increases with the increase in temperature and velocity at constant operating pressure (Iyota et al. 2001; Pronyk et al. 2004). However, experimental studies have shown that improvements in drying kinetics did not always result in higher quality products (Pronyk et al. 2004).

In the case of low-pressure superheated steam drying (LPSSD) there is no external steam superheater in the system. The saturated steam upon entering the low-pressure drying chamber becomes low-pressure superheated steam since the temperature is already well above the saturation temperature at the reduced pressure of the drying chamber (Devahastin and Suvarnakuta 2008). LPSSD combines the advantages of drying at reduced temperature and pressure with those of conventional atmospheric-pressure superheated steam drying (Devahastin and Suvarnakuta 2008).

Intermittent Drying

The concept of intermittent drying refers to the application of time-varying operating conditions, i.e., time-varying temperature, operating pressure, and/or gas fl w rate (Chou and Chua 2001; Chua et al. 2003). The types of intermittencies employed include on-off pulsating or cyclic/ramp and arbitrary variations of the process parameters (heat input, chamber pressure, and air velocity) wherein the frequency, mode, and the amplitude may be fi ed or variable in time (Chua et al. 2003). In conventional drying, it is generally observed that the drying process takes place mainly in the falling rate period where the rate of migration of water from within the solid to the surface rather than the external conditions is important. Thus, continuous heating as is employed in traditional convective drying results in overheating or overdrying of the surface layers that may cause higher quality changes in appearance and nutritional value. In order to have an optimum control on drying rate, time-varying drying schemes in various dryers have been demonstrated as beneficia strategies (Pan et al. 1999a; Pan et al. 1999b; Chua et al. 2003; Thomkapanich et al. 2007). For example, a tempering period at ambient conditions in-between a continuous supply of heat for drying down to critical moisture content and finis drying provides redistribution of temperature and moisture content, and not only shortens the effective drying time but also improves the quality (Pan et al. 1999a; Pan et al. 1999b). Combination of convective drying method with radiant heating in intermittent mode (Chua et al. 2000), and drying in pulsed flui bed or in a spouted bed are examples of intermittent drying with periodic heat supply (Kudra 2008).

Dehydration by successive decompression makes use of application of alternating vacuum and pressure phases until the desired moisture content is obtained (Chua and Chou 2004). Low pressure application may be continuous at a fi ed level, intermittent, or have a prescribed pattern (Chua and Chou 2004). Chua and Chou (2004) have used a successive pressure drop method for drying potato and carrot, and reported that increase in the number of pressure cycles and higher pressure differences increased the drying rate, but at low pressure levels greater shrinkage was observed in potato.

Electric Field Applications

Application of electric field to vegetables as pretreatment method has been shown to be a promising process for the improvement of both drying rate and the quality (Barbosa-Cánovas and Sepúlveda 2005). Enhancement

of the drying rate is due to the disintegration of the plant tissue during electrical fiel application so that moisture loss from the damaged cells becomes easy (Lebovka et al. 2006, 2007). The electric fiel applications for vegetable dehydration are summarized below:

1. Electrical resistance (ohmic) heating: In this process, the material is placed in between two electrodes and alternating current is allowed to pass through the material, generating heat inside the tissue and thus resulting in temperature increase (Lebovka et al. 2006). A good contact between the material surface and the electrodes is required for effective heating (Fellows 2000). For particulate foods, particles are placed in suitable liquids before subjecting to the electrical fiel or sandwiched between the two electrodes (Lima and Sastry 1999; Lebovka et al. 2006). However, in a two-component system consisting of a liquid and particles, the liquid and the particles should have comparable electrical resistances in order to be heated at an equal rate, otherwise their heating rates would be different from each other (Fellows 2000). Ohmic pretreatment has been shown to cause increased drying rates both in convective (Lima and Sastry 1999; Lebovka et al. 2006) and freeze drying (Zhong and Lima 2003) processes. The electric fiel strength, total electric energy input, as well as the frequency and the wave form are all effective on the drying rate (Lima and Sastry 1999; Zhong and Lima 2003; Lebovka et al. 2006).
2. High-intensity pulsed electric fiel (PEF) application: Ohmic treatment is at the fiel strength under 100 V/cm and the application time continues until the temperature measured at the center of the particle reaches a predetermined value. Alternatively, the material is treated with a direct current electric fiel at a strength of 0.5–1.5 kV/cm for a treatment time within 10^{-4}–10^{-2} seconds to produce the same effect on dehydration rate as ohmic heating but without heating the sample (Ade-Omowaye et al. 2001). This technology is termed as high-intensity pulsed electric fiel (PEF) and has been shown to be effective in increasing the drying rate of carrot (Rastogi et al. 1999; Gachovska et al. 2008), okra (Adedeji et al. 2008), potato (Arevalo et al. 2004; Lebovka et al. 2007), and red beetroots (Shynkaryk et al. 2008). Field strength, number and duration of pulses, and hence the total treatment time are some of the factors involved in PEF processing. However, if the total time for the PEF is long, increase in temperature due to ohmic heating effect during PEF treatment is seen (Lebovka et al. 2007). It has also been shown that PEF can be successfully combined with osmotic dehydration to provide additional improvements in mass transfer (Ade-Omowaye et al. 2002; Amami et al. 2007; Amami et al. 2008).
3. Electrohydrodynamic (EHD) drying: In EHD drying the material to be dried is placed on a fi ed horizontal grounded metallic plate to which a vertically movable electrode with a sharp pointed needle is projected (Chen and Mujumdar 2002). Application of a high voltage between the pointed and the grounded electrode generates an ionic wind (corona effect) which is responsible for the evaporation of water from the food material (Chen and Mujumdar 2002; Bajgai et al. 2006). Factors affecting the drying rate are the level of applied voltage, the electrode gap, sharpness, and the number of the pointed electrodes.

Osmotic Drying

Osmotic drying (OD) is a method in which pieces of food material are soaked in an osmoactive solution wherein the moisture

transfer from food into the solution is effected by the natural osmosis through the cell wall that acts as a semipermeable membrane. The potential benefit of OD are reduced process energy requirements and better quality products (Shi 2008). Solutions of sugars (sucrose, glucose, and fructose), glycerol, starch syrup, sodium chloride, as well as mixtures of sugars or of sucrose and salt are tested for a variety of fruits and vegetables. The driving force for water removal is the concentration gradient between the osmotic solution and the intercellular fluid Since the amount of weight loss that can be achieved by this method is in the order of 30–50%, the osmosed fruits and vegetables are to be dried to the safe storage moisture level by some kind of drying operation such as air, vacuum, freeze, or microwave drying.

The effectiveness of OD depends on: (a) the operational conditions (temperature, contact time, amount of solution, application of vacuum); (b) composition, concentration, and the amount of osmotic solution; (c) size, shape, and pretreatment (freezing, blanching, chemical) of the material to be osmosed (Deng and Zhao 2008; Shi 2008). During OD solute uptake and soluble solids loss are the main phenomena occurring along with the loss of water from the material. By proper choice of the type and concentration of the osmotic solution and of the process parameters, the composition of the material can be modifie and thus the drying behavior can be improved (Torringa et al. 2001; Shukla and Singh 2007; Al-Harahsheh et al. 2009). However, the large volume of residual flui that must be disposed of after the process is completed is the main problem with OD.

Explosion Puffing and "Controlled Sudden Decompression to Vacuum"

The idea behind explosion puffin is to induce a porous structure and hence good rehydrability to the particles drying in conventional hot air dryers. In this method, partially dried material (at about 15–35% moisture content) is heated (30–60 seconds) directly (superheated steam) or indirectly through the walls (gas flam or electric heaters) in a sealed rotating cylindrical vessel ("gun") during which time a high pressure develops (2–4 bars) inside the gun (Grabowski et al. 2006). Then the door of the gun is opened suddenly so that explosion of the material from the gun is accompanied by the expansion of structure (puffing with very rapid evaporation of water. The puffed product is then further dried to the safe storage moisture content. Because of its porous structure the end product has good rehydration property. The process can be operated batch-wise or continuously. The main problem with explosion puffin is the high product temperature after puffing which is about 100°C at atmospheric pressure that is inconvenient for heat-sensitive materials like fruits and vegetables. The method which is called "Controlled Sudden Decompression", or DIC after the French name "*Décompression Instantanée Controllée*," eliminates this drawback because the decompression is toward a vacuum of 0.1 bar. In DIC method, the temperature after decompression is around 40°C instead of 100°C as in decompression to atmospheric pressure. Because of the great temperature difference between the two states just before and just after decompression, more steam is generated, resulting in drier products and higher expansion compared to explosion puffin (Louka and Allaf 2004). A fina drying stage may be required in the DIC process as well. Haddad et al. (2008) have shown that microwave-assisted air dehydration as the fina stage of drying decreased the drying time considerably (5 minutes compared to 2 hours). Air injection after decompression to vacuum to provide an intense cooling and stepwise increase in saturated steam pressure have been found advantageous in the application of DIC process (Louka and Allaf 2004).

Acoustic Drying

Sound energy in drying applications has been effective in improving both the mass transfer rates and the product quality (García-Pérez et al. 2006). The beneficia use of sound energy in food dehydration has been shown in OD (Deng and Zhao 2008), convective (García-Pérez et al. 2009), freeze (Xu et al. 2009), or fluidize bed drying (García-Pérez et al. 2006). The application of sound energy involves gas/solid (García-Pérez et al. 2009), liquid/solid (Jambrak et al. 2007), or direct contact applications (Gallego-Juárez et al. 2007). Rehydration properties of ultrasound-treated samples were found to be higher than those of untreated ones (Jambrak et al. 2007). However, ultrasound-assisted drying mostly remains to be at laboratory scale.

Process Modifications

In Figure 14.1, the main elements and the related features of a drying process are shown. A drying system is define by suitable combinations of these varying features. Traditional vegetable dryers are mostly convective, fi ed, or fluidize bed type dryers operating with continuous heating at atmospheric conditions where the drying medium is usually hot air. Vacuum and freeze drying methods are employed to obtain better quality products but they are more costly than convective drying, traditionally operated batch-wise, and need long drying times.

It is generally found that a suitable combination of innovative concepts with the existing dryer or drying system (including pre- and postdrying equipments) provides improvements in various aspects of drying like drying rate, energy efficien y, and quality of the end product or economies of operation. The *Handbook of Industrial Drying* (Mujumdar 2006) is an excellent source of the latest achievements in the dryers and drying area. In Table 14.1 a brief description of some of the novel fluidize bed dryers is given to show the

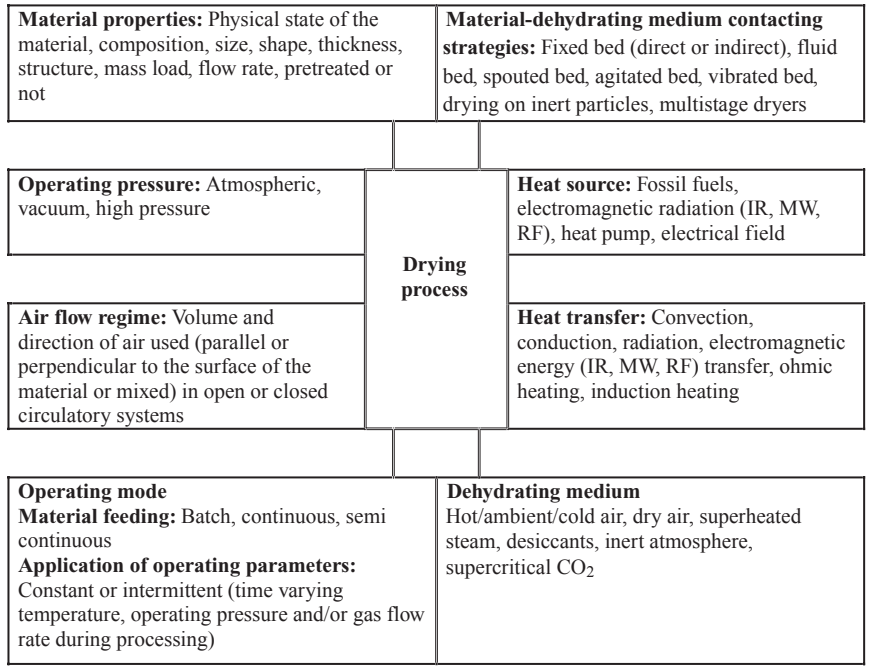

Figure 14.1 Elements of a drying process.

Table 14.1 Description of some of the new fluidized bed dryers for drying

Dryer type	Description
Multistage and multiprocess dryers	Two or more processes or different types of fluidizatio systems are incorporated in a single unit.
Hybrid fluidize bed dryers	A first-stag drying is followed by a fluidize bed dryer for a second-stage drying.
Pulsating fluidize bed dryers	Fluidizing gas fl w is not continuous but the bed of particles is fluidize periodically.
Fluidized bed dryers with immersed heat exchangers	Fluidized beds are equipped with internal heaters or immersed tubes. Both convective and conduction heating are effected.
Vibrated fluidize bed dryers	Vibration is combined with an upward fl w of air in the fluidize bed. Both the fluidizatio gas velocity and attrition are lowered.
Agitated fluidize bed dryers	The agitator serves as a mixer in the dryer. By agitation, a homogeneous fluidize bed is formed without channeling or formation of large bubbles.
Centrifugal fluidize bed dryer	The centrifugal fluidize bed dryer works on the same principle as the conventional fluidize bed dryer except that a rotating chamber is used.
Fluidized bed dryers of inert particles	The inert particles as an auxiliary phase form the fluidize or spouted bed and the suspension is fed into the moving or circulating bed of the inert particles. A thin layer formed on the surface of inert particles dries out in a very short time and is peeled off due to attrition by particle–particle and particle–wall collisions.
Spouted bed dryers	A high velocity jet of gas (spouting air) introduced into a bed of particles transports them to the bed surface and then thrusts them to the freeboard region. After losing their momentum, these particles fall back onto the bed surface, thus creating a circulating motion of the particles.
Recirculating fluidize bed dryers	A tubular draft tube is inserted into an ordinary spouted fluidize bed so that spouting gas stream passes through the draft tube. Unlike spouted beds, there is no limitation of maximum spoutable bed height and minimum spouting velocity.
Jetting fluidize bed dryers	If a fairly large jet replaces the conical centrally located jet in a spout bed, a jetting fluidize bed is formed. One distinctive feature of jetting fluidize bed is that bubbles are formed instead of dilute phase spout.
Fluidized bed dryers with internal baffle	Internal baffle are inserted into a fluidize bed to divide the bed into several compartments in order to limit bubble growth and coalescence.
Superheated steam fluidize bed dryers	Superheated steam is used as the fluidizin medium.
Heat pump fluidize bed dryers	A fluidize bed drying system is combined with heat pump drying system, so that dehumidifie and heated air is charged into the chamber from the bottom of the chamber.

Source: Compiled from Mujumdar (2006) and Hui et al. (2008).

variety of modification that can be done. In the development of a new technology the main concern is to have better control on the heat and mass transfer rates to and from the wet material. Microwave heating and heat pump drying are good examples of developments achieved in fruit and vegetable drying that have some industrial applications already.

Microwave-related Drying Processes

Microwave drying draws the attention of researchers because of its instantaneous volumetric heating effect. In order to remove the water evaporated from the surface of the material, a forced air stream (microwave convective drying or microwave drying) or vacuum (microwave vacuum drying) is employed (Orsat et al. 2007; Chou and Chua 2001). Microwave drying has been successfully employed to increase the drying rate and/or the quality of various vegetables, e.g., mushrooms (Funebo and Ohlsson 1998), potatoes (Khraisheh et al. 2004), okra (Dadali et al. 2007a), spinach (Dadali et al. 2007b), and carrots (Prakash et al. 2004). In microwave

drying the controlling factors are power density and the air fl w rate. Sharma and Prasad (2001) have reported that the effective diffusivity increased with applied microwave power and temperature at constant velocity of air, but increasing air velocity at constant microwave power and temperature caused a decrease in effective diffusivity indicating the cooling effect of high velocity air. Although increasing the microwave power increases the drying rate (Prakash et al. 2004; Alibas 2007; Dadali et al. 2007a; Dadali et al. 2007b) at higher levels of microwave power, the product temperature increases that causes color degradation as in hot air drying (Sharma and Prasad 2001; Sutar and Prasad 2007).

Microwave energy is also found beneficia in vacuum and freeze drying where the convection heat transfer is absent or during the falling rate period of drying where the low thermal conductivity of the dried layer slows down the heat transfer to the inner sections of the food material. In those cases, fast heating of the moist center increases the vapor pressure differential in favor of increased moisture vapor transfer to the surface. Microwave vacuum drying combines the advantages of fast heating of microwave energy and evaporation of water at low temperature (Cui et al. 2004; Sutar and Prasad 2007). Microwave vacuum-dried carrot slices (Lin et al. 1998) and tomatoes (Durance and Wang 2002) were characterized by their low bulk density and high rehydration ratio. Sutar and Prasad (2007) reported that during microwave vacuum drying of carrot slices, the drying rate increased with the increase in microwave power but the effect of vacuum on drying rate was insignificant indicating that internal mass transport was the controlling factor in the process. Microwave vacuum drying was successfully applied to green peas (Chauhan and Srivastava 2009), potato (Markowski et al. 2009; Bondaruk et al. 2007), carrot (Yaghmaee and Durance 2007; Sutar and Prasad 2007; Stepień 2008), parsley (Yaghmaee and Durance 2007), cabbage (Yanyang et al. 2004), mushrooms (Giri and Prasad 2007; Funebo and Ohlsson 1998), and garlic (Baysal et al. 2003).

Yanyang et al. (2004) have reported that application of microwave energy increased the drying rate during the falling rate period for cabbage slices. Beneficia effects of microwave finis drying following hot air drying, like energy efficien y, puffing color retention, and improved rehydration ability, were reported by others (Durance and Wang 2002; Alibas 2007; Orsat et al. 2007). Fast heating in microwave fiel can sometimes lead to puffin which may or may not be beneficial However, Baysal et al. (2003) reported that there was not much improvement in rehydration ratio of garlic and carrot samples dried by microwave energy as compared to hot air drying.

Microwave heating in freeze drying has the potential of increasing the drying rate by eliminating the problem of the conduction under vacuum because the microwave energy is directly absorbed by the material irrespective of the partial pressure in the chamber (Elia and Barresi 1998). However, the difficult in controlling the fina quality of the product due to plasma discharge, a phenomenon causing burning on the product surface, prevents microwave-assisted freeze drying from commercialization (Elia and Barresi 1998; Zhang et al. 2006).

It has been shown that the combination of osmotic dehydration with microwave has eliminated the problem of unwanted temperature rise of the product during falling rate period of the drying process (Al-Harahsheh et al. 2009). Absorption of microwave energy depends strongly on the dielectric properties of the material, which in turn are strongly dependent on the composition, moisture content, and the temperature (Heredia et al. 2007). During osmotic dehydration, water and soluble solid contents are modifie by way of moisture loss and solute gain and hence the dielectric properties of the samples subjected to osmotic dehydration change (dielectric constant decreases, loss factor

increases), facilitating absorption of energy without much temperature rise in the product (Reyes et al. 2007; Al-Harahsheh et al. 2009). However, the magnitude of change in dielectric properties depends on the type of osmotic solution and the material used (Heredia et al. 2007).

There are studies on the use of microwave energy in spouted bed (Feng and Tang 1998), fluidize bed (Stanisławski 2005; Souraki et al. 2009), and rotary dryers (Kaensup et al. 2002). Application of microwave energy intermittently (Ahrné et al. 2007) or in incremental stages (Wang and Xi 2005; Yaghmaee and Durance 2007) has resulted in increased energy efficien y.

Heat Pump-related Drying Processes

Heat pump drying is an attractive method providing water removal at minimal energy cost (Orsat and Raghavan 2009). Pal et al. (2008) studied the drying characteristics of green sweet pepper in a heat pump dryer in the temperature range of 30–40°C and found that drying time was less than that in hot air drying at 45°C. Besides, the retention of total chlorophyll content and ascorbic acid content was higher in heat pump–dried samples with higher rehydration ratios and sensory scores. A simulation study done by Lee and Kim (2009) indicated that heat pump drying took 1.0–1.5 times longer than hot air drying but energy saving was considerable. Queiroz et al. (2004) have dried tomatoes adequately in a heat pump drier and reported that compared to an electric resistance drying system, use of heat pump can generate an energy economy of about 40%.

Performance of a heat pump drier can be increased by various combinations. Hawlader et al. (2006) studied drying of apple, guava, and potato in a heat pump dryer under carbon dioxide or nitrogen gas atmosphere. They observed that under inert gas atmosphere, the product appearance and structure were better than that under conventional heat pump drying, leading to fast rehydration ratio, and the quality too was comparable with that obtained by vacuum or freeze drying. Alves-Filho (2002) used heat pump drier in combination with a cold expander to obtain free fl wing powders from cranberry and potato-turnip mixture pastes. In this method, the pasted material is firs cold extruded to obtain a porous structure in frozen state and then dried in two steps: the firs step being atmospheric freeze drying at −5°C and −10°C, and the second step being drying at 20°C and 30°C. The end products were free-fl wing powders with an attractive natural color.

Special Drying Techniques

Atmospheric Freeze Drying

In freeze drying operation, food is firs frozen (−20°C) and then a controlled amount of heat under vacuum is applied to promote sublimation during which ice is directly changed to vapor and subsequently condenses as ice on a refrigeration coil, typically held at −55°C (Claussen et al. 2007). In spite of the suitability of the process for the production of highest quality product in terms of shrinkage, rehydration ability, and other quality attributes (color, texture, taste), the long drying time, very high capital and processing costs, and the need for special packaging to avoid oxidation and moisture pickup make this method suitable only for materials that have high market value (Nijhuis et al. 1998). Besides, it is a batch process. Hence, the strategies employed for the technological development of freeze drying operation for the purpose of reducing drying time are concentrated on the elimination of vacuum and/or condenser to cut down the operational costs, to convert the system to continuous process, or to improve heat transfer by making use of microwave energy (Kudra and Mujumdar 2002; Ratti 2008).

Atmospheric freeze drying (AFD) is a process where the water is evaporated at atmospheric pressure from the material held at

subfreezing temperatures by a desiccant (Rahman and Mujumdar 2008b) or by refrigeration coils (Alves-Filho et al. 2007). Higher temperatures in the range of −3°C to −10°C are employed compared to vacuum freeze drying (Claussen et al. 2007). Potential advantages of atmospheric freeze drying are the ability to operate the system continuously, the low initial cost because of the elimination of expensive vacuum-associated components, and the production of high quality products comparable to the freeze-dried ones (Claussen et al. 2007). However, since water vapor removal is controlled by mass transfer in AFD, the drying rate slows down when compared with conventional freeze drying (Ratti 2001).

Alves-Filho et al. (2007) have presented a concise mathematical analysis of drying kinetics of red pepper in an atmospheric freeze dryer coupled with a heat pump. Drying experiments were conducted at subfreezing temperatures (−3°C, −5°C, −10°C) and above freezing (at 20°C) temperatures. As the temperature increased, the drying time was decreased. The drying rate was about six times higher at 20°C compared to that at −10°C. Although better quality attributes in terms of color and rehydration ratio were obtained for samples dried at subfreezing temperatures, samples dried at 20°C were also of comparable quality. Based on their observations, they suggested combining sublimation with evaporation to improve the dryer capacity without sacrificin the quality (Alves-Filho et al. 2007).

Rahman and Mujumdar (2008b) presented an atmospheric freeze drying system coupled with a vibrated fluidize bed with adsorbent and multimode heat input under atmospheric pressure coupled with a vortex air cooler. Potato and carrot cubes dried at −6°C and −10°C and it was observed that drying kinetics was remarkably improved with the use of adsorbent, such that it took 6 hours to dry to the same moisture level compared to 8 hours without the adsorbent. Vibrated fluidize bed with added adsorbent produced better quality products in terms of rehydration ratio, color, and porosity compared to fi ed bed and vibration without adsorbent. The reduction in drying time makes the system advantageous compared to fi ed bed or vibrated/agitated beds without adsorbent and in comparison to vacuum freeze drying.

Refractance Window® Drying

Refractance Window (RW) drying has been studied as a potential alternative method to freeze drying, spray drying, and drum drying for the production of fla es and powders. The equipment consists of a transparent plastic conveyor band moving over circulating water at 90–95°C in a shallow trough (Nindo et al. 2007). Pureed products that are spread as a thin fil on the moving belt dry rapidly, typically in 3–5 minutes. Heat transfer is mainly by conduction and radiation from water to the sample to be dehydrated and by convection from the heated sample to the surrounding air. In Refractance Window drying, the heated surface is below the boiling point of the water as opposed to 120–170°C in drum driers (Nindo et al. 2007). The cooling section of the equipment is to reduce the temperature of the dried product. The advantages of Refractance Window drying include rapid drying at low temperature where the actual product temperature is below 70°C, lower installation and operation costs (around half of that required for freeze dryers), prevention of the product from being contaminated, higher thermal efficien y because of the reuse of hot water, production of higher quality products (Nindo et al. 2007), and 4–6 logs reduction in microbial load (Nindo et al. 2003a). Nindo et al. (2003a) demonstrated that increasing the water temperature increased the drying rate while drying pumpkin puree. Addition of glycerol or other similar chemicals in order to further increase the temperature of working water was also suggested but not tested. Carrots (Abonyi et al. 2002) and asparagus

(Nindo et al. 2003b) are also successfully dried by RW technology. Retention of color and total α- and β-carotene in RW drying was comparable to that in freeze drying and better than drum drying (Abonyi et al. 2002).

Supercritical Carbon Dioxide Drying

Supercritical CO_2 ($scCO_2$) is widely used for extraction purposes in the food industry as an alternative to toxic organic solvents (Brunner 2005). In a very recent study, $scCO_2$ was proposed as a potential drying medium for carrot cylinders (raw or cooked with $L = 2.5$ cm and $d = 0.4$ cm) (Brown et al. 2008). The drying experiments were carried out either with pure $scCO_2$ or $scCO_2$ with added ethanol ("ethanol modified" for which the solubility of water is higher than that in pure $scCO_2$ and compared with convective drying. In this study, carrot samples were treated with compressed CO_2 fl wing at a rate of about 2 L/min (at STP) at a constant pressure of 20 MPa and the temperatures were kept at 40°C, 50°C, or 60°C for both $scCO_2$ and convective drying processes. Drying experiments with ethanol modifie $scCO_2$ was followed for additional 30 min pure $scCO_2$ drying to remove all ethanol from the system and thus to prevent the carrots from being wetted by the residual ethanol prior to depressurization. Effects of various parameters on drying rate, microstructure, texture, and rehydration ability were determined. It was observed that although the heat and mass transfer mechanisms were different from conventional drying method, increasing the temperature increased the drying rate in $scCO_2$ drying similar to air drying. Retention of the original structure and color was better than air drying, and the texture of rehydrated samples that were dried with modifie $scCO_2$ was even closer to the original texture of raw carrot. This work has shown that use of pure and modifie $scCO_2$ as a drying medium had potential for obtaining a high-quality product, though in a longer drying time compared to hot air drying.

Conclusions

Maximization of the quality of the end product while minimizing or at least reducing the cost and impact on environment of a dehydration process are the challenges before scientists studying food drying. Even a brief examination of the current literature produces a large number of studies presenting various creative ideas and methods. It is hoped that some of the novel technologies presented in this chapter have shown how unlimited the novel thinking is. Most of the studies proposed in scientifi literature are tested at laboratory level. However, taking the concept and making it a real process needs a close cooperation between the academia and the industry. It is believed that higher quality expectations of consumers would accelerate the industrialization of novel concepts of drying in the near future.

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Chapter 15

Minimal Processing and Novel Technologies Applied to Vegetables

Jasim Ahmed and Tanweer Alam

Introduction

The conventional processes for vegetables such as canning and drying have somewhat negative effects on their nutritional and sensory qualities. The aim of the minimal processing (MP) and novel technologies, such as high-pressure processing (HPP), pulsed electric field and ionizing radiation, is to deliver fresh-like vegetables with a shelf-life of about a week at refrigerated (~4°C) temperatures, and ensuring food safety, nutritional and sensory qualities (Wiley 1994). The minimal processing operations include grading, washing, sorting for size and defects, trimming, peeling, slicing or chopping, packaging, and appropriate storage. These operations are aimed at producing convenient fresh-like products that can be prepared and consumed directly (Burns 1995).

The earlier concept of minimal processing was to maintain freshness by keeping biological tissues alive, but now it also includes steps to slow down cellular metabolism (e.g., respiration and enzymatic changes) to extend shelf-life and fresh-like qualities (Huxoll and Bolin 1989; Ohlsson 1994). The minimally processed vegetable products offer various advantages such as (1) convenience by saving consumers' time for washing, peeling, cutting, and other preparatory steps, (2) supply of a variety of ready-to-eat items with uniform quality, (3) prepackaging for more efficien portion control, and (4) potentially lower transportation costs. In this chapter, we discuss processing and quality of minimally processed vegetables (MPV) and application of selected new technologies in minimal processing.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Production of MP Vegetable

To maintain fresh-like qualities, MP vegetables are normally produced closer to the production centers. The choice of vegetables and their varieties is important criteria, and the harvested vegetables are stored refrigerated before the good manufacturing practices (GMP) and hazard analysis critical control points (HACCP) based processing operations, which are briefl described below (Figure 15.1):

Cleaning and washing: This helps to eliminate soil, dirt, pesticide residues, and lowers the product temperature. The washing system has to ensure adequate surface contact by agitation and enough contact time for sanitizers. Different types of salt (sodium hypochlorite, potassium bicarbonate, calcium chloride) have been used to sanitize and surface sterilization of the product. Chlorine dioxide (ClO_2) has received attention as a decontaminant for vegetables, largely

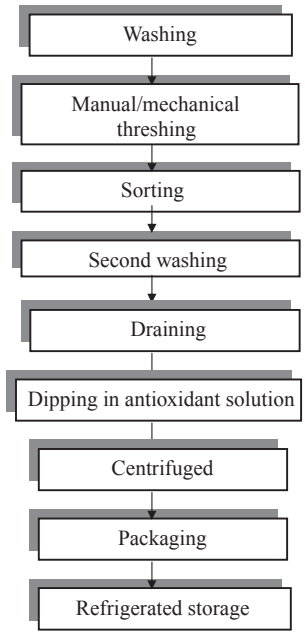

Figure 15.1 A flow diagram of typical minimal processing operations for vegetable.

because its effica y is less affected by pH and organic matter and it does not react with ammonia to form chloramines, as do liquid chlorine and hypochlorites (Beuchat and Brackett 1990). Dipping whole vegetables, cucumbers, green bell pepper, and zucchini in 5–10% hydrogen peroxide (H_2O_2) for not more than 2 minutes prior to slicing is effective in delaying tissue softening.

Peeling: There are different types of peeling method available. Most of these are mechanical operations; however, peeling may be done by thermal and chemical methods also. Care must be taken to avoid bruising and cellular damages (Huxoll and Bolin 1989) because these injuries to plant tissue initiate enzymatic changes (Watada et al. 1990) and any step taken to inactivate enzyme may diminish the fresh-like quality of the product. Peeling on an industrial scale is generally accomplished mechanically (e.g., rotating carborundum drums), chemically or in high-pressure steam peelers (Wiley 1994).

Cutting and shredding: The cutting and shredding must be performed with sharp stainless steel knives or blades. It was reported that chopped lettuce prepared with a sharp knife had a shelf-life double than the lettuce chopped with a dull knife. Further, slicing manually with a blunt knife or with machine blades showed higher *Escherichia coli* and *Listeria innocua* counts during storage than slicing manually with a razor blade (Gleeson and O'Beirne 2005).

Anti-browning treatment of cut vegetables: The enzymatic browning is one of the limiting factors affecting the storage of fresh-cut vegetables (Brecht 1995). In vegetables, browning occurs due to the oxidation of polyphenols. Oxidative browning is catalyzed by polyphenol oxidase (PPO). The browning caused by PPO can be prevented by (i) exclusion of molecular oxygen, (ii) incorporation of reducing agents (ascorbate, thiols, bisulfite) (iii) thermal treatments, and (iv) lowering of pH to below 4.5 (Whitaker and Lee 1995).

Several techniques, such as the application of sulfite and ascorbic acid, have been proposed to prevent browning in fresh-cut products (Sapers and Miller 1992). The use of sulfit has been reduced in the food products worldwide because there is a significan increase in the number of people showing allergic reactions (Wiley 1994). Calcium chloride (0.5–1.0%) maintains firmnes and reduces microbial growth of carrot shreds. A citric acid dip inhibited the development of browning and extended storage life (Kim and Klieber 1997). Citric acid and ascorbic acid alone or in combination with potassium sorbate in the case of potato seem to be promising alternatives for sulfites particularly when hand peeling is used.

Packaging and storage: MPV should be packaged in appropriate material, with suitable moisture- and gas-barrier properties. It is suggested to store processed and packaged vegetables at low temperature (~4°C) to minimize enzymatic activities. In addition, refrigerated storage results in less biochemical and microbiological changes (Elliot and Michenoer 1965).

Physiological Effects of Cutting Vegetable Tissue

The physiology of minimally processed vegetable is essentially the physiology of the wounded tissue. The type of processing applied during minimal processing (e.g., abrasion peeling, slicing, chopping, or shredding) differs from traditional processing in that the tissue remains viable or fresh during subsequent handling (Brecht 1995). However, the wounding of tissue accelerates deterioration and senescence in vegetables and consequently increases respiration and ethylene production rates. The factors that can affect the intensity of wound response in minimally processed tissues include variety, physiological maturity, extent of wounding, temperature, oxygen and carbon dioxide concentration, water vapor pressure, and various inhibitors. Excellent reviews on physiological aspects of MP have been reported by Huxoll et al. (1989), King and Bolin (1989), and Millers (1992).

Effect of Cultivar and Related Factors

Toivonen and De Ell (2002) reported that the response of cultivars to cutting differs in production of sulfur volatiles and accumulation of phenolics, browning, membrane deterioration, and response to high CO_2 and susceptibility to microbial attack. Hence, it is important to consider the effect of cultivar on initial physiology and quality of raw vegetables and the subsequent impact on the acceptability of minimally processed and packaged vegetables by the consumers.

Physiological maturity: Impact of the physiological maturity of vegetables on the wounding response has been studied by several researchers. Immature carrots on injury produced greater amounts of isocoumarin, a compound responsible for bitterness, compared to mature carrots (Lafuente et al. 1996). Most vegetables are better suited to minimal processing in less mature physiological stages; some commodities such as bell pepper may be most suitable at more advanced stages of maturity (Toivonen and De Ell 2002).

Preharvest crop management: Good pest and disease management, irrigation, and calcium nutrition are some preharvest factors that have significan effect on the quality of MPV (Toivonen and De Ell 2002). The climatic conditions and geographic location play significan roles in fresh-cut vegetables. It was found that carrots of the same cultivar grown in different geographical regions produced different levels of phenolics in response to shredding (Babic et al. 1993).

Quality of Minimally Processed Vegetables

As a result of tissue damage during preparation (e.g., cutting, slicing, shredding, peeling, and trimming), MP vegetables exhibit rapid quality deterioration (e.g., browning, off-fl vor, and tissue softening) under ambient storage conditions (Ahvenainen 1996). In addition, exudates from the cut surface can serve as a medium for fungal and bacterial growth, increasing the health risks for the consumers (Brecht 1995). Further, due to continued respiration and enzymatic activity, MP vegetables can suffer changes in nutritional values.

Effect on Selected Nutrients

Unit operations such as cutting and slicing expose large surface area of vegetables to atmospheric oxygen. Ascorbic acid is significantl affected by light, oxygen, heat, enzymes, and metals (Albrechet et al. 1991). Gimnez et al. (2003) observed up to 66% loss of ascorbic acid during storage of minimally processed borage for 15 days (*Borrago officinali*). Slicing of lettuce reduced ascorbic acid, and the maximum retention was found in manually sliced (Barry-Ryan and O'Beirne 1999). In fresh spinach, Simonetti et al. (1991) reported a 10% decrease in β-carotene at 4–6°C after 21 days. Kaur and Kapoor (2000) reported β-carotene losses of up to 18% after 8 days at 4°C although no changes were reported for the xanthophylls neoxanthin, violaxanthin, and lutein. A significan loss of β-carotene was reported while minimally processed carrots were exposed to atmospheric oxygen (Howard and Dewi 1996).

Effect on Sensory Qualities

Texture

Textural changes are among the main causes of quality loss for minimally processed vegetables. However, the texture is rarely maintained for more than 1 week even under optimal storage conditions. The MPV that preserve firm crunchy textures are highly desirable because consumers associate these textures with freshness and wholesomeness (Bourne 2002). Processing results in loss of turgor and consequently affects texture (Alzamora et al. 2000). The changes occurring in cells during senescence include conversion of insoluble protopectin to pectin, decrease in cellulose crystallinity, decrease in galacturonic acid, reduction in cell volume, thinning of cell walls, folding of cell walls, decrease in uronic acid, and increase in soluble uronide (Labavitch 1981; King and Bolin 1989). The enzymes catalyze depolymerization of cell membrane and cell walls, and cause loss of cellular turgor and hence, texture (Huxoll et al. 1989; King and Bolin 1989). Therefore, membrane integrity must be maintained, and the onset of senescence must be delayed to maintain the quality of MPV (Rolle and Chism 1987).

Martın-Diana et al. (2007) studied textural and microstructural changes in fresh-cut lettuce over 12-day storage period. The lettuce was treated with 120 ppm chlorine and with 15 g/L calcium lactate at room temperature (18–20°C) and at 50°C (heat-shock). The fresh-cut lettuce treated with chlorine showed a higher loss of turgor than samples treated with calcium lactate at room temperature and at 50°C. The texture analysis of lettuce confirme that calcium lactate-treated samples had significantl higher crispness values than samples washed with chlorine. A combination of calcium lactate and 50°C washing temperature maintained the sensory quality and texture of fresh-cut lettuce better than the calcium lactate or chlorine washing treatments at room temperature.

Color and Appearance

A minimally processed product should have a fresh appearance, an acceptable color and free from defects (Shah and Nath 2006). The discoloration is the main factor that influence their appearance. For example, decreased green pigmentation in fresh-cut lettuce may result from senescence, heat exposure, or acidification browning may be caused by enzymes; and white blush development in carrots may be caused by desiccation (Garcia and Barrett 2002). Celery leaves turn yellow during storage, which is undesirable to consumers. An unacceptable color change from green to yellow was observed within 20 days of storage (Rizzo and Muratore 2009).

Tristimulus colorimetry has been accepted as the best and simplest instrumental method for specifying visual perception of food products (Ahmed and Ramaswamy 2006). Visual color change and chlorophyll degradation

of spinach during storage temperature and period indicated that color differences (ΔE) increased at all storage temperatures and were most rapid at higher temperatures (Gnanasekharan et al. 1992; Ahmed et al. 2002; Pandrangi and Laborde 2004).

Flavor

Flavor changes may occur due to the loss of compounds, which are responsible for good fl vor or from the accumulation of compounds that produce off-odors. Removal of peel tissues during minimal processing of carrots promoted diffusion of volatile fl vor terpenoids and loss of 72% of total terpenoids in over 2 weeks of storage (Howard and Dewi 1996). Development of off-fl vors may be due to either physiological or microbiological degradation. Microbial metabolites may also produce off-fl vor in the products that are undergoing spoilage. Lipoxygenase (LOX) plays significan role in fl vor changes. Flavor production by LOX pathway is generally quiescent unless triggered by maceration of cell damage (Gardner 1991). The free radical intermediates generated by LOX damage biological membranes and produce a number of free fatty acids (Biale 1975). These free fatty acids are the major precursors of volatiles, which are responsible for undesirable aroma of stored product.

Effect on Microbial Quality

The fresh vegetables are contaminated at the farm environment and during postharvest handling and processing (Beuchat 1996). The damage to the surface tissues during preparatory stages of minimal processing exposes the cytoplasm and provides a potentially richer source of nutrients for the microorganisms than the intact produce. This together with the high water activity facilitates microbial growth in minimally processed fruits and vegetables. The nature and number of contaminating microorganisms depend on the type of the commodity and environmental conditions. Coliforms, fecal coliforms, pectinolytic species, lactic acid bacteria, and yeast and molds have been isolated from the cut surfaces and minimally processed fruits and vegetables (Brackett 1994). The microbial counts ranged from 10^1 to 10^9 cfu/g depending on the type of vegetables (Haerd 2002). Most (80–90%) of the bacteria were Gram-negative rods, predominantly pseudomonads (Nguyen-The and Carlin 1994; Bennick et al. 1998). The mold counts on cut lettuce, shredded vegetable packs and shredded carrots were reported to increase from 10^2 to 10^8 cfu/g. However, the degree of spoilage did not always correlate with the microbial populations, and the spoilage was microbe-specifi (Haerd 2002).

Novel Technologies in Minimal Processing of Vegetables

Emerging novel technologies including irradiation, ozone treatment, ultrasound, pulsed electric fields HPP, ultraviolet rays, ohmic heating, radio frequency, and microwave heating are being investigated for food processing. These technologies offer advantages over conventional canning and drying in terms of retention of nutritional, quality (color, texture), microbial, and sensory characteristics. However, the cost of the novel processing technologies is relatively high, and their commercialization is still in early stages. Interestingly, the consumer awareness about these technologies is also limited. Table 15.1 shows data from a 2006 US survey to assess awareness about HPP's role in enhancing food safety, general attitudes about new processing techniques, and consumer willingness to pay for HPP-processed products (Hicks et al. 2008). The survey respondents were less aware of alternative technologies, such as irradiation, UV light, and ozone. Initially, only 8% of survey respondents reported awareness of HPP; however, following an explanation of the technology in the survey questions, 37%

Table 15.1 Consumer awareness of traditional versus alternative food-processing technologies

Traditional technology	Percent aware ($n = 1,204$)	Alternative technology	Percent aware ($n = 1,204$)
Canning	95	UV light	45
Freezing	94	Radio frequency	10
Cooking (heating)	92	Pulsed electric fiel	3
Microwaving	80	Irradiation	54
Drying	78	Pulsed light	3
Pasteurization	94	Ozone	11
Freeze-drying	88	Ohmic heating	2
Concentration	73	Electromagnetic	6
Smoking (meat/fish	89	High pressure	37

Source: Hicks et al. 2008.

of respondents indicated they were familiar with the technology, but perhaps not the exact terminology.

In the following section, brief description of novel technologies and their applications to vegetable processing is discussed.

Ionizing Radiation

A low-dose irradiation (0.19 kGy) significantly reduced microbial population and moderately increased respiration in packaged cut lettuce and shredded carrot (Hagenmaier and Baker 1997). A dose of 1 kGy of irradiation decreased the number of bacteria and fungi in fresh-cut celery by the order of 10^2 and 10^1, respectively, and the number of *E. coli* was decreased to less than 30 (Lu et al. 2005). In addition, their results showed that PPO and respiration rate of irradiated fresh-cut celery were lower than those of nonirradiated. The vitamin C, soluble solids, total sugars, and the sensory quality of irradiated celery were also better than the nonirradiated.

Evaluation of the irradiation effects (0.5–2.0 kGy) on MPV (coriander, mint, parsley, lettuce, and watercress) showed that there was no difference in the overall sensory and physical properties after irradiation of up to 1 kGy (Trigo et al. 2009). Based on the D_{10}, the amount of radiation necessary to kill 1×10^{-5} *E. coli* and *L. innocua* was between 0.70 and 1.55 kGy. The shelf-life of irradiated coriander, mint, and lettuce samples treated with 0.5 kGy ionizing radiation increased by 2, 3, and 4 days, respectively, as compared to nonirradiated samples.

Pulsed Electric Field

The pulse electric fiel (PEF) treatment is the second most popular food preservation method among novel technologies. It is expected that application of PEF treatment would be less detrimental than heat treatment for plant tissue ingredients such as pigments, vitamins, and fl voring agents. This process has been studied as a nonthermal treatment for food pasteurization (Eshtiaghi and Knorr 2002). However, the PEF technology is mostly suitable for liquid foods to increase their shelflif while maintaining the organoleptic qualities. During the past few years, a significan effort has been made to use this technology on a commercial scale for pasteurization of food (Huang and Wang 2009). The PEF treatment of liquid foods is based on the application of high-intensity electric fiel to the food product as it fl ws between two electrodes. In general, PEF treatment systems consist of a pulse generator, treatment chambers, a fluid-handin system, and monitoring systems (Rivas et al. 2006), in which a PEF treatment chamber is used to house electrodes and deliver a high voltage to the food material. The chamber is mostly composed

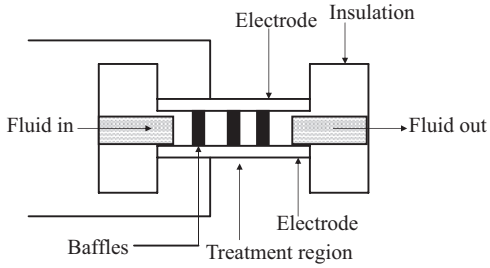

Figure 15.2 A continuous pulse electric field for liquid food processing.

of two electrodes held in position by insulating material, which forms an enclosure containing food material. PEF treatment of flui food is shown in Figure 15.2. The design of the treatment chamber is one of the important factors in the development of the PEF treatment for nonthermal pasteurization, as it should impart uniform electric fiel to foods with a minimum increase in temperature and the electrodes should be designed to minimize the effect of electrolysis (Toepf et al. 2005).

The PEF treatment process may be either static or continuous. While in the static processing, discrete portions of flui foodstuff are treated as a unit by subjecting all the flui to a PEF treatment chamber, in which uniform fiel strength is substantially applied to all elements of foodstuff to be treated; in the continuous processing, the treated foodstuff is fl wing into and emitted from the PEF treatment system in a steady stream by a pump (Wan et al. 2009), and the design of the treatment chamber is a gradual development from static treatment chambers to continuous treatment chambers.

PEF Treatment for Vegetables

Lebovka et al. (2004) studied the effect of combined mild heat and PEF treatments on the texture of carrots and potatoes. The PEF treatment caused a nonthermal rupture of cellular membranes and loss of the turgor component of cells. Despite this effect, however, the carrot and, especially, the potatoes retained hardness after the PEF treatments. The loss of turgor, induced by PEF, did not change the texture properties of the carrot and, especially, potato, where starch is the major component of the dry matter.

Ohmic Heating

Ohmic heating (OH) is define as a process where electric currents (primarily alternating current) are passed through foods or other materials with the primary purpose of heating. Heat is generated volumetrically, which results in rapid and uniform heating, thus the product does not experience a large temperature gradient within itself. In some cases, it is possible to heat the center of the particle faster than the liquid (Sastry and Palaniappan 1992). OH has great potential in a large number of food processing applications; FDA (1998) considered this process for future applications including its use in blanching, evaporation, dehydration, fermentation, and extraction.

The OH is based on the passage of electrical alternating current (AC) through a body like a liquid particulate system, which serves as an electrical resistance. The novelty of such electric heating system is on direct transfer of energy from the electromagnetic source to the food material, without heating the heat transfer surface. AC voltage is applied to the electrodes at both ends of the product's body (Figure 15.3). The rate of heating is directly proportional to the square of the electric fiel strength and the electrical conductivity. The electrical conductivity may be varied by appropriate selection of electrode distance or voltage applied. The electrical conductivity increases as function of temperature, which is also another benefi of OH. Further incorporating electrolytes such as salt can enhance the electrical conductivity.

In continuous processes, the product fl ws continuously throughout the heating, holding, and cooling sections similar to pasteurization of liquid foods except the process can handle

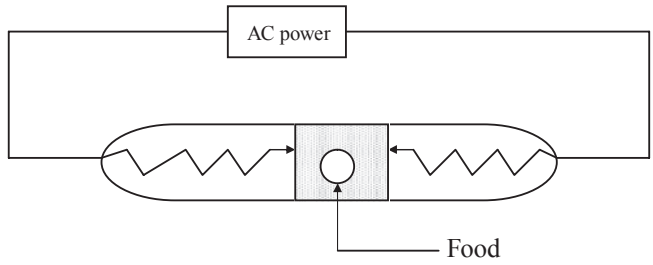

Figure 15.3 An ohmic heating unit.

particulate. Viscous slurry is pumped to the continuous fl w OH system via a feed pump. The slurry is passed through series of electrodes in the OH column followed by the holding section where the product retains for a definit residence time to achieve commercial sterility. The product then passes through the cooling section and packed aseptically.

The possible advantages of a continuous process are an increase in production capacity, a reduction in power consumption, improved treatment homogeneity, and less damage to the particles (Biss et al. 1989). However, the passage from a batch to continuous processing (high temperature short time, HTST) should satisfy numerous criteria: to produce a constant fl w of a homogeneous suspension without blocking or mechanical degradation of particles, while operating over a range of concentrations or electrical conductivities.

The major factors influencin particle velocity in a stream of carrier fluid are viscosity, relative density (particle to fluid) relative size (particle to tube), particle shape, and concentration of the solid phase in the flui (Chandarana and Unverferth 1996). Therefore, it is essential to have a good knowledge of the physical, mechanical, thermal, and electrical properties of the particles and the carrier flui to develop continuous thermal processing. The uses of food-compatible electrodes, which are currently available, produce correct electrical current density.

It is observed that the knowledge and the control of the product's properties lead to the identificatio of several limiting factors (maximal concentration and mechanical degradation of particles, duct plugging, heterogeneity of the suspension fl w or electrical conductivity, heterogeneity in generated heat and heat transfer, widespread of sterilization, or cooking efficiencies in relation with the process or heating technologies. The published physical property data are not suitable for industrial use because most materials are heterogeneous and have a complex structure, and model systems tend to omit many of the minor ingredients in commercial formulations.

OH Treatment of Vegetables

Generally, solid vegetable particles have lower electrical conductivities than liquids, but many factors affect the electrical conductivity: electrolyte concentration, particle orientation and shape, particle concentration, food composition changes and heating effects, viscosity, the temperature, and the liquid/solid electrical conductivity ratio (de Alwis et al. 1989; Sastry and Palaniappan 1992; Khalaf and Sastry 1996; Wang and Sastry 1997; Marcotte et al. 1998). Generally, the size and the shape of the particles are the same (sphere, cylinder), and data from experiments using real food products, as in canned food, are insufficient

OH has been experimented with a wide variety of shelf-stable low- and high-acid products, or refrigerated extended shelf-life products the technology was considered to be viable. OH may provide an effective and an

alternative method for blanching, particularly of whole large vegetables where the process may be accomplished in a relatively short time regardless of the shape and the size of the product (Ruhlman et al. 2001). The energy, dissipated by the electric current passing through the product, is capable of heating it uniformly and at very fast rate regardless of its shape or size. Such a process eliminates any need for dicing of these large vegetables as commonly done prior to water blanching. Therefore, by eliminating the need for dicing, blanching by OH may considerably reduce the extent of solute leaching, as compared to a hot water process, by a favorable combination of a low surface-to-volume ratio and a short blanching time. For example, in the case of whole beets, the extent of soluble pigment loss during blanching by OH was significantl lower than that of 1 cm cubes of the same product during the equivalent process in hot water.

Icier et al. (2006) studied inactivation of peroxidase enzyme during blanching of pea puree using ohmic and conventional heating. The puree samples were heated from 30°C to 100°C and held at 100°C to achieve adequate blanching. The conventional blanching was performed in 100°C water bath. The ohmic blanching at 50 V/cm gave the shortest critical inactivation time of 54 seconds with the best color quality.

The feasibility of processing caulifl wer by OH was investigated by Eliot-Godéreaux et al. (2001). Caulifl wer floret were sterilized in a 10 kW APV continuous OH pilot plant with different configuration of pretreatments and processing conditions. Optimal conditions of treatment are associated with a low-temperature precooking of caulifl wer, a high fl w rate, and a sufficien electrical conductivity of florets The stability of fina products was examined, and textural qualities were evaluated by mechanical measurements. OH treatments resulted in attractive appearance of the product, with better firmnes and a high proportion of 1 cm particles. Stabilities at 25°C and 37°C were verified one case showing the product even stable at 55°C.

Lima and Sastry (1999) found that the lower the frequency of AC used in OH, the faster the hot-air drying rate of sweet potato. Wang and Sastry (2000) showed that ohmically treating sweet potato prior to drying accelerated the hot-air drying rate significantl compared to raw, conventionally treated, and microwaved samples.

Ohmically heated vegetable tissue has been shown to increase hot-air drying rate, shift desorption isotherms, and increase juice extraction yields with respect to untreated, conventionally heated, and microwaved samples. Zhong and Lima (2003) studied ohmically heated sweet potato tissue to enhance the vacuum drying rate of these samples with respect to untreated samples. Sweet potato cubes were ohmically heated and were then placed in a freeze dryer. Results showed that the vacuum drying rates of ohmically heated samples were faster than raw samples for most treatment combinations, and that the maximum reduction of drying time was 24%. Minimal ohmic treatment can result in a signifi cant decrease in vacuum drying time, which could have important economic and product quality implications.

The application of OH for selected vegetables is illustrated in Table 15.2.

High Pressure Processing

Among novel processing technologies, HPP remains the front-runner. HPP applies pressures of 400–600 MPa at ambient temperature to inactivate enzymes and vegetative microorganisms. At the same time, it offers an advantage in minimal deleterious effects on food quality attributes (e.g., color, fl vor, and nutritional value). Pressure is transmitted uniformly and instantaneously throughout the food, which results in a very homogeneous processing impact. To achieve complete inactivation of enzymes, vegetative

Table 15.2 Ohmic heating applied to vegetables

Process parameters	Vegetables and findin	References
Electrodes were connected to an AC voltage source (e.g., 380 V), whereby current was passing through the product via that liquid medium	Blanching of whole vegetable possible under OH that is as effective as sliced vegetables; leaching loss is less	Mizrahi (1996)
10 kW industrial ohmic heater; APV Baker, UK	OH treatments gave a product of attractive appearance, with interesting firmnes properties and a high proportion of particles 1 cm of caulifl wer flore	Eliot-Godéreaux et al. (2001)
EFS 50–90 V/cm; currents 0.1–2.3 A	OH of sweet potato before vacuum drying significantl reduced drying time	Zhong and Lima (2003)
OH temperature of 100°C at 50 Hz frequency; voltages 20, 30, 40, and 50 V/cm	The ohmic blanching applied to pea puree effectively inactivated peroxidase enzyme at less time than the water blanching; the ohmic blanching gave the shortest critical inactivation time of 54 seconds with the best color quality	Icier et al. (2006)

EFS, electrical fiel strength.

microorganisms, as well as spores, high pressure must be combined with a second inactivating factor, which is elevated temperature (Roeck et al. 2008). For vegetable products, particularly cut vegetables, the process is still in early stages. Selected studies in this fiel are shown in Table 15.3. However, the HPP has already been commercialized to a limited extent in Japan, France, the United States, Canada, and some other countries.

Table 15.3 The effect of high-pressure treatment on vegetables

Vegetable type	Process parameters	Major observation	References
Mushroom	200–1,000 MPa; room temperature	PPO activity decreased above 800 MPa for 30 minutes; process is irreversible Intense brown color; *L* decreased; *a* and *b* increased significantl	Liu et al. (2009)
Brocolli	100–150 MPa; 45°C	Myrosinase activity decreased	Eylen et al. (2008)
Whole green bean	500 MPa; 50°C	Retention of firmnes and ascorbic acid compared to conventional preservation methods	Krebbers et al. (2002)
Carambola slice	800 MPa; 40°C for 3 minutes	Maintain best color	
Potato cylinder	200 MPa; −20°C	PPO activity remained constant after freezing and thawing processes; color, drip loss, texture, and microstructure showing better responses	Urrutia-Benet et al. (2007)
Carrot	100–300 MPa; 20°C for 2 minutes	Hardness losses of 5, 25, and 50% were found, respectively	Araya et al. (2007)
Carrot	100–400 MPa (50–70°C); calcium chloride (0.5–1.5% w/v)	Combined treatments increased the hardness of the samples by 9.16 times	Rastogi et al. (2008)
Tomato puree	300–700 MPa; 60 minutes (65°C)	No color degradation of tomato appeared under combined thermal and high-pressure treatment	Rodrigo et al. (2007)

There are two principles that well describe the effects of high pressure: (i) The principle of Le Chatelier, which describes that any phenomenon (phase transition, chemical reactivity and reaction, change in molecular configu ration) accompanied by a decrease in volume will be increased by pressure. In addition, the reaction rate increases with increasing temperature (Arrhenius' law). (ii) Pressure is instantaneously and uniformly transmitted independent of the size and the geometry of the food—what is known as isostatic principle.

The high-pressure chamber is fille with pressure-transmitting flui (commonly water), and high pressure (HP) is generated by compression (direct or indirect) or by heating the pressure medium. Once the desired pressure is achieved, it maintains in that level and no additional energy has to be spent.

HP processing for food and the high-pressure vessel are illustrated in Figures 15.4 and 15.5, respectively. The food material packed in fl xible packaging material is placed in the pressure vessel and closed; the pressure-transmitting medium is applied after degassing of the vessel, and pressure is applied through a high-pressure pump. The resulting volume change due to compression is about 4% at 100 MPa at room temperature and 15% at 600 MPa. The food remains under pressure for specifie treatment time, and

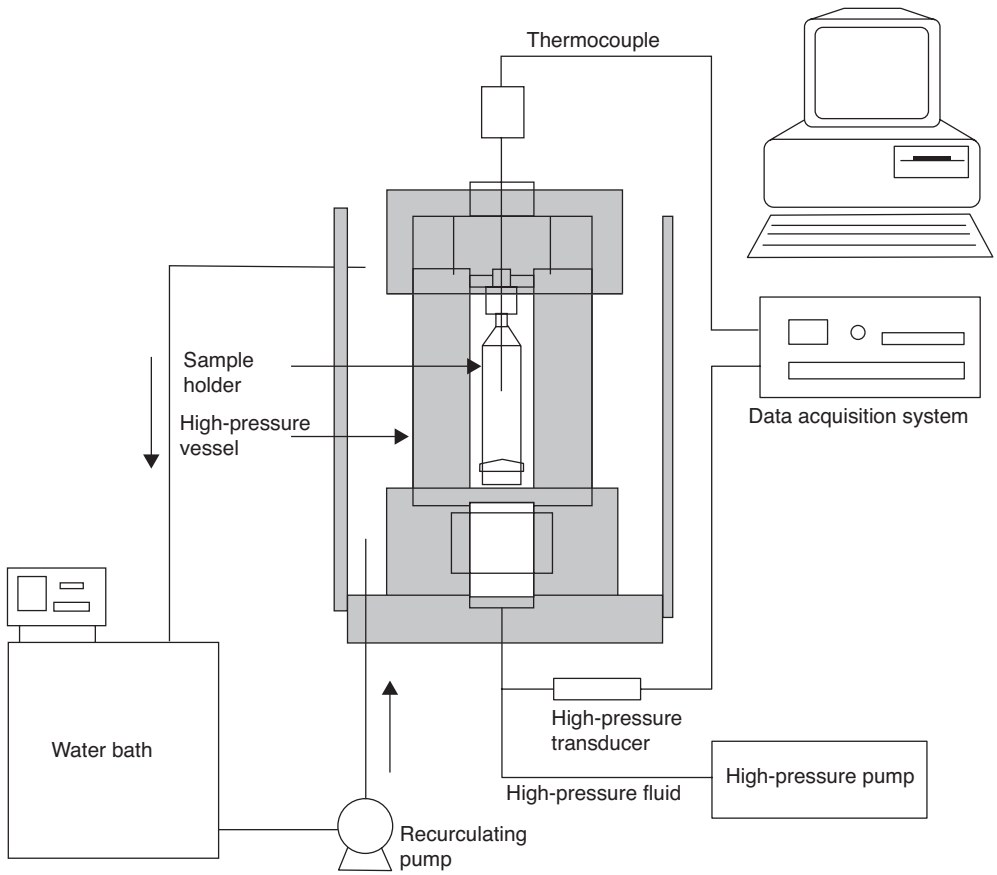

Figure 15.4 High-pressure processing of food. (Adapted from Patazca et al. (2007).)

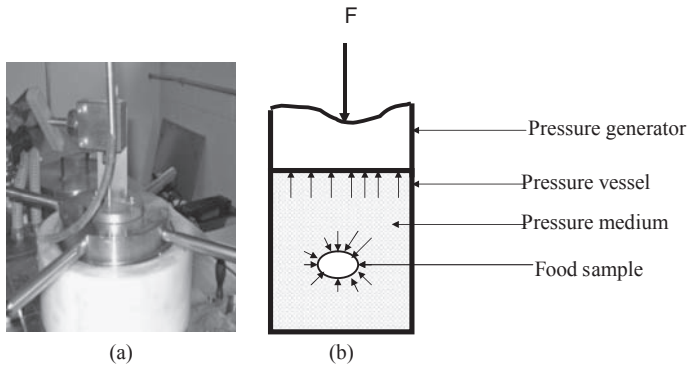

Figure 15.5 A high-pressure vessel: (a) top view and (b) food under pressure in the vessel.

then the chamber is decompressed and treated food is taken out.

High-Pressure Treatment for Vegetables

The primary objective of HP processing of vegetables is the reduction of microorganisms of public health concern as well as spoilage microorganisms, and enzymes. Enzymes are completely inactivated by ultrahigh pressure. Enzymes such as PPO have been inactivated by application of high pressure at low temperature (Hendricks et al. 1998; Weemaes et al. 1999). Various studies indicated reversibility of enzyme activity during storage at ambient pressure and temperature. Generally, pressure up to 350 MPa can be applied to vegetables without noticeable change on texture or structure (Knorr 1995). However, higher pressure has been shown to affect texture and cause discoloration in some commodities; some contradictory results have been reported for HPP-treated vegetables where browning has been noticed after HPP treatment and the products became unacceptable to the consumers because of retention of peroxidase and polyphenol oxidase enzymes (Gomes and Ledward 1996; Mersens et al. 1997; Basak and Ramaswamy 1998). The selection of HP processing depends on various factors such as type of foods, chemical composition, type of microorganisms present in food, initial microbial load, and reaction kinetics of microbial death and nutrient loss.

The effect of high-pressure treatment on mushroom was studied by Liu et al. (2009). Pressurization had a significan effect on the activity of PPO. At pressure of 600 MPa, an increase in the activity was noticed, which is probably due to a transition from the latent to the active state of the enzyme. Higher pressures resulted in an inactivation of the enzyme as a result of denaturation. There were no significan changes in the activity of PPO in 48 hours after pressure treatment. Liu et al. (2009) demonstrated that after high-pressure treatment, the color of mushrooms was significantly affected by the activity of PPO. When fresh mushrooms were pressurized, the lightness reduced significantl compared to the blanched sample. Pressure treatments of 600 or 800 MPa of nonevacuated mushrooms resulted in a dark brown color. The highest pressure used, 950 MPa, gave a slightly better color, but it was still an intense brown.

The combined pressure–temperature (P/T) stability and activity of broccoli myrosinase were investigated by Eylen et al. (2008). With regard to the effect of HP/T treatments on myrosinase activity, it was observed that there was only a limited effect of pressure on activity. The optimal temperature at atmospheric pressure was 40°C, while at elevated pressure the highest activity was found at 45°C

and 100 MPa. In addition, the effect of thermal and HP/T treatments on the cell lysis of broccoli tissue was examined. It was observed that a mild HP/T treatment could inflic cell damage.

Krebbers et al. (2002) studied the effects of HPP treatment and pulsed high-pressure (pHPP) treatment on texture, color, ascorbic acid content, and peroxidase activity of whole green beans and compared it to conventional preservation techniques. The samples were preheated at 75°C for 2 minutes, transferred to the high-pressure apparatus, and processed at 75°C, holding time 80 seconds at 1,000 MPa, with a second pressure pulse of 1,000 MPa after 30 seconds at 0.1 MPa. Due to adiabatic compression, the maximum temperatures at the firs pulse in the vessel for HPP and pHPP were 45 and 105°C, respectively.

Both pressure treatments (HPP and pHPP) exhibited a better retention of firmnes and ascorbic acid for green beans compared to conventional preservation methods. Similarly, pHPP resulted in more than 99% inactivation of peroxidase, whereas after HPP 76% of the initial peroxidase activity remained and further decreased during storage. Tristimulus color values (L, a, and b values) of pressure-treated beans are presented in Table 15.4. HPP treatment increased green color by a marginal increase in $-a$ value. It is suggested that application of HPP (100–800 MPa) causes permeabilization of plant and microbial cells (Dornenburg and Knorr 1993). This causes damage to the chloroplast, resulting in leakage of chlorophyll into the intercellular space. This phenomenon is probably the cause of the (initial) more intense bright green color on the surface of the HPP beans.

Table 15.4 The effect of high-pressure treatment on tristimulus color values of green beans

Sample type	L	$-a$	b
Control	41.5	16.1	22.1
HPP	33.4	16.9	20.4
pHPP	26.6	01.1	14.8

Araya et al. (2007) studied the effects of high pressure on texture of carrot. A reduction of 5–50% in hardness was observed for treatments at 100, 200, and 300 MPa at 20°C for 2 minutes, respectively. At higher pressure levels no further increase in texture losses occurred. It is well known that water under pressure can be compressed up to 15% of its original volume at 600 MPa (22°C) (Castro et al. 2007). Thus, it is expected that above a threshold pressure the tissue might not further compress or be disrupted during processing, hence no further texture loss was observed. The initial hardness loss of carrot is considered as an instantaneous pulse softening or IPS (Basak and Ramaswamy 1998). Their study of pressure-treated carrots showed an IPS of 13.5% and 47% after 10 minutes at 100 and 200 MPa, respectively, although no significan changes in texture were observed after 60 minutes holding time at 100 MPa.

The effect of various physical and chemical pretreatments (pressure 100–400 MPa; temperature 50–70°C; calcium chloride 0.5–1.5%), and their combinations on carrot texture was studied after pressure-assisted thermal processing (PATP) and thermal processing by Rastogi et al. (2008). Pressure (200 MPa), heat (60°C), and calcium chloride (1.0%) pretreatments increased product hardness by 1.2, 2.0, and 2.4 times after PATP and 2.7, 3.6, and 2.4 times, respectively, after thermal processing. The calcium content of the samples positively influence the hardness. The microstructure analysis of PATP carrots indicated that the combined high pressure, heat, and calcium pretreatments well preserved cell structure.

The force–displacement profile for raw and processed carrots are illustrated in Figure 15.6. A shift in displacement at maximum force from 2.5 to 5.0 mm is apparent between the raw and the 550 MPa (for 30 minutes) treated sample, respectively. The peak force required to cut through the sample increased from 21 N for the raw sample to 43 N for the high-pressure processed product.

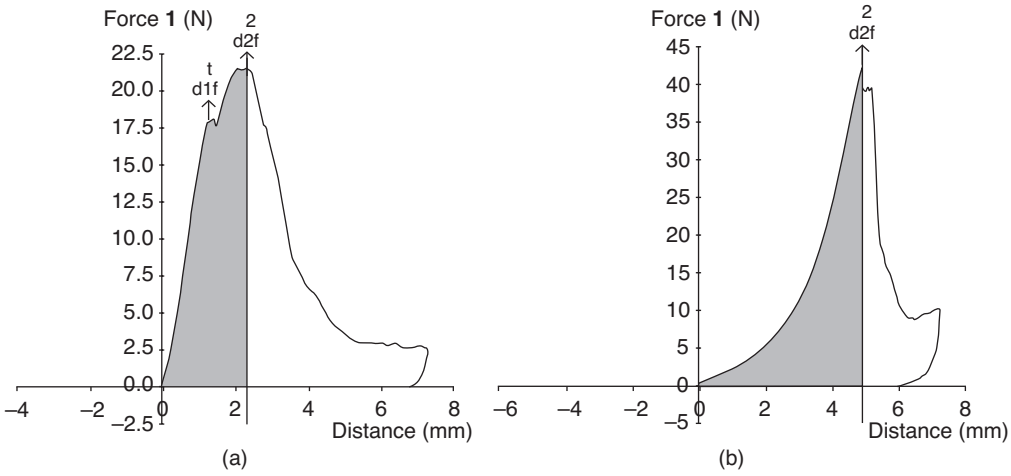

Figure 15.6 Force–displacement curves for the raw carrot sample (a) and high-pressure processed (550 MPa, 30 minutes) carrot sample (b) (Araya et al. 2007).

Bacterial spores highly resistant to pressure and treatment over 1,200 MPa are required for their inactivation. Yeasts, molds, and vegetative cells are pressure sensitive and can be inactivated by milder treatments at from 300 to 600 MPa. Hong and Kim (2001) studied the storage quality of chopped garlic treated with organic acids followed by HPP treatment of 600 MPa, for 1 minute; they reported that the treatment conferred best storage stability to chopped garlic.

Conclusion

This chapter summarizes the principles, influencin factors, and application of minimal processing together with the development of novel technologies to improve the quality, safety, and shelf life of vegetables to meet increasing consumer demand. Minimal processing of vegetables is intended for keeping the freshness of the vegetables in a convenient form without losing its nutritional quality. Because of their composition and physicochemical properties, MPV are considered to be highly perishable when they are not subjected to preservation processes. A number of preservative processes are being used, which include addition of chemical additives, reduction in pH, and use of modifie atmospheric packaging. Recent developments in novel technologies and compatibility for vegetable processing have been explored and discussed. HPP at elevated temperature could be a reality for processing of low-acid vegetables by keeping freshness and safety.

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Chapter 16

Processing of Vegetable Juice and Blends

James S. B. Wu and S-C Shen

Introduction

Vegetable juice and blends are among the major processed vegetable products. They are liquid foods prepared from vegetables as the major raw material. Juices can be classifie into three types, namely clear juice, cloudy juice and pulpy juice, based on the appearance which is reflecte by the content and size of insoluble solids. Clear juice contains no insoluble solids. Cloudy juice is translucent, containing homogeneously suspended tiny insoluble particles. Pulpy juice contains coarse particles that may floa on the surface, suspend in the liquid, or precipitate to the bottom. Cloudy juice is the most popular form of vegetable juice and blends on the market. This chapter reviews processing and quality aspects of vegetable juice and blends.

Heat Processing and Quality

Vegetable juices are obtained by the use of mechanical devices that disintegrate the vegetable and separate the juice as a flui from the solids. The raw juice undergoes processing to make it safe and preserve its quality.

Thermal processing, including blanching, is an important method of preserving foods, and for maintaining sensory attributes such as texture, fl vor, and color. When a vegetable is disintegrated without a previous heat treatment, the enzymes from the cells may be free to act upon the released protoplasmic substances and catalyze undesirable reactions. Most of the vegetables need to be blanched at a temperature high enough to inactivate the enzymes during the early stage of processing. However, blanching process itself may cause some deteriorative effect to the nutritional integrity and the sensory quality attributes of the product. The challenge is to identify an optimum blanching process which inactivates the enzymes properly while preserves the sensory quality attributes and nutritional integrity of the juice most ideally.

Vegetable juice and blends can be a low-acid food at a pH above 4.6, an acid food at a pH between 4.0 and 4.6, or a high-acid food at a pH lower than 4.0. In the preservation of low-acid vegetable juice and blends for long-term storage at ambient temperature, a high-temperature sterilization is often required. The sterilization is much more severe than blanching and often causes serious quality deteriorations such as discoloration, especially loss of chlorophylls in green leafy vegetable juices, off-fl vor, off-taste, coagulation, flocculatio and precipitation. The marketing of many low-acid vegetable juice products is thus hindered.

Acidificatio may convert low-acid juice to an acidic juice and allow the use of milder sterilization conditions, and in many cases improve the quality of the product. Unfortunately, the reduction of pH may cause some

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detrimental side effects, notably the accelerated destruction of chlorophylls in green leafy vegetable juice. The appearance of the brown color downgrades the juice quality thus limiting the use of acidification The canning of green leafy vegetable juices with good color retention remains a difficul task in the industry. Flash sterilization at an ultra-high temperature followed with aseptic packaging may be helpful. However, discoloration may still occur rapidly in the packed product at ambient temperature storage.

Health Functions of Vegetable Juice

Various health functions of vegetable juice have been reported in recent years. Diets rich in fruits and vegetables were found to be protective against the risks for chronic diseases, such as cardiovascular diseases (CVD), arthritis, chronic inflammation and cancers (Middleton et al. 2000; Saleem et al. 2002; Prior 2003; Zhang et al. 2005; Chen et al. 2006). These protective effects are attributed to the presence of various functional components, such as carotenoids, vitamin C, vitamin E, minerals, and fibe (Roy et al. 2007).

In vitro supplementation with deep colored vegetable juices demonstrated immunomodulatory potential via the regulation of Th1/Th2 cytokine secretions, especially Th1 cytokines (Lin and Tang 2008). Vegetable juice may also play an important role in delaying the onset of Alzheimer's disease, particularly among those who are at high risk for the disease (Dai et al. 2006).

Classification of Vegetable Juice and Blends

Based on the pH value, we can classify processed vegetable juice and blends into four categories as follows:

1. Juices prepared from normally acidic produces, such as tomato, rhubarb, and naranjilla.
2. Acidifie vegetable juice and blends. The major raw material is a low-acid or slightly acidic vegetable. The acidifying agent can be an organic acid; citric acid is the most common, or a fruit juice or another vegetable juice with higher acidity, such as citrus, pineapple, tomato, sauerkraut, and rhubarb juices. Tomato juice blends and acidifie carrot juice are examples of products in this category.
3. Acidic juices obtained from fermented vegetables. Lactic bacteria are commonly involved in the fermentation process that reduces the pH. Sauerkraut juice is the most important commercial product in this category.
4. Nonacidifie low-acid vegetable juice and blends, which must be processed at a relatively high temperature to kill microbial spores. There are not many commercial products in this category on the market. Non-acidifie juices of carrot and asparagus are among them.

The processing of the major vegetable juice and blends, covering tomato, tomato juice blends, carrot, sauerkraut and asparagus, as illustrative products to cover all the abovementioned categories is described below.

Tomato Juice

Tomato is an important agricultural commodity in the world. The cultivated tomato plant (*Lycopersicum esculentum*) belongs to the nightshade family (Solaceae). It is a perennial plant that almost universally grows as an annual, although botanically a fruit tomato is considered a dietary vegetable.

The production of tomato around the world exceeded 130 million tons in 2007 (FAO – http://www.faostat.fao.org). The top six tomato-producing countries were China, the United States, India, Turkey, Egypt, and Italy.

Tomato juice is the most important vegetable juice in the industry. Tomato juice and juice products, such as tomato puree, tomato

paste, ketchup, tomato sauces, and tomato soups, are commonly seen on the market.

According to FDA's standard of identity (Marsling 2004), tomato juice is the unfermented liquid extracted from mature tomatoes of red or reddish varieties and strained free from peel, seeds, and other coarse or hard substances while retaining finel divided insoluble solids from the fles of tomato. It may be homogenized, seasoned with salt, acidified concentrated (and later reconstituted with water and/or tomato juice to a tomato soluble solids content of not less than 5.0%), but may not be diluted. It is intended for direct consumption and preserved by heat sterilization, refrigeration, or freezing.

FDA's standard of quality requires tomato juice to be characterized by a strength and redness of color not less than the composite color produced by spinning the combination of 53% of the area from Munsell color disc 1, 28% from disc 2, and 19% from either disc 3 or disc 4 alone, or 9.5% from each of disc 3 and disc 4, whichever most nearly matches the appearance of the tomato juice, and by a number of defects not more than 2 per 500 mL in the forms of peel fragments 3.2 mm or greater in length and blemishes such as dark brown or black particles greater than 1.6 mm in length in addition to the presence of three or more pieces of whole seeds or seed fragments 3.2 mm or greater in length.

Tomato juice has the characteristic color and mildly acid fl vor of tomatoes. It is served at any time of the day as an appetizer, a juice, or a component of cocktail drink. It also find a variety of uses in cooking, preparation of jellied salads for example. Nutritionally, it is an important source of vitamins A and C and has a fir place in both standard and special diets (Leonard 1980). Its composition is shown in Table 16.1.

The manufacture of tomato juice in the factory can be either from fresh tomato fruit or from tomato concentrate (tomato puree or tomato paste). Juice from the fresh fruit is called "NFC (not-from-concentrate) juice," whereas that from the concentrate "reconstituted juice." NFC juice is generally considered having better quality than reconstituted juice. The manufacture of NFC tomato juice involves a series of operations (Figure 16.1) explained below.

Table 16.1 Composition of canned tomato juice

Nutrients	Units	Values per 100 g
Macronutrients		
Carbohydrate	g	4.24
Protein	g	0.76
Total dietary fibe	g	0.4
Total lipid (fat)	g	0.05
Vitamins		
Vitamin A	IU	450
Vitamin B complex		
Folate, total	mcg	20
Niacin	mg	0.673
Pantothenic acid	mg	0.250
Ribofl vin	mg	0.031
Thiamin	mg	0.047
Vitamin B_6	mg	0.111
Vitamin C (total ascorbic acid)	mg	18.3
Vitamin E (α-tocopherol)	mg	0.32
Vitamin K (phylloquinone)	mcg	2.3
Minerals		
Calcium	mg	10
Copper	mg	0.061
Iron	mg	0.43
Magnesium	mg	11
Manganese	mg	0.070
Phosphorus	mg	18
Potassium	mg	229
Selenium	mcg	0.3
Sodium	mg	10
Zinc	mg	0.15
Carotenoids		
β-Carotene	mcg	270
Lycopene	mcg	9,037
Lutein and zeaxanthin	mcg	60
Phytoene	mcg	1,900
Phytofluen	mcg	830
Water	g	93.90

Source: USDA (2006).

Sorting of Tomatoes

Tomatoes are usually passed across a conveyor with inspectors in position alongside to remove extraneous materials and defective fruit. The major defects to be concerned about are overripening, shriveling, discoloration, worm injury, mold and rot.

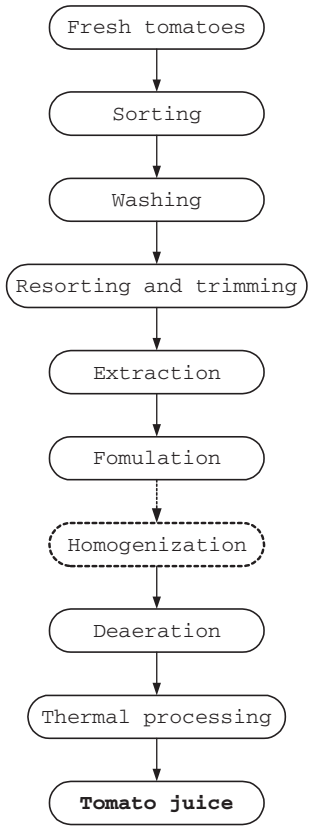

Figure 16.1 A flowchart for the industrial production of tomato juice.

Washing of Tomatoes

The washing operation is to remove contaminants. There are many ways of washing using various equipments. Agitation, heating, and the use of alkali, detergents, wetting agents, foaming agents, and disinfectants have been recommended and proved to be helpful. However, a simple soaking in water, which is changed constantly and maintained at up to 200 ppm of available chlorine, with agitation for about 5 minutes followed by spraying with clean water that reaches every part of the surface with sufficien force works properly on most occasions. Water sprays are usually operated at 0.55–0.69 MPa (80–100 psig) pressure, which removes dirt, microorganisms, and soft decomposed parts without damage to the sound tomatoes (Wu and Nelson 1997).

Resorting and Trimming of Tomatoes

These operations remove the remaining defective fruit, the defective parts, and the oversized cores to ensure good quality of tomato juice. The work is usually done on a roller conveyor, which turns the tomatoes over as they pass through the sorting and trimming area.

To evaluate the cleanliness of fresh tomatoes and the effectiveness of washing, sorting, and trimming in eliminating defective materials, it is customary to take juice samples from the production line and examine by Howard mold count method (NFPA 1992).

Extraction of Tomato Juice

After leaving the trimming area, tomatoes are fed into a juice extraction system to be comminuted into a macerate to start a "hot-break" or "cold-break" process, and then to be extracted for juice. In a typical hot-break process, the macerate is heated rapidly to 82°C (180°F) or above to inactivate pectic enzymes and to facilitate the dissolution of pectin. In the cold-break process, no heat treatment is involved before and during juice extraction. The decision between hot-break and cold-break is mainly based on the desired characteristics of the juice. The hot-break process often produces tomato juice with higher consistency and more cooked tomato fl vor, while the "cold-break" produces juice with some loss in consistency but effectively retains ascorbic acid, fresh tomato fl vor, and natural color (Wu and Nelson 1997). The yield of cold-break tomato juice may be somewhat less than that of hot-break. Tomatoes to be subjected to the cold-break process may be scalded right before resorting and trimming to loosen the peel, so that little fles will cling to it during extraction and reduce the yield.

There are two major types of extractor in the tomato industry: the screw type and the paddle type. Screw-type extractors press tomatoes between a screw and a screen. Paddle-type extractors, such as a common pulper-finishe , beat the tomato against screens. The perforations in the screen are normally about 0.5–0.8 mm (0.02–0.03 in.) in diameter (Lopez 1987). The size of perforations in the finishin screen of a paddle-type extractor is in the same range. Either type of extractor may be adjusted to acquire a high or low yield of juice. A high extraction would yield 3% skins and seeds and 97% juice. However, it may be commercially feasible to extract only 70–80% juice with good quality and leave a very moist residual containing useful tomato material, which can be reextracted for use in other tomato products (Leonard 1980).

Formulation

Salting may smooth the acid taste of tomato juice. The sodium chloride to be added usually varies from 0.5 to 1.25% (w/w). However, lower-salt or no-salt health products are also marketed successfully.

Acidificatio improves the quality of tomato juice directly through the adjustment in Brix/acid ratio, which relates to taste quality, and indirectly through the reduction in pH. A lower pH permits less severity in sterilization and retains more color, consistency, fresh fl vor, and ascorbic acid. Citric acid is commonly used for acidity adjustment (Wu and Nelson 1997).

Occasionally, other additive such as honey is added to tomato juice to improve the taste.

Homogenization

For preventing settling of the solids and to produce a thicker bodied product, tomato juice is sometimes homogenized to break up the suspended particles before canning in machines of the type used for dairy products. An example is to force the juice through narrow orifice at a pressure of 6.9–9.7 MPa (1,000–1,400 psi) at a juice temperature of about 65°C (150°F) (Lopez 1987).

Deaeration

A vacuum deaeration process on tomato juice is usually done to remove the occluded air and the dissolved air right before thermal processing. The deaeration process improves the color, fl vor and ascorbic acid retention in the product. The effect is especially obvious on cold-break juice (Wu and Nelson 1997). It is important to engineer the processing line so that reaeration will not happen to deaerated juice.

Deaeration may also be applied after pasteurization or high-temperature presterilization to remove air incorporated by pumping and, in the case of presterilized juice, to cool the juice to fillin temperature and to prevent foaming in the fille bowl.

Thermal Processing

Tomato juice is an acidic product. However, its natural pH value is normally higher than 4.0, thus permitting the growth of the heat-resistant bacterium *Bacillus coagulans*. This organism has a $D_{110°C}$ value of about 0.5 minute and a *z*-value of about 14°C (Rodrigo et al. 1990). A thermal process that achieves a sterilization value of $F_0 = 0.7$ minute is considered adequate to destroy *B. coagulans* in the juice (Sognefest and Jackson 1947), providing that the factory is in good sanitary condition and that the tomato fruits have been washed properly. In the industry, tomato juice is normally subjected to one of the following thermal processes.

In-Can Processing Without Presterilization

All enameled cans and glass bottles are usually used in the canning of tomato juice. Prior

to filling the cans should be spray washed with large volume of water at a minimum temperature of 82°C (180°F) to remove dusts and adhering materials.

Standard juice filler are adjusted to give a maximum fill which gives the best retention of quality and ascorbic acid. Tomato juice ought to be fille into a can at a minimum temperature of 88°C (190°F) immediately followed with closing to obtain sufficien vacuum. Strainers are sometimes used ahead of the fille bowl.

The sterilization process is usually done in a conventional stationary retort or a rotary continuous sterilizer. The cans are normally processed at 116–121°C (240–250°F) to achieve $F_0 = 0.7$ minute, and followed by cooling in chlorinated water to 35–43°C (95–109°F).

Flash Presterilization Followed by In-Can Processing

The juice is heated in a tubular or plate heat exchanger to a temperature substantially above the boiling point, held for a short interval to achieve $F_0 = 0.7$ minute, then cooled rapidly below the boiling point, followed by fillin into cans at a temperature no lower than 93°C (200°F), closing, inverting, and then holding in a steam environment or boiling water bath for a certain duration depending on the size of can, for example, 3 minutes for No. 10 cans and up to 10 minutes for very small cans. After the holding period, the cans are cooled in chlorinated water to 35–43°C (95–109°F) (Wu and Nelson 1997).

Aseptic Packaging

Tomato juice can also be aseptically processed. It is heated in a heat exchanger system to a temperature well above 100°C (212°F) and held for a short period to achieve $F_0 = 0.7$ minute with some margin, cooled rapidly to about 40°C (105°F), and then packaged aseptically in fl xible containers such as Tetra Brik from Tetra Pak Company.

Tomato Juice Blends

Various vegetables, fruits, and their products may be used in vegetable juice blends or vegetable/fruit juice blends. Among them, cocktail-type tomato juice blends containing appreciable amounts of juice from other vegetables are popular items on the market. For example, a blend made of tomato, carrot, celery, spinach, parsley, beets, and sweet green peppers juices, acidifie with lemon juice and citric acid, fl vored with salt and spice and enriched with vitamin C has been selling good for many years.

Tomato juice adds fl vor, body, and nutritive value and lowers pH of the juice blends below 4.6 to be acidic. All the vegetable and fruit ingredients are usually prepared separately and blended together before thermal processing. Various seasonings may also be added for fl vor and ascorbic acid for nutrient fortification The formulation varies from factory to factory. The rest of the processing procedure is similar to that used in the manufacture of tomato juice.

Bioactivity of Tomato Lycopene

Tomato fruit and their processed products are a major source of lycopene. It is a carotenoid and the primary pigment responsible for the distinctive red color of ripe tomatoes and tomato products. These food items supply more than 85% of all the dietary lycopene.

Table 16.2 shows the lycopene contents of tomato and some commonly consumed tomato products. The amount of lycopene in fresh tomatoes varies with the variety, maturity, and environmental conditions. The concentrations of lycopene are 0.72–20 mg/100 g in fresh tomatoes (Shi and Le Maguer 2000) and 5.00–11.60 mg/100 g in tomato juice (Clinton 1998), respectively.

Table 16.2 Lycopene contents of tomato and tomato products

Items	Lycopene content (mg/ 100 g wet basis)
Tomato fresh*	0.72–20
Tomato juice†	5.00–11.60
Tomato sauce†	6.20
Tomato paste†	5.40–150.00
Tomato soup, condensed†	7.99
Ketchup†	9.90–13.44
Pizza sauce, canned†	12.71
Spaghetti sauce‡	9.3–18.2
Barbecue sauce‡	7.6
Whole canned tomato§	5.87–42.14

*Adapted from Shi and Le Maguer (2000).
†Adapted from Clinton (1998).
‡Adapted from Lugasi et al. (2004).
§Adapted from Marković et al. (2006).

Lycopene is a lipophilic, 40-carbon atom, highly unsaturated, straight chain hydrocarbon consisting of 11 conjugated and 2 non-conjugated double bonds. Due to the presence of double bonds in the structure, lycopene can exist in both the *cis* and *trans* isomeric forms. Naturally occurred lycopene is primarily in the all *trans* forms. However, it may undergo mono- or polyisomerization by light, heat, in the sterilization of tomato juice for example, and chemical reaction to be converted to *cis* forms (Figure 16.2). Several *cis* isomers of lycopene, including 5-*cis*, 7-*cis*, 9-*cis*, 11-*cis*, and 13-*cis* isomers, have been proved to be more antioxidative than the all *trans* isomers (Chasse et al. 2001).

Endogenously or exogenously generated reactive oxygen species have been proposed in playing a major role in the pathogenesis and progression of several chronic diseases including cancer and CVD. Reactive oxygen species may react with cellular components, causing oxidative damage to cellular biomolecules such as lipids, proteins, and DNA (Halliwell 1994; Witztum 1994; Ames et al. 1995; Pincemail 1995). Lycopene possesses the capacity to inactivate hydrogen peroxide and nitrogen dioxide effectively. Because of its high number of conjugated dienes, lycopene is the most potent singlet oxygen quencher among natural carotenoids. The in vitro quenching constant of lycopene has been found to be more than twice that of the β-carotene and 100 times that of the α-tocopherol (Agarwal and Rao 2000).

Lycopene reduces the risks of CVD, cancer, osteoporosis and several other human diseases. The evidences come from epidemiological studies as well as tissue culture studies using human cell lines, animal studies and also human clinical trials.

Cardiovascular Diseases

CVD is among the main causes of death in Western countries. Oxidation of low-density lipoprotein (LDL) is thought to play a key role in the pathogenesis of arteriosclerosis, which is the major underlying disorder leading to CVD. Lipophilic compounds contained in tomatoes can prevent CVD by modulating the atherogenic process in vascular endothelium mediated by oxidized low-density lipoproteins (LDLox).

Agarwal and Rao (1998) investigated the effect of dietary supplementation of lycopene on LDL oxidation in 19 healthy humans. They consumed tomato sauce, tomato juice or lycopene oleoresin capsules for 1 week each and have shown to experience a reduction in the level of LDLox. The average decreases of TBARS (thiobarbituric acid reactive substances) and conjugated dienes of LDL for the treated group over control were 25 and

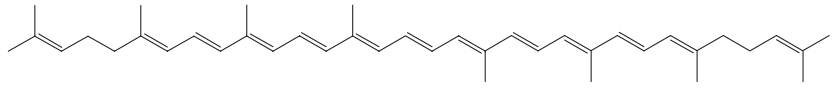

Figure 16.2 The chemical structure of lycopene (all *trans* forms).

13%, respectively. Sesso et al. (2003, 2005) reported that women and men with a higher intake of tomato products rich in lycopene corresponded with a lower risk of CVD. Visioli et al. (2003) reported that when a group of 12 healthy women ate enough tomato products to provide them with 8 mg of lycopene daily for 3 weeks, their LDL cholesterol was much less susceptible to free radical oxidation. These results suggest the effect of lycopene in decreasing risk for CVD.

Cancer

An epidemiology study conducted by Giovannocci et al. (1995) firs revealed the inverse relationship between the consumption of tomato and the risk of prostate cancer. They assessed dietary habits and the incidence of prostate cancer in approximately 48,000 men for 4 years. The results showed that men who consumed ten or more servings per week of lycopene-rich products, including tomatoes, tomato sauce, and pizza sauce, were 34% less likely, and those who consumed four to fi e servings per week were 20% less likely to develop prostate cancer. Follow-up studies demonstrated that lycopene intake as well as the serum lycopene level was inversely related to the incidences of cancers in prostate, breast, cervix, ovary, liver, lung, digestive tracts and other organ sites (Giovannucci 1999). Lycopene may also be useful as a therapeutic agent in prostate cancer. Kucuk et al. (2001) in a randomized clinical trial evaluated the effect of lycopene supplementation in prostate cancer patients. They suggested a 30 mg daily supplementation of lycopene may be suffi cient to modulate clinical markers of prostate cancer.

Pancreatic cancer is one of the deadliest cancers. In a 3-year study conducted by Nkondjock et al. (2005), 462 persons with pancreatic cancer were matched with 4,721 individuals free of the disease. The results showed that lycopene, provided mainly by tomatoes, was associated with a 31% reduction in pancreatic cancer risk among men when comparing the highest and lowest quartiles of intake.

Osteoporosis

Osteoporosis is among common aging-associated metabolic diseases. The reduction in bone mass in osteoporosis is due to the accelerated bone resorption and diminished bone formation. Osteoclasts induce bone resorption, while osteoblasts stimulate bone formation. Kim et al. (2003) reported the effect of lycopene to promote the proliferation of human osteoblast-like osteosarcoma SaOS-2 cells. The finding that lycopene has a stimulatory effect on the differentiation marker alkaline phosphatase of osteoblasts (Park et al. 1997), as well as its inhibitory effect on osteoclasts formation (Ishimi et al. 1999; Rao et al. 2003) are also evidences of the contribution from lycopene in bone health.

Postmenopausal osteoporosis occurs primarily among women over the age of 50. Rao et al. (2007) in a clinical study evaluated the role of lycopene in decreasing the risk of osteoporosis in postmenopausal women aged 50–60 years. Their results showed that groups with higher dietary lycopene intakes correlated positively with the serum lycopene level. They also found a direct correlation between the serum lycopene level and the decrease in the risk of osteoclasts. They suggested that lycopene reduces the risk of osteoclasts via antioxidation.

Other Human Diseases

Rao and Balachandran (2003) elaborated on the possible role of lycopene in neurodegenerative diseases including Alzheimer's disease, Parkinson's disease, and vascular dementia. Due to its high demands in oxygen uptake, high lipid content and low antioxidant capacity, human brain represents a vulnerable organ for oxidative damage. Lycopene has been shown to cross the blood–brain barrier and

be present in the central nervous system. Significantl , the lower level of lycopene was reported in the blood of Parkinson's disease and vascular dementia patients.

Longnecker et al. (2000) suggested that lycopene provides protection against amyotrophic lateral sclerosis disorder in humans.

The antioxidant property of lycopene has also attracted scientifi research into its protective role in hypertension. Lycopene supplementation at 15 mg per day for 8 weeks was shown to decrease systolic blood pressure from the baseline value of 144 mmHg down to 134 mmHg as the average in mildly hypertensive subjects (Paran 2006).

Researchers also investigated the role of lycopene in protecting sperms from oxidative damage leading to infertility (Palan and Naz 1996). Men with antibody-mediated infertility were found to have lower semen lycopene levels than fertile controls. After consuming daily dosage of 8 mg lycopene for 12 months, a significan increase in serum lycopene concentration and improvements in sperm motility, sperm motility index, sperm morphology, and functional sperm concentration were observed.

A daily intake of 5–7 mg is recommended for healthy humans to maintain the circulation of lycopene at a level sufficien to combat oxidative stress and prevent chronic diseases. Under diseased conditions, higher levels of lycopene ranging from 35 to 75 mg per day may be required (Heath et al. 2006).

Carrot Juice

Carrot plants (*Daucus carota* L.) belong to family Umobeliferae. They are commonly biennial. Their edible roots are sphere or cone in shape. Cultivated carrots originated in Afghanistan and Central Asia. They are now widely grown in Asia and Europe. The Eastern/Asiatic carrots have reddish purple or yellow roots, and Western carrots have orange, yellow, red, or white roots. The Western orange carrots developed from yellow carrots for high carotenoid content have become the more popular cultivars. Carrots are usually mechanically harvested 90–120 days after planting to be eaten as fresh, cooked, or processed into juice (Tsao and Lo 2004).

Carrot juice contains approximately 8% soluble solids, with a titratable acidity 0.1–0.2% and a pH of about 6. The most important nutrient in carrot juice and the major source of its orange color is β-carotene, at approximately 6 mg/100 g wet basis.

A typical process for the making of carrot juice is described below.

Washing and Peeling of Carrots

An efficien regular spray wash is all that is required for cleaning. Carrots adhered with much dirt should be well soaked in water before passing through the spray.

Different methods are used for the peeling of carrots. A regular mechanical peeler or a steam peeler works well. In the steam peeler, carrots are flash-heate in steam at high pressure first The pressure is suddenly released to produce cracks and blisters in and under the peel. A mechanical brush is then applied to scratch off the peel. The bitter character associated with stem and skin is lessened by peeling.

Blanching of Carrots

Blanching of carrots, especially in slightly acidifie water, prior to juice extraction improves the color and cloud stability of the juice (Bates and Koburger 1974; Sims et al. 1993; Reiter et al. 2003). Peeled carrots are subjected to blanching in boiling water aimed to inactivate pectic enzymes. The inhibition of pectinesterase in the carrot conserves high-methoxy pectin in the juice. The juice from nonblanching carrots contains more low-methoxy pectin that may coagulate with carotenoids to reduce the red and yellow color values. A blanching process may also soften the texture of carrots, and increase the

recovery of juice as a consequence (Munsch et al. 1986).

Extraction for Carrot Juice

The blanched carrot is extracted through a paddle pulper-finishe to obtain the juice. The size of perforations in the finishin screen of the extractor for carrots is the same as that for tomatoes.

The cellular structure of carrots may alter in enzymatic treatment and affect the yield of juice. Anastasakis et al. (1987) treated carrot puree with cellulase, hemicellulase, pectinesterase, or commercial Rohament PC (a mixture of pectin glycosidase and cellulase) before finishin and found the improvement in juice yield. Liu (1998) added 0.005% commercial pectic enzyme to blanched carrot puree and held at 45–50°C for 60 minutes. The juice recovery of the enzyme-treated samples was found to be significantl higher than that of the non-enzyme-treated ones. Liao et al. (2007) also reported that treating carrot puree with commercial pectic enzyme increased the yield, total soluble solids content, and carotenoid content of carrot juice by approximately 20%, 1%, and 26 mg/kg, respectively.

Acidification and Salting

Carrots may easily be contaminated with thermophilic spoilage microorganisms such as *Erwinia carotovora* and *Rhizopus stolonifer*. Some of these organisms are thermally resistant spore formers in low-acid foods. Therefore, carrot juice is usually acidifie with citric acid to pH 4.2 or lower. Acidificatio increases the juice yield from carrot puree (Demir et al. 2007), reduces the required severity of thermal processing of carrot juice, and produces a product with better quality, including higher cloud stability (Reiter et al. 2003). An adequate amount of salt, 0.33% for example, may also be added to help bring out the carrot fl vor in the juice.

Thermal Processing

Nonacidifie carrot juice, with a pH between 5.5 and 6.5, is a low-acid beverage that has to be sterilized at a high temperature. The juice is homogenized to prevent precipitation of the insoluble materials during thermal processing. The carrot juice may then be fille into cans and sterilized at 121°C (250°F) or higher (Pederson 1975). Kim and Gerber (1988) compared qualities of canned, frozen, and fresh nonacidifie carrot juices. They found that the fl vor qualities of frozen carrot and fresh juice are matched well, while canned juice with a significan cooking odor is unsatisfactory. A better-fl vored juice is obtained from mature carrots than from young carrots.

Acidifie carrot juice is usually sterilized at 105°C for 30 seconds minimum in the industry (Kim et al. 2001).

Sauerkraut Juice

Fermentation is an ancient food preservation method to retain or to develop desirable quality characteristics and nutrient values. Among fermented vegetable products, only sauerkraut and kimchi from cabbage, pickles from cucumber, and olives are of economic importance (Li 2004). Sauerkraut juice has been collected from sauerkraut and commercialized for almost 100 years. The making of sauerkraut juice from fresh cabbage is described in the following.

Trimming, Shredding, and Salting of Cabbage

Numerous varieties of cabbages have been extensively grown for sauerkraut production. In the industrial process, cabbage is harvested mechanically and transported via a conveyor to the corer. The cored head is conveyed to the trimming table where outer leaves and bad spots are removed. The trimmed cabbage is then mechanically shredded. Salt at

2.25–2.5 kg per 100 kg is applied evenly to the cabbage shreds while they are being fille into cleaned vats for fermentation.

Fermentation of Cabbage

A vat is fille with cabbage shreds, and then covered with a plastic sheet that is weighted with water. The proper temperature of fermentation is around 20°C (68°F). The duration is 4 weeks or more.

The rate of fermentation varies with the temperature. At a temperature above 21°C (70°F), fermentation is rapid and the desirable acidity of at least 1.8% lactic acid may be achieved in a few weeks. Cabbage packed into vats at temperatures of 10–21°C (50–70°F) ferments more slowly, but the product will retain its color, fl vor, and other quality characteristics for a longer storage period than that fermented at a higher temperature. Cabbage packed at 4–10°C (40–50°F) ferments very slowly (Downing 1996).

Sauerkraut fermentation is a complex microbiological process involving a succession of various types of microorganisms. Among them, the bacteria convert sugars and related compounds to lactic acid, alcohol, carbon dioxide, mannitol, and other substances present in less amounts. Raw cabbage contains sufficien number of desirable lactic acid bacteria for spontaneous fermentation. In the early stage of fermentation, most of the lactic acid bacteria are the heterofermentative (gas-forming) species such as *Leuconostoc mesenteroides*. The carbon dioxide creates an anaerobic environment that promotes the growth of desirable lactic acid bacteria but excludes the presence of oxidative fungi. After about 8 days of fermentation, the homofermentative (non-gas-forming) lactic acid bacterium *Lactobacillus plantarum* becomes dominant. Other homofermentative lactic acid bacteria, *Lactobacillus brevis* and *Pediococcus cerevisiae* for instance, may also contribute to product development (Hang 2004). The fermentation is considered complete when the pH of the sauerkraut has reached 3.8–3.9 or the titratable acidity, expressed as lactic acid, has reached 1.5%.

Collection of Sauerkraut Juice

Completely fermented sauerkraut normally possesses a total acid of 1.5–1.6% lactic acid and less than 2.25% salt. The sauerkraut juice is recovered after the sauerkraut is removed from the vat. The sauerkraut juice can also be collected from the fermented sauerkraut by using a hydraulic press (Wiänder and Ryhanen 2005). Different batches of juice from several vats are blended together. Because the blended juice is considered too sour for direct consumption as a beverage, it is generally diluted with hot water to approximately 1.4% acidity with reduced salt content before canning (Pederson 1975). The diluted blended sauerkraut juice is usually filtrate through a fin screen or folded cheesecloth to discard the larger particles.

Thermal Processing

The next step in sauerkraut juice processing is to hot-fil the finishe juice into cans made of electrolytic tin plate bodies and enameled ends and seamed. It is undesirable to sterilize sauerkraut juice at high temperatures because it is acidic. The processing temperature of 71–74°C (160–165°F) is enough to kill all organisms present (Pederson 1975). The cans are often conveyed through a steam chamber of 74–77°C (165–170°F) for about 5 minutes. If a sealing temperature of 77–82°C (170–180°F) is obtained, the steam chamber process will not be necessary. The sealed cans are water-cooled to about 38°C (100°F) and then stored in a cool place (Downing 1996).

Asparagus Juice

Asparagus is the young shoot of asparagus plant (*Asparagus officinali* , family Liliaceae). Asparagus juice contains little chlorophyll, and therefore encounters no serious

discoloration problem in processing. Asparagus juice is a popular vegetable juice in tropical and subtropical areas.

There are two different types of commercial asparagus juice. One tastes salty whereas the other tastes sweet. Both are produced using fresh asparagus as the raw material. To avoid the occurrence of bitter taste, asparagus should be processed as soon as possible after harvest.

The asparagus is washed. The basal part is trimmed off to improve the taste of the product. The spears are blanched in boiling water for 2–5 minutes to inactivate the enzymes. The blanched asparagus is cut into small pieces, macerated in a mill, and screw-pressed to extract the crude juice. It is then refine by centrifugation.

In the making of salty asparagus juice, the refine juice is seasoned with 0.75% salt, fille into 8 oz cans, sterilized in the retort at 116°C (241°F) for 20 minutes, and then cooled. In the making of sweetened asparagus juice drink, the it is diluted with potable water to 20–30% juice content, added with sugar to 12°Brix, and slightly acidifie with 0.1% citric acid. The mixture is flash-heate to 90°C (194°F), fille into 250 mL cans, sterilized at 110°C (230°F) for 10 minutes, and then water-cooled to room temperature.

Nonconventional Processing Technologies

There is a perpetual demand by the consumers for processed foods that retain better freshness and nutrition. Therefore, scientists and producers are always searching for new preservation technologies that exert less detrimental effect on foods than conventional thermal processing would do. Among them, high-pressure processing, pulsed electric field treatment, and ionizing radiation processing are applicable to vegetable juices.

High Hydrostatic Pressure Processing

High hydrostatic pressure processing is an important nonconventional processing technology. A pressure between 200 and 700 MPa is applied to inactivate vegetative microorganisms and to preserve food. Its application on vegetable products offers a chance for producing food with high quality, improved safety, and increased shelflif (Butz et al. 2003). Industrial applications are already there in Japan, the United States, France, and Spain. High hydrostatic pressure processing has been studied for the preparation of vegetable juices, including carrot juice (Kim et al., 2001; Postal et al. 2005), tomato juice (Dede et al. 2007; Hsu 2008), and broccoli juice (Houška et al. 2006). A high hydrostatic pressure process at elevated temperature can be more effective than the process at ambient temperature for the production of high-quality vegetable juice.

Kim et al. (2001) reported that a process at 400 MPa and 70°C (158°F) for 10 minutes inhibited more than 95% of the activity of quality-related enzymes in nonblanched, nonacidifie carrot juice. The optimum process condition was estimated to be at 395–445 MPa and 70°C (158°F) for 8–11 minutes. Balogh et al. (2004) investigated the effect of high pressure (700–800 MPa) combined with thermal (50–60°C or 122–140°F) process on the pectin methyl esterase in nonacidifie carrot juice, and established a first-orde kinetic model for the inactivation of this enzyme. Postal et al. (2005) reported a linear relationship between the log value of *Escherichia coli* MG1655 inactivation and the holding time among the pressure (150–600 MPa)–temperature (5–45°C or 41–113°F) combinations in nonacidifie carrot juice.

Dede et al. (2007) reduced the microbial load of tomato and nonacidifie carrot juices to an undetectable level with a treatment 259 MPa/35°C (95°F) for 15 minutes and obtained a product with quality better than the conventional one.

Crelier et al. (2001) completely inactivated tomato pectin methyl esterase at 800 MPa and 70°C (158°F) for 20 minutes. Hsu (2008) found that a treatment at 500 MPa/4 or 25°C

(39 or 77°F) for 10 minutes on tomato juice preserved better quality as compared with hot-break at 92°C for 2 minutes and cold-break at 60°C for 2 minutes.

Houška et al. (2006) reported that high hydrostatic pressure pasteurization without heating is capable to preserve sulforaphane in broccoli juice.

High hydrostatic pressure processing still has some issues such as scale-up and the high operating cost. For these reasons, its industrial application in vegetable juice processing is currently limited.

Pulsed Electric Field Treatment

Pulsed electric fiel treatment is an emerging nonthermal treatment applicable to liquid foods. This novel technology offers a potential for extending the shelf-life of juices with excellent freshness. Studies in orange–carrot juice blend have demonstrated that pulsed electric fiel treatment has nonthermal lethal effects on microorganisms including *L. plantarum* and *E. coli* (Rodrigo et al. 2001, 2003). A study on the processing of non-acidifie carrot juice found that the level of *E. coli* inactivation increased with the increment of the electric fiel strength from 5 to 20 kV/cm, and with the number of pulses from 207 to 1,449 (Zhong et al. 2005).

Rivas et al. (2006) reported that the shelf-life of a pulsed electric field-treate carrot juice blend was 4 weeks at 2°C (36°F). Aguiló-Aguayo et al. (2008) reported a 82% pectin methyl esterase inactivation in tomato juice treated at 35 kV/cm for 1,500 μs using bipolar 4 μs pulses at 100 Hz. The pulsed electric field-treate tomato juice had a higher value of lightness than the thermally processed (90°C or 194°F for 1 minute) one. Odriozola-Serrano et al. (2008) found the pulsed electric field-treate (35 kV/cm for 1,500 μs in bipolar 4 μs pulses at 100 Hz, with an energy density of 8,269 kJ/L) tomato juice retained higher lycopene and vitamin C contents than the juice thermally processed at 90°C (194°F) for 30 seconds. Another study demonstrated that the pulsed electric fiel treatment at a pulse width up to 2.5 μs reduced nonenzymatic browning of tomato juice (Aguiló-Aguayo et al. 2009).

Ionizing Radiation

Ionizing radiation is highly effective in inactivating microorganisms in various vegetables. It offers a safe alternative as a food decontamination method. Song et al. (2006) applied γ-radiation to sterilize vegetable juices and assessed the effectiveness for inactivating *Salmonella typhimurium* and *E. coli*. They found that the D values of *S. typhimurium* in non-acidifie carrot and kale juices were 0.445 ± 0.004 and 0.441 ± 0.006 kGy, while those of *E. coli* were 0.301 ± 0.005 and 0.299 ± 0.006 kGy. The total phenol content of the irradiated juice during 3 days of storage at a cold-chain temperature (10°C or 50°F) increased significantl , while that of the non-irradiated juice decreased. Song et al. (2007) reported that all the aerobic and coliform bacteria in nonacidifie carrot juice were eliminated by irradiation at a dose of 3 kGy, whereas about 10^2 CFU/mL of the bacteria survived in kale juice irradiated at up to 5 kGy.

Conclusion

A greater portion of vegetables is being commercially processed than ever before. Vegetable juice and blends are among the major products. This chapter describes the manufacture of vegetable juice and blends using tomato, carrot, cabbage, and asparagus as the starting materials.

Many studies on the health functions of vegetable juice and blends are on the way. New formulations and techniques are emerging for the processing of these products with better quality and higher safety for consumers. The advances on these fronts would help successful development of more healthy and palatable products in the future.

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Chapter 17

Vegetable Fermentation and Pickling

Nejib Guizani

Introduction

Along with cooking, smoking, and sun-drying, fermentation is one of the oldest methods of food preservation. Fermented foods were discovered before mankind had any knowledge of microorganisms (Guizani and Mothershaw 2006). They have formed a traditional part of the diet in almost all cultures and are an important segment of the food processing industry (Fellows 2002).

Various factors influenc the rate at which microorganisms grow in foods. These include the intrinsic properties of the foods (nutrient content, pH, redox potential, water activity, etc.) as well as the extrinsic factors related to the conditions under which they are stored, e.g., temperature and relative humidity. The preservation of foods is generally based on eliminating microorganisms or controlling their growth and the overall composition of the microflora To reduce or prevent microbial spoilage of foods four basic principles can be applied: (1) minimize the level of microbial contamination; (2) inhibit the growth of the contaminating microflora (3) kill the contaminating microorganisms; and (4) remove the contaminating microorganisms. The fermentation involves a combination of the firs three principles, and is achieved by creating an environment for the growth of specifi microorganisms that can impart desirable taste, fl vor, texture, or appearance to foods (Guizani and Mothershaw 2007). The majority of fermented foods are based on lactic acid bacteria, and yeasts, and to a lesser extent, molds. The preservation of vegetables by fermentation is thought to have originated before recorded history and technology developed by trial and error (Fleming et al. 1995). The important commercially fermented vegetables are cucumbers, cabbage, olives, and peppers. However, several other vegetables, including onions, tomatoes, mango, caulifl wer, carrots, turnips, okra, artichokes, and beans, are also pickled in smaller quantities. In this chapter, we review various aspects related to fermentation of vegetables.

Principles of Pickling

Pickling is the preservation of foods by the addition of salt and/or vinegar as a primary means of preservation. The commercial preservation of vegetables by pickling is accomplished by two general processes: (1) brining; and (2) direct acidification with or without a mild heat process (pasteurization), and various combinations of these two processes. Refrigeration is used to extend the shelf life of certain products (Fleming and Moore 1983). Salting or brining is achieved by mixing the cut or whole vegetable with dry salt, as with cabbage, or by placing the fresh vegetables in a salt solution, as with most other vegetables. The brined or salted vegetables may or may not undergo a microbial fermentation involving a mixture of

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microorganism mainly lactic acid bacteria and yeasts, depending on the concentration of salt used. Lactic acid is produced naturally in fermented vegetables. Direct acidificatio is accomplished by the addition of acetic acid in the form of vinegar, and preservation may be accomplished by pasteurization, addition of preservatives (sodium benzoate, potassium sorbate, and sulfur dioxide), refrigeration, or a combination of these treatments. Acidifie vegetables are therefore nonfermented products.

Fermentation

Principles

Fermentation is a biochemical processes in which changes are brought about in organic substrates (mostly carbohydrate) resulting in the conversion of degradable food components into more stable forms usually by the action of microorganisms. Preservation of foods by fermentation depends on the principle of oxidation of carbohydrates and related derivatives to generate end products which are generally acids, alcohol, and carbon dioxide. These end products control the growth of food spoilage microorganisms and because the oxidation is only partial, the food still contains nutrients (Caplice and Fitzgerald 1999). Lactic acid bacteria are the most important group of microorganisms used in the fermentation of vegetables to produce stable products. The microorganisms can improve their own competitiveness by changing the environment, so that it becomes inhibitory or lethal to other organisms, while stimulating their own growth and this selection is the basis for preservation by fermentation. Lactic acid bacteria usually involve the production of some compounds, which are inhibitory to other microorganisms. They may thus produce both antimicrobial compounds with a relatively broad inhibition spectrum (i.e., organic acids, hydrogen peroxide, and nisin) as well as compounds with a rather narrow antimicrobial spectrum (bacteriocins). In addition, fermentation will result in a change in the sensory (fl vor, odor, etc.) and/or functional properties of a food to produce an end product that is desirable to the consumer.

Fermentation Processes

Fermentation can be accomplished using one of three processes: spontaneous fermentation, back-slopping, or inoculation with the use of selected starter cultures. Spontaneous fermentations are the processes where biochemical changes have taken place without the starter cultures. They typically result from the competitive activities of a variety of indigenous microorganisms. The process is dominated by those microorganisms that are best adapted to the food substrate and to process parameters (carbon to nitrogen ratio, temperature, pH, oxygen). Such fermentations are quite often carried out by a succession of microorganisms dominated by lactic acid bacteria followed by various species of yeasts. Lactic acid bacteria produce lactic acid and other antimicrobial substances that inhibit the growth of harmful bacteria and spoilage agents. Yeasts produce mainly aroma components and alcohols. The majority of industrial processes such as sauerkraut fermentations are still conducted as spontaneous processes.

In back-slopping, material from a previous batch of a fermented product is used to inoculate the new batch to initiate the new process. Through this practice of back-slopping, the initial phase of fermentation process is shortened and the risk of fermentation failure reduced (Holzapfel 2002), however it makes it "semicontinuous."

Inoculation with the selected starter cultures is used when it is possible to inactivate the indigenous flor by heat treatment of the raw material, permitting the growth of only the added starter microorganisms (Josephsen and Jespersen 2006). However, the heat treatment brings about undesirable changes to the

texture of some raw materials (i.e., fruits and vegetables). Modern starter cultures are selected either as a single or multiple strains, depending on their adaptation to a substrate or a raw material. The starter culture to be used (i.e., single strain vs multiple strains) is determined by the attributes of the substrate, consumer expectations, and technical requirements.

Benefits of Fermentation

Fermentation is a relatively inexpensive and energy efficien means of preserving perishable vegetables. It requires very little sophisticated equipment, either to carry out the fermentation or for subsequent storage of the fermented product. The procedures can often be carried out in the home (Motarjemi and Nout 1996). Therefore, the process could be very appropriate in developing countries for preserving surplus vegetables. Fermentation has been employed for generations to preserve food for consumption at a later date thus improving food security. Fermentation improves the safety of foods, by decreasing the risks of pathogens and toxins achieving the infective or toxigenic level, and extends the shelf life by inhibiting the growth of spoilage agents which cause the sensory changes that make the food unacceptable to the consumer. In addition, a number of studies have shown that consumers regard fermented food products as healthy and natural, increasing consumer demands and, hence, profitabilit (Hamstra 1993).

Microorganisms Used in Fermented Foods

A variety of groups of microorganisms (*Lactobacilli*, *Leuconostoc*, *Pediococci*) are frequently used in fermented foods. Lactic acid bacteria and yeasts have been reported to be dominant in the fermentation of vegetables.

Bacterial Starter Culture

Bacterial starter culture is a culture of bacterial strains that are either pure or mixed, which is used to initiate a fermentation process. The use of lactic acid bacteria as starter cultures in the production of fermented foods is one of the oldest food processing practices utilized. It is designed to stabilize food products while obtaining specific desired sensory and organoleptic properties. The fact that fermented products, which naturally contain these microorganisms and the antimicrobials they may produce, have been consumed traditionally without any negative health effects, has given lactic acid bacteria GRAS (generally recognized as safe) status (Giraffa et al. 1994).

In many cases, the most obvious change during lactic acid fermentation is the production of acid and subsequent lowering of pH that results in an increase in sourness and a decrease in sweetness (McFeeters 2004). Lactic acid bacteria comprise of a versatile group of microorganisms that possess a range of common properties; all produce lactic acid which can kill or inhibit many other microorganisms (Axelsson 1998). Lactic acid bacteria are generally mesophilic but can grow at temperatures as low as 5°C or as high as 45°C. Similarly while the majority of the strains grow at pH 4.0–4.5, some are active at even pH 9.6 and others at pH 3.2 (Caplice and Fitzgerald 1999). The important properties of lactic acid bacteria used in vegetable fermentation are presented in Table 17.1. In general, excluding some streptococci, lactic acid bacteria are harmless to humans. This makes lactic acid bacteria ideal agents for food preservation.

The pathways by which hexoses are metabolized divide lactic acid bacteria into two groups: homofermetative and heterofermentative. Lactic acid bacteria are subdivided on the basis of their action on glucose fermentation. Homofermenters such as *Pediococcus*, *Streptococcus*, *Lactococcus*, and some Lactobacilli produce lactic acid as the major or

Table 17.1 Important properties of lactic acid bacteria commonly used in vegetable fermentations

Property	*Lactobacillus*		*Leuconostoc*	*Pediococcus*
	brevis	*plantarum*	*mesenteroides*	*pentosaceus*
Morphology	Rods—single	Rods—single or short chains	Oval cocci—pairs	Cocci—pairs and tetrads
Optimum growth temperature (°C)	30	30–35	20–25	35
Homofermentative		+		+
Heterofermentative	+		+	
Main product Molar ration	Lactate:acetate:CO_2 1:1:1	Lactate	Lactate:acetate:CO_2 1:1:1	Lactate
Lactic acid produced from glucose	DL	DL, D(−), L(+)	D(−)	DL, L(+)

Sources: Daeschel and Fleming (1984), Guizani and Mothershaw (2007), Fleming et al. (1995) Adams and Moss (2000).

sole product from glucose (Kandler 1983; London 1990). Heterofermenters, such as *Weissella*and *Leuconostoc*, have an important role in producing fl vonoid components such as acetaldehydes and diacetyl.

Lactic acid bacteria have a range of methods for outcompeting other microorganisms (Guizani and Mothershaw 2006, 2007). Their most effective mechanism is to grow readily in most foods, producing acid which lowers the pH rapidly to a point where other competing organisms can no longer survive (Steinkraus 1983). Lactobacilli also lack catalase and therefore have the ability to produce hydrogen peroxide (Hurst and Collins-Thompson 1979), which is inhibitory to spoilage organisms (Steinkraus 1983), while lactobacilli are relatively resistant to hydrogen peroxide (Wheater et al. 1952). The role of hydrogen peroxide as a preservative is likely to be minor, especially when compared to acid production. Carbon dioxide produced by heterofermenters also has a preservative effect resulting partially from its contribution to anaerobiosis (Steinkraus 1983). In addition, lactic acid bacteria have an enormous potential to inhibit microorganisms through the production of bacteriocin (Caplice and Fitzgerald 1999; Leroy and De Vuyst 2004; Drider et al. 2006).

Lactic acid bacteria are nutritionally fastidious and require supplements including vitamins and amino acids. Cabbage, cucumbers, and olives used for brining apparently contain all of the essential nutrients for growth of lactic acid bacteria normally associated with fermentation of these commodities. Spanish-style green olives subjected to inadequate alkali and leaching treatments could provide an exception (Daeschel and Fleming 1984).

A range of potential health benefit has been associated with the consumption of lactic acid bacteria (Guizani and Mothershaw 2006). Some benefit are associated with the growth and activity of lactic acid bacteria during food fermentations and some from the resultant colonization of the gastrointestinal tract. Many of these health claims are still controversial (Gorbach 1990) and are the subject of research to identify and substantiate specifi roles (Gilliland 1990; Gorbach 1990; Hammes and Tichaczek 1994).

Yeasts

Yeasts are characterized by a wide dispersion in the natural habitats but are most frequently isolated from carbohydrate-rich substrates, such as fruits and plant nectars (Adams

and Moss 2000). However, several species have been able to adapt to different environments. Yeasts are rarely toxic or pathogenic and are generally acceptable to consumers (Suomalainen and Oura 1971). Yeasts are unicellular eukaryotic microorganisms classifie in the kingdom Fungi, with about 1,500 species described (Kurtzman and Fell 2006). However, only a small number are regularly used to make alcoholic beverages (Adams and Moss 2000). Several species are involved in the fermentation of wine, beer, bread, caper, cucumber, and other vegetables. *Saccharomyces cerevisiae* is the most frequently used species and has many variants available. *S. cerevisiae* ferments glucose but does not ferment lactose or starch directly. Yeasts are used to produce ethanol, CO_2, fl vor, and aroma. Other metabolic products including minor amounts of ethyl acetate, fusel alcohols (pentanol, isopentanol, and isobutanol), sulfur compounds, and leakage of amino acids and nucleotides can all contribute to the sensory changes induced by yeasts (Suomalainen and Oura 1971).

Yeasts are also significan as spoilage microorganisms, especially in food and beverages with a low pH, high salt concentrations, and low temperatures (Stratford 2006). This is the case for table olive production, where a habitual low pH and high NaCl concentration occurs in the fina product (Garrido Fernández et al. 1997).

Molds

Molds are fungal species that have filamen tous hyphae. Molds are aerobic and have the greatest array of enzymes. Molds are important to the food industry, as both spoilers and preservers of foods and, are particularly used in fermentations for fl vor development. Certain molds produce antibiotics while mycotoxin production by others is a major concern in the food industry. Some molds are used in the food industry to produce specifi enzymes, such as amylases for use in bread making. Some species, such as *Aspergillus oryzae*, are used in fermentations of soybeans to make miso and soysauce. *Mucor* and *Rhizopus* are also used in some traditional food fermentations. *Rhizopus oligosporus* is considered essential in the production of tempeh from soybeans.

Microbial Sequence in Fermented Vegetables

The fermentation of vegetables depends not on any single organism, but on a consortium of bacteria representing several different genera and species. A given organism (or group of organisms) initiates growth and becomes established for a period of time. Due to accumulation of inhibitory compounds, growth slows down and gives way to other species that are less sensitive to those factors.

Many researchers have reported a sequential involvement for different species of lactic acid bacteria (Pederson and Albury 1969; Stamer et al. 1971; Stamer 1975 Pederson 1979). The succession of specifi lactic acid bacteria during natural fermentation of vegetables is dependent on the chemical (substrates, salt concentration, and pH) and physical (vegetable type, temperature) environments (Harris et al. 1992). Fleming (1982) divided the microbial growth during natural fermentation of vegetables into four sequential stages: (1) initiation, which includes growth of various gram-positive and gram-negative bacteria present on the vegetable; (2) primary fermentation, which includes growth of lactic acid bacteria with or without growth of fermentative yeasts; (3) secondary fermentation, which includes growth of fermentative yeasts once the growth of lactic acid bacteria has been inhibited by low pH, provided that fermentable carbohydrates remain; and (4) postfermentation, occurring once the fermentable carbohydrates have been exhausted, which is characterized by the absence of microbial growth under anaerobic conditions but showing surface growth of oxidative

microorganisms when the brine is exposed to the atmosphere.

For sauerkraut production, Leuconostoc mesenteroides grows first producing lactic acid, acetic acid, and CO_2, followed by the growth of Lactobacillus brevis, and finall Lactobacillus plantarum grows, producing more acid and, thus, lowering the pH to below 4.0. This allows the cabbage to be preserved for long periods of time under anaerobic conditions.

The lactic acid bacteria chiefl responsible for production of high-salt pickles is initially *Pediococcus cerevisiae* followed by the more acid-tolerant *L. plantarum* and *L. brevis*. *L. mesenteroides* makes little contribution in the high-salt pickles but is active in low-salt pickles (Dennis 1987).

The microbiology of the olive lactic acid fermentation is complex with a number of microbial strains being involved. Vaughn et al. (1972) have divided the normal olive fermentation into three stages. The initial stage is the most important from the standpoint of potential spoilage if the brines are not acidified Acidificatio eliminates the original contaminating population of dangerous gram-negative and gram-positive spoilage bacteria and, at the same time, provides an optimum pH for activity of the lactic acid bacteria (Fornachon et al. 1940). The natural flor of green olives, consisting of a variety of bacteria, yeasts, and molds carries out the fermentation with the lactic acid bacteria becoming prominent during the intermediate stage. *L. mesenteroides* and *P. cerevisiae* are the firs lactics to predominate, followed by lactobacilli, mainly *L. plantarum* and *L. brevis* (Vaughn 1975).

Diverse groups of lactic acid bacteria have been identifie during the fermentation of Kimchi (Lim et al. 1989; Park et al. 1990; Shin et al. 1996). Some important species thought to be responsible for Kimchi fermentation include *L. mesenteroides, Leuconostoc pseudomesenteroides* and *Leuconostoc lactis,* as well as *L. brevis* and *L. plantarum.* *L. mesenteroides* was reported to predominate in the early stages of fermentation and to be responsible for the initial anaerobic state of kimchi, as the pH gradually falls to 4.0, *L. plantarum* becomes predominant (Mheen and Kwon 1984; Kim and Chun 2005).

Starter Cultures

Fermented foods may be produced by the action of fermentative microorganisms naturally found on the raw materials or in the production environment. However, to improve reliability and obtain more consistent fermentation, "starter cultures" are frequently used. Such starter cultures must possess appropriate traits, and to be effective, they must be able to predominate over the naturally occurring lactic acid bacteria. Starter cultures may be pure or mixed cultures. Using mixed starter cultures can reduce the risks of bacteriophage infection (Daly 1983) and improve the quality of the foods when the organisms are mutually beneficial Food fermentations frequently involve a complex succession of microorganisms induced by dynamic environmental conditions. In addition, the isolation of broad-spectrum bacteriocin-producing lactic acid bacteria from naturally fermented vegetables indicates that antimicrobial proteins also play a role in the ecology of traditionally fermented foods (Daeschel and Klaenhammer 1985; Andersson 1986; Daeschel et al. 1990; Jimenez-Diaz et al. 1990). The specifi roles and culture interactions of bacteriocin-producing strains in natural ecosystems remain undefined However, bacteriocin-producing starter cultures capable of growth in vegetable brines may have a competitive advantage that could be exploited in the development of commercial starter cultures for fermented vegetable products (Harris et al. 1992).

Fermentative microorganisms must be safe to the consumer and must produce substantial amounts of the desired end product(s). For practical reasons, the organisms should

be easy to handle and grow well, so that they can be enabled to outcompete undesirable microorganisms. The organism also needs to be genetically stable with consistent performance both during and between food batches. In many traditional fermentations the natural microflor were used for the fermentation. Even so, some form of inoculation was frequently performed using simple techniques like the use of one batch of food to inoculate the next batch, or the repeated use of the same container (Holzapfel 2002). Natural fermentations have a degree of unpredictability, which may be unsatisfactory when a process is industrialized. Starter cultures are increasingly used to improve not only the reliability, but also the reproducibility and the rate at which the fermentation is initiated.

Although a large number of lactic acid bacteria starters are routinely used in dairy, meat, and baked goods fermentations, only a few cultures have been used for vegetable fermentations. *L. plantarum* is the commercial starter most frequently used in the fermentation of cucumbers, cabbages, and olives (Molin 2001; Montete et al. 2006).

Examples of Fermented Vegetables

A large number of vegetables are preserved by lactic acid fermentation around the world. The most important commercially fermented vegetables in the west are cabbage (sauerkraut), cucumbers, and olives. Others include carrots, caulifl wer, celery, okra, onions, and peppers. When vegetables are placed in a solution of sodium chloride of appropriate concentration, they undergo fermentation. Most of these commercial fermentations do not involve the use of starter cultures and are the result of naturally occurring microorganisms and the environmental conditions such as salt concentration, pH, and temperature of the brine (Breidt et al. 2007). Brine solutions are prepared in the fermentation of most vegetables; however, salt can be added in the dry form as in the case of sauerkraut. The concentration of sodium chloride used depends upon the tendency of the particular vegetable to soften during brining and may range from 1 to 8% (Daeschel and Fleming 1984). The fermentation yields lactic acid as the major product. The salt extracts liquid from the vegetable which serves as a substrate for growth of lactic acid bacteria. Growth of undesirable spoilage microorganisms is restricted by the salt. Aerobic conditions should be maintained during fermentation to allow naturally occurring microorganisms to grow and produce enough lactic acid, and to prevent growth of spoilage microorganisms. In some countries, fermentation of certain vegetables (e.g., cucumbers) is controlled by the addition of acetic acid to prevent growth of spoilage microorganisms, buffered with sodium acetate or sodium hydroxide, and inoculated with *L. plantarum* alone or in association with *Pediococcus cerevisae*. The controlled fermentation reduces economic losses and leads to a more uniform product over a shorter period of time.

Fermented Cucumbers

There are many pickled products produced from cucumbers. Two methods are available for pickle processing including the lactic fermentation and the "fresh pack" techniques. The latter technique does not require a fermentation to ensure stability and involves direct acidificatio with vinegar or acetic acid followed by either pasteurization or refrigerated storage. Figure 17.1 shows the fl w diagrams for three different methods of cucumber processing (Fleming and Moore 1983; Duncan 1987; Brady 1994; Fleming et al. 1995). Fresh-pack pickles processed in the U.S. and their recipes are summarized in Table 17.2.

Most commercial cucumber fermentations rely on the activity of naturally occurring microorganisms and the control of the environmental conditions such as salt concentration,

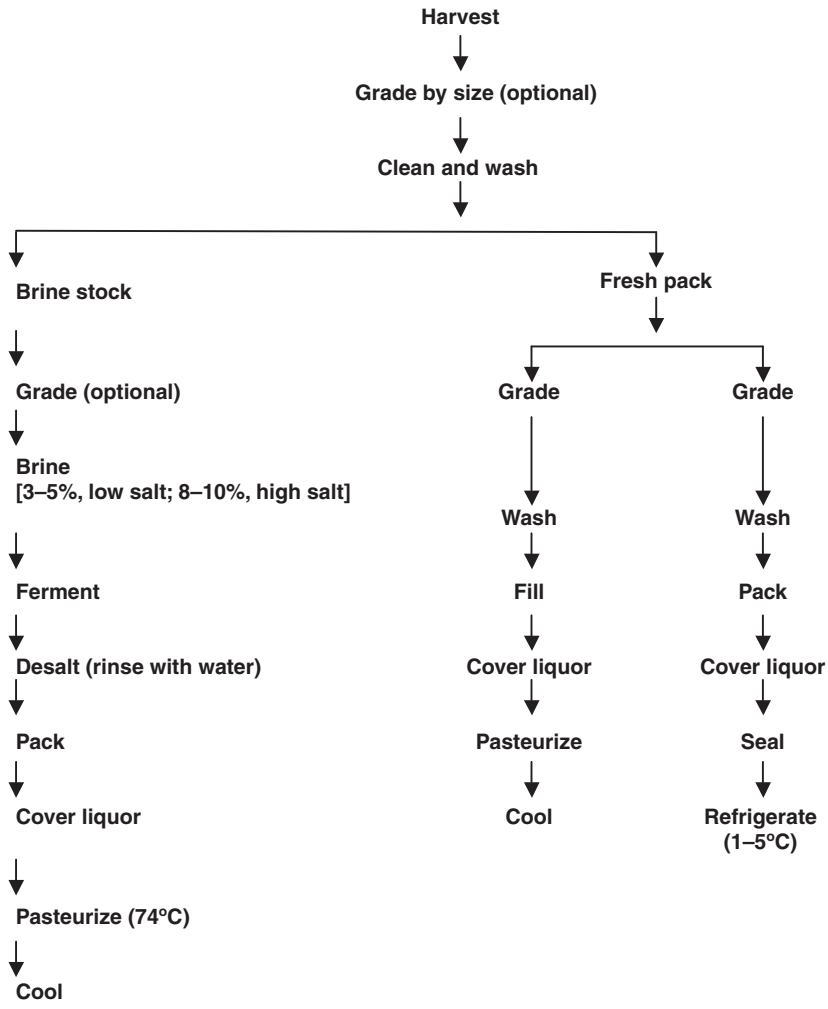

Figure 17.1 Basic steps for three methods of cucumber processing. (Adapted form Fleming and Moore 1983; Fleming 1984; Duncan 1987; Brady 1994).

pH, and temperature of the brine. Cucumbers for pickling are harvested while still immature. The fermentation of cucumbers varies according to the salt concentration used, and two quite different products can be produced, namely high-salt stock (8–10% increasing to 15%) and low-salt dill pickles (3–5% salt containing dill and spices) (Dennis 1987). Usually, the salt solution is poured onto the cucumbers in tanks and then fermentation is allowed to proceed, if necessary, glucose is added to stimulate activity. Fermentation takes place at 18–20°C and yields lactic acid, CO_2, some volatile acids, ethanol and small amounts of various aroma substances (Belitz and Grosch 1999).

Once the cucumbers have been brined and the tank closed, there is a rapid development of microorganisms in the brine. The normal mixed flor of the cucumbers forms the initiating culture. The rapidity of the fermentation is correlated with the concentration of salt in the brine and its temperature. In general, the lower the salt concentration, the more kinds

Table 17.2 USDA* and Minnesota methods for making fresh-pack pickles

USDA methods	Minnesota methods
Quick fresh-pack dill pickles • 8 lbs. of 3–5-inch pickling cucumbers • 2 gallons of water • $1\frac{1}{4}$ cups canning or pickling salt • $1\frac{1}{2}$ quarts vinegar (5% acidity) • $\frac{1}{4}$ cup sugar • 2 quarts water • 2 tablespoon whole mixed pickling spice • About 3 tablespoon (tbsp) whole mustard seed (1 teaspoon (tsp) per pint jar) • About 14 heads of fresh dill ($1\frac{1}{2}$ tsp/pint jar) or $4\frac{1}{2}$ tbsp dill seed ($1\frac{1}{2}$ tsp/pint jar)	*Fresh-pack or quick dill pickles* • Dill heads, washed • Onion slices, $\frac{1}{2}$ inch thick • Garlic cloves • Carrot slices (optional for added color) • Brine: mix the following ingredients thoroughly ○ 6 cups water ○ 2 cups vinegar, 4–6% acidity ○ $\frac{1}{3}$ cup canning salt (to retain firmness
Bread-and-butter pickles • 6 lbs of 4–5-inch pickling cucumbers • 8 cups thinly sliced onions (about 3 lbs) • $\frac{1}{2}$ cup canning or pickling salt • 4 cups vinegar, 5% acidity • $4\frac{1}{2}$ cups sugar • 2 tbsp mustard seed • $1\frac{1}{2}$ tbsp celery seed • 1 tbsp ground turmeric • 1 cup pickling lime (optional)	*Pepper relish* • 4 cups onions, ground • 4 cups cabbage, ground • 4 cups green tomatoes, ground • 9 large green peppers, ground • 9 large red peppers, ground • $\frac{1}{2}$ cup salt • 6 cups sugar • 4 cups vinegar, 4–6% acidity • 2 cups water • 1 tbsp celery seed • 1 tbsp mustard seed • $1\frac{1}{2}$ tsp turmeric
Quick sweet pickles May be canned as either strips or slices. • 8 lbs of 3–4-inch pickling cucumbers • $\frac{1}{3}$ cup canning or pickling salt • $4\frac{1}{2}$ cups sugar • $3\frac{1}{2}$ cups vinegar, 5% acidity • 2 tsp celery seed • 1 tbsp whole allspice • 2 tbsp mustard seed • 1 cup pickling lime (optional for use in variation below for firme pickles)	*Watermelon Pickle* • 6 lbs or $\frac{1}{2}$ large watermelon rind, unpared • $\frac{3}{4}$ cup canning salt • 3 q water • 2 quarts. (2 trays) ice cubes • 8 cups ($2\frac{1}{4}$ quarts) sugar • 3 cups vinegar, white • 3 cups water • 1 tbsp (about 48) whole cloves • 6 pieces stick cinnamon, 1-inch pieces

Source: Adapted from Schafer (2000).
*United States Department of Agriculture.

of bacteria will grow at the start, the faster the acid production, and the greater the acidity produced. The lactic acid initially formed is later metabolized partly by fil yeast or oxidative yeasts that grow on the surface of the brine, thus slightly increasing the original pH value of the fermenting medium (Belitz and Grosch 1999).

The controlled fermentation of cucumbers offers a means of eliminating many of the spoilage problems. In controlled fermentations, the cucumbers are washed and soaked in a chlorinated 25° salinometer brine The brine is acidifie with acetic acid, buffered with sodium acetate or sodium hydroxide, and inoculated with *L. plantarum* alone or in association with *P. cerevisae* (Banwart 1989; Jay 1998). The procedure is intended to eliminate the initiation and secondary fermentation steps that take place in the natural fermentation (Fleming 1984). The initial acidificatio of the cover brine inhibits growth by acid-sensitive gram-positive and gram-negative bacteria and thus favors growth by

lactic acid bacteria. Addition of sodium acetate or sodium hydroxide after 24 hours neutralizes the acid and renders the pH favorable for the growth of the added culture and ensures that all sugars are fermented by the added culture. The buffering, therefore, eliminates secondary fermentation by yeasts. Purging dissolved CO_2 from brines with N_2 is intended to prevent bloater damage (hollow cucumbers) and is widely used by the pickle industry. The controlled fermentation reduces economic losses and leads to a more uniform product over a shorter period of time (Prescott and Dunn 1959). In addition, with controlled fermentation, the need to add more salt during storage is reduced. This is important because nowadays people are seeking low-salt diets and the US Environmental Protection Agency is phasing out the dumping of brine into streams (Banwart 1989).

The two main defects of pickles are bloaters and softening. Pickled cucumbers are often softened due to endogenous or microbial pectolytic enzymes (Belitz and Grosch 1999). Softening is caused by microorganisms growing inside or on the cucumbers (Adams and Moss 2000). Pectolytic organisms causing pickle softening belong to the genera *Bacillus*, *Fusarium*, *Penicillium*, *Phoma*, *Cladosporium*, *Alternaria*, *Mucor*, *Aspergillus*, and others (Jay 1998). Bloaters are those pickles that floa on the brine and are hollow or have large air spaces in the interior. This condition is caused by gas-forming microorganisms, i.e., gaseous fermentation. *Enterobacter* spp., lactobacilli, and pediococci have been implicated as causes of bloaters (Jay 1998). Off-fl vors and odors in fermented cucumbers result from the growth of undesirable microorganisms during the secondary fermentation (Kim and Breidt 2007).

Sauerkraut

Sauerkraut is the product resulting from the natural lactic acid fermentation of shredded fresh cabbage to which salt is added. Sound heads of cabbage are washed, and the outer leaves and defective leaves are removed. The core is removed and the leaves are shredded to give a larger total surface area and to allow extraction of juice. Salt is added to the shredded cabbage at a concentration of 2.25–2.5%. The salt, along with packing, extracts liquid from the vegetable, which serves as a substrate for growth of lactic acid bacteria. Figure 17.2 shows the main steps in the manufacture of sauerkraut. When the vat or tank is full, a plastic sheet is used as a cover to keep out dirt and air.

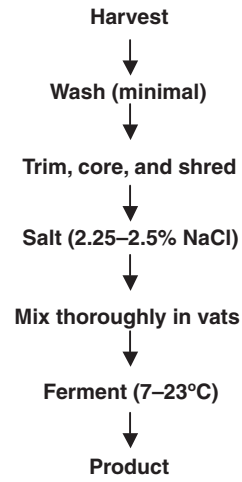

Figure 17.2 Main steps in the manufacture of sauerkraut. (Sources: Daeschel and Fleming 1984; Andersson 1986; Adams and Moss 2000; Guizani and Mothershow 2006).

Conditions should be maintained as anaerobic as possible to prevent growth of microorganisms that might spoil the sauerkraut (Steinkraus 1983). When properly shredded and salted, the cabbage undergoes fermentation by a sequence of lactic acid bacteria that results in the distinctive fl vor of sauerkraut (Pederson and Albury 1969; Stamer et al. 1971; Stamer 1975; Pederson 1979). Figure 17.3 represents an idealized model for successive growth of lactic acid bacteria during the sauerkraut fermentation (Hutkins 2006). *L. mesenteroides* is a major species in the early,

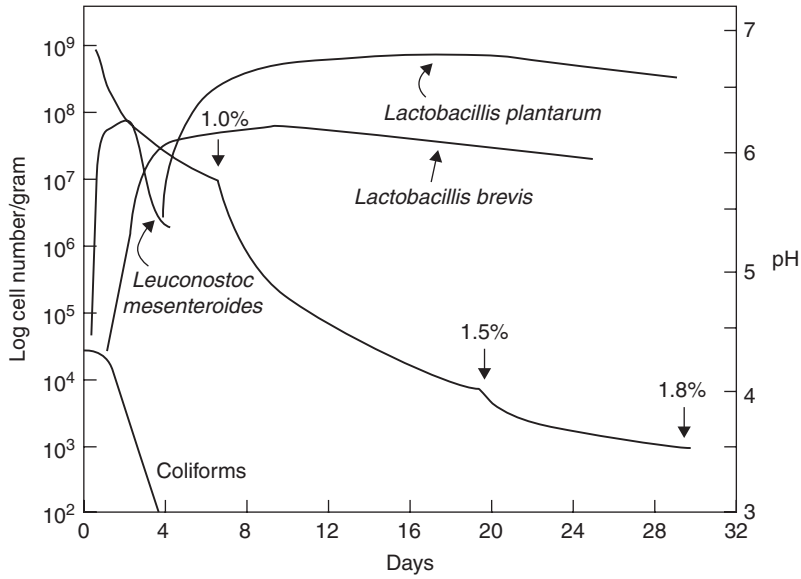

Figure 17.3 Idealized model for successive growth of lactic acid bacteria during the sauerkraut fermentation. (From Hutkins 2006, Reprint with permission of John Wiley & Sons, Inc).

heterofermentative stage of fermentation producing lactic acid, acetic acid, and CO_2. This stage largely dictates the production of fl vor volatiles and the balance between lactic and acetic acids (Pederson and Albury 1969). The pH of the product is lowered quickly, thus limiting the activity of undesirable microorganisms and enzymes that might soften the cabbage shreds. The carbon dioxide flushe out residual oxygen making the fermentation anaerobic which stimulates the growth of many lactic acid bacteria. Then *L. brevis* and *P. cerevisae* grow continuing the acid production. Finally *L. plantarum*, a major species involved in the late, homofermentative stage of fermentation, produces more acid and lowers the pH to below 4.0, allowing the cabbage to be preserved for long periods of time under anaerobic conditions.

Overall, sauerkraut fl vor is affected by the acidity, the salt concentration, as well as the volatile organic compounds. Fleming et al. (1995) reported that taste panels demonstrated a preference for fully fermented sauerkraut containing 1–1.5% titratable acidity (TA, calculated as lactic acid) which was consistent with the good quality range of 1.1–1.5% TA reported by Pederson (1940).

The end products formed during the fermentation of the cabbage contain significan amounts of lactic acid and a small amount of acetic acid and propionic acid, and a mixture of gases, CO_2 being the most important. Minor end products also appear. Diacetyl and acetaldehyde were reported by Hrdlicka et al. (1967) cited by Lee et al. (1976) as the primary carbonyls produced during kraut fermentation. According to Lee et al. (1976), the major amount of the volatiles in sauerkraut is accounted for by acetal, isoamyl alcohol, *n*-hexanol, ethyl lactate, *cis*-hex-3-ene-1-ol, and allyl isothiocyanate. *Cis*-hex-3-ene-1-ol and allyl isothiocyanate are the predominant volatiles that defin the character of sauerkraut but do not contribute significantl to its quality. Instead, the fresh, fruity aroma of compounds such as ethyl butyrate, isoamyl acetate, *n*-hexyl acetate, and mesityl oxide probably are more important in determining the acceptability of sauerkraut.

Microbial spoilage of sauerkraut can induce changes in texture, color, and fl vor. Sauerkraut softening occurs when fermentation takes place at a very high temperature, when the cabbage is exposed to air, too little salt is added, or by faulty fermentation when the lactic acid content remains too low (Belitz and Grosch 1999). Pink Kraut is caused by the surface growth of yeasts mainly of *Torula* spp., especially *T. glutinus* (Jay 1998). Rotted sauerkraut may be caused by bacteria, molds, and/or yeasts. Keeping air from the fermentation is important in controlling molds and yeasts. Refrigeration and heat processing after packaging are also important treatments to maintain a microbiologically stable product. (Banwart 1989).

Olives

Table olives (this subject is discussed in a chapter on olives and is only briefl mentioned here) are probably the most popular fermented vegetable in the Western world and a major part of the Mediterranean diet together with olive oil (Panagou et al. 2008). Table olives are prepared from specificall cultivated fruit varieties harvested at predetermined stages of maturation. The most important industrial preparations are the Spanish preparation for green olives, the Californian preparation for black oxidized olives, and the Greek preparation for naturally black olives (Garrido Fernández et al. 1997) (Figure 17.4).

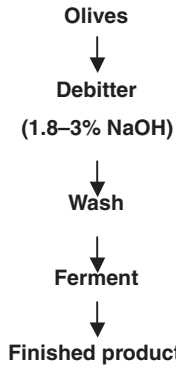

Figure 17.4 Flow chart for the preparation of Spanish style olives.

Kimchi

Kimchi is a general term applied to a Korean product made by the lactic acid fermentation of salted vegetables (dry salted or brined) with or without secondary ingredients (Fleming et al. 1995). It is similar to sauerkraut in Europe and the United States. There are numerous variations of kimchi depending on the production technique. Materials used for kimchi preparation are divided into basic groups, primary vegetables and secondary vegetables. The two most frequently used primary vegetables are Chinese cabbage and radishes. Other primary vegetables used less frequently include cucumbers, green onions, turnips, green peppers, Chinese leeks, Indian mustard greens, spinach, and eggplant. Kimchi produced from cabbage as the primary vegetable, along with secondary vegetables, is the most popular product. Secondary ingredients include vegetables (radish, Indian mustard greens, water celery, and carrot), seafoods (shrimp, oyster, squid), fruit (pine nut, pear, apple), seasoning (salt, salted fermented fis sauce, sugar, monosodium glutamate) and cereals (cooked rice, cooked wheat flou , cooked rice flour (Lee and Cho 1990; Fleming et al. 1995).

Appropriate cultivars of Chinese cabbage with light-green colored soft leaves and compact structures with no defects, are required for production of kimchi. After removing outer leaves and roots from the cabbage, it is cut into small pieces. The prepared cabbage is placed in a salt solution (8–15%) for 2–7 hours to increase the salt content of the cabbage in the range 2.0–4.0% (w/w). It is then rinsed several times with fresh water and drained to remove extra water. The minor ingredients (garlic, red pepper, green onion, ginger) are chopped and mixed with secondary vegetables such as shredded radish,

and stuffed between the salted cabbage leaves. The kimchi is packed in an earthen jar, buried in the ground, and pressed with a stone placed inside in order to keep the ingredients immersed in the juice. Kimchi fermentation is carried out by various microorganisms present in the raw materials and ingredients used in the preparation of kimchi. The most important microorganisms in kimchi fermentation are lactic acid bacteria and include *L. mesenteroides*, *Leuconostoc dextranicum*, *Lactobacillus leichmanii*, and *Lactobacillus sake*. Other lactic acid bacteria found during the course of the kimchi fermentation include *L. plantarum*, *Lactobacillus fermentum*, *L. brevis*, *Streptococcus faecalis*, and *Pediococcus pentosaceus* (Shim et al. 1990; Shin et al. 1996). Kimchi is considered perishable. After fermentation, the product can be left to mature for several weeks at refrigeration temperature. If stored under warm conditions, the kimchi must be consumed soon after production as it deteriorates rapidly.

Pickled Roots

Carrots and turnips are pickled separately or as a mixture in many areas of the world such as the Middle East, Asia, and Africa. These products are usually fermented using a homemade process. However, the use of adapted inocula has improved the quality of these fermented products. High quality fermented carrots have been successfully produced by controlled fermentations using a mixed culture of *L. plantarum*, *L. brevis*, *P. cerevisiae*, and *L.* mesenteroides (Niketic-Aleksic et al. 1973). In Russia, beetroot is pickled by cleaning, slicing, and placing in a container with salt. A fl w diagram for the preparation of pickled roots is shown in Figure 17.5.

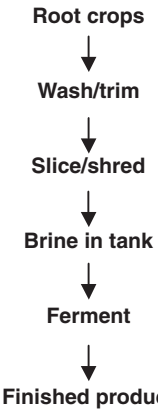

Figure 17.5 Flow chart for the preparation of pickled roots. (Adapted from Andersson 1986).

Brined Pickled Mango

Brined pickled mango has been traditionally processed from mature green mango in many Asian, African, and Latin American countries. It is a major product of India, Pakistan, and Bangladesh and has the highest market share as compared to other processed mango products. Green mango pickle is a hot, spicy pickle with a sour taste. It is eaten as a condiment. Preservation is achieved by a combination of salt, increased acidity, and to a small extent the spices.

Fresh, fully mature green mangoes must be carefully selected to ensure a good quality product. The best pickles are obtained from fruit at early maturity when the fruit has reached almost maximum size but still fir and unripe. Riper fruit results in pickles with a fruity odor and lacking the characteristic and predominant green mango fl vor.

The green mangoes are inspected and any damaged fruit rejected. The fruit is washed in clean water and drained. The fruit is then cut using sharp knives with preferably stainless blades. The sliced mangoes are soaked in 10–12% salt brine solution containing sodium metabisulfit (1,000 ppm) and 1% calcium chloride. The containers are stored until the mangoes are pickled. The brine is then drained off and spices are mixed with the mango slices (Redelinghuys and Van Der Riet 1978).

The mixture is then packed and oil added onto the surface of the mixture. The mangoes

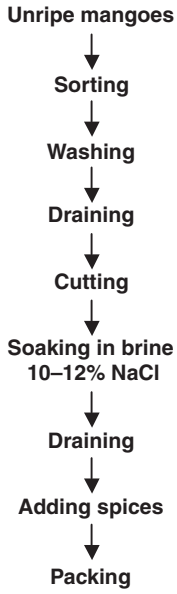

Figure 17.6 Flow chart for the preparation of pickled green mangoes.

should be firml pressed down in the container. Good quality vegetable oil such as sunfl wer oil should be used and finel ground chilli powder can be added to the oil for fla vor and color. Mango pickle can be packed in small polythene bags and sealed or in clean jars and capped. Mango pickle keeps well if stored in a cool place. If it is processed well, it can be kept for several months. Due to the high acid level of the fina product, the risk of food poisoning is low (Fellows 1997). The fl w chart of pickled green mango is shown in Figure 17.6.

Nonsalted Lactic Acid Bacteria Products

Gundruk (Pickled Leafy Vegetable)

Gundruk is a popular homemade pickled product made in Nepal. Gundruk is obtained from the fermentation of leafy vegetables during the months of October and November. Gundruk is a major source of minerals particularly during the off-season when the diet consists of mostly starchy tubers and maize, which tend to be low in minerals. It is served as a side dish along with the main meal and is also used as an appetizer (Karki 1986). The process is similar to sauerkraut production except that no salt is added to the shredded leaves prior to gundruk fermentation. Leaves of mustard, radish, and caulifl wer are allowed to wilt for 1 or 2 days and then shredded with a knife or sickle. Shredded leaves are tightly packed in an earthenware pot and warm water (at about 30°C) is added to cover all the leaves. The pot is then kept in a warm place. After 5–7 days, a mild acidic taste indicates the end of fermentation and the gundruk is removed and sun-dried. The ambient temperature at the time of fermentation is about 18°C (Karki 1986; Jones 1994). The predominant microorganisms during gundruk fermentation are *Pediococcus* and *Lactobacillus* species. The fermentation is initiated by *Lactobacillus cellobiosus* and *L. plantarum*, and other homolactics begin to grow vigorously from the third day onwards. *P. pentosaceus* increases in number on the fift day and thereafter declines (Karki 1986). During fermentation, the pH drops slowly to a fina value of 4.0 and the amount of acid (as lactic) increases to about 1% on the sixth day.

Sinki (Pickled Radish)

Sinki is a sour pickle prepared from radish taproots. It is consumed traditionally in India, Nepal, and parts of Bhutan, where it is used as a base for soup or eaten as a pickle. Fresh radish roots are harvested, washed, and wilted by sun-drying for 1–2 days. They are then shredded, rewashed, and packed tightly into an earthenware or glass jar, which is sealed and left to ferment. The optimum fermentation time is 12 days at 30°C. There is a second processing method involving fermentation in a clay-lined pit for 2–3 months (Karki 1986). Sinki fermentation is initiated by *L. fermentum* and *L. brevis*, followed by *L. plantarum*. During fermentation the pH drops from 6.7 to

3.3. After fermentation, the radish substrate is sun-dried to a moisture level of about 21% (Steinkraus 1996). For consumption, sinki is rinsed in water for 2 minutes, squeezed to remove the excess water, and fried with salt, tomato, onion, and green chilli. The fried mixture is then boiled in rice water and served hot as soup along with the main meal (Steinkraus 1996).

Sunki

Sunki is a nonsalted and fermented Japanese vegetable product prepared in the winter season from the leaves of "Otaki-turnip." Sunki is consumed with rice and in miso soup. The Otaki-turnip is boiled and inoculated with "Zumi" (a wild small apple) and dried Sunki from the previous year and allowed to ferment for 1–2 months. The microorganisms involved include *L. plantarum*, *L. brevis*, *Bacillus coagulans*, and *P. pentosaceus* (Makayama 1957 cited by Battcock and Azam-Ali, 1998).

Acidified Vegetables

Acidifie vegetables are nonfermented products produced by the addition of an acid, commonly acetic acid, as an acidulant. Examples of acidifie vegetables include cucumbers, red table beets, pearl and silver onions, paprika peppers, mixed vegetables, which also include caulifl wer, carrots, onions, peas, mushrooms, asparagus, tender corncobs, celery, parsley roots, parsnip, kohlrabi, pumpkin, and pepperoni peppers (Belitz and Grosch 1999). At concentrations of 3.6% or above, acetic acid-acidifie foods can be preserved without the addition of any other antimicrobial agents or the use of heat treatments (Bell and Etchells 1952; Campbell-Platt and Anderson 1988). Many acidifie vegetables products contain between 0.5 and 2% of acetic acid and are pasteurized to prevent spoilage as well as to ensure safety. The addition of sugar and sodium benzoate allows the use of lower concentrations of acetic acid. For nonfermented sweet pickles, the combination of heat treatments, acid levels, and sugar concentration serve to prevent microbial growth (Breidt et al. 2007). Fresh pack cucumber pickle products typically contain between 0.5 and 1% of acetic acid. A recommended pasteurization procedure consists of heating to an internal temperature of 74°C for 15 minutes for fresh pack cucumber as well as for pickled fresh peppers at relatively low concentrations of sodium chloride and acetic acid (Monroe et al. 1969).

Conclusion

Fermented vegetables have played and will continue to play an important role by providing a safe and nutritious commodity with an extended shelf life and unique desirable organoleptic traits. Enhancing the quality and reducing the spoilage are goals for future developments of fermented vegetables. These goals can be achieved by controlling the fermentation process through the integration of physical, chemical, and biological factors.

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Chapter 18

Vegetable Parts, Herbs, and Essential Oils

Sri Yuliani and Bhesh Bhandari

Introduction

The terms "herbs" and "spices" are often used interchangeably since both refer to aromatic parts of plants. The word "herb" comes from the Latin word "*herba*," meaning a medical plant. Herbs are botanically classifie as perennials that wither after blooming and their stems are not woody (Hirasa and Takemasa 1998). In a narrow sense, herbs are soft-stemmed plants; both fresh and dried forms of leaves and fl wers are used for seasoning foods (Lewis 1984). The herbs are valued for their medicinal and aromatic properties and are often grown and harvested for these applications (Peter and Babu 2004). The word "spice" comes from the Latin word "*species*" meaning specifi kind. Spices are derived from different parts of the plants such as seeds, leaves, fl wers, buds, fruits, bark, or rhizomes and cultivated for their aromatic, fragrant, pungent, or other desirable properties (Hirasa and Takemasa 1998; Uhl 2000). Some edible herbs are categorized as spices but spices do not have any plant classificatio as they only refer to parts of the plant.

More than 400 herbs and spices are in use in the world. These aromatic vegetable materials have long been used as fl vorings and colorings, and are responsible for taste, aroma, and appearance of foods and beverages. Since ancient times, herbs and spices have also been known for their medicinal and preservative properties. Their beneficia effects are associated with their antimicrobial, antioxidant, and medicinal properties including antidiabetic, anti-inflammator , and anti-carcinogenic. These properties have been attributed to their intrinsic active constituents categorized as polyphenols, terpenes, vanilloids, or organosulfur compounds (Kaefer and Milner 2008).

Traditionally, herbs for food ingredients were prepared freshly from seeds, leaves, bark, fl wers, and rhizomes. Herbs and spices are often dried, fin or coarse grinded for storage. Pure extracts and powders are also available for use. There is a growing interest in herbs and spices for food, pharmaceutical, or cosmetic applications in proportion to the rising global demand for natural products. Herbal additives are being incorporated into food manufacturing such as ready-to-eat snacks and bars, cosmetic and toiletry formulations such as body lotion, facial cream, shampoo, and soaps. Herbs are also available in the form of capsules, powders, tablets, or soft gel as dietary supplements in the market.

This chapter provides information on herbs and their processing and packaging. Plant parts and their active constituents are described at the beginning of the chapter followed by their functional properties. A specifi discussion on microencapsulation of herbs and spices is also presented.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Composition of Herbs and Spices

Herb and Spice Parts

The aromatic and medicinal properties of herbs and spices are derived from different parts of plant such as seeds (coriander, caraway), leaves (bay, parsley, basil), fl wer (saffron), fl wer bud (clove), fruits (cardamom, fennel), bulbs (onion, garlic), rhizomes (ginger, turmeric), stalk (lemongrass), and bark (cinnamon). Some herbs have only one part of the plant, while others have many different parts that can be used (Table 18.1). The parts of the plants would differ somewhat in their taste and smell, and this determines their suitability for a particular application.

Herb and Spice Forms

Herbs and spices are available in many forms such as fresh, dried, whole, ground, crushed, and extractives. Each form has its advantages and disadvantages. Fresh herbs and spices are more desirable since they provide fresh aroma and taste. The pleasant aroma is attributed to the volatile oils (Peter and Babu 2004). These components can be lost during harvesting, handling, storing, and processing. As the fl vor is intact in the plant tissue and cell, preliminary preparation such as grinding, crushing, slicing, roasting or flakin of whole herbs and spices to rupture the cellular tissue is required before incorporating herbs and spices into food processing (Uhl 2000; Hirasa and Takemasa 1998). Herbs and spices are often used in their dried forms because they are less bulky, easier to process, have longer shelf life and higher fla vor intensity. The herb and spice extractives contain volatile and nonvolatile oils having specifi and standardized fl vor characteristics (Uhl 2000). The volatile essential oils impart specifi ('fresh or sharp') sensation and aroma herbs and spices while the non-volatiles include fi ed oils, gums, resins, and hydrophilic compounds that contribute to the "bite" character (Uhl 2000). The major constituents of volatile oils are terpenes including mono-, di-, and sesquiterpenes. Monoterpenes are very volatile and contribute to the strong aroma characteristics (Uhl 2000; Hirasa and Takemasa 1998). The extractives can be in liquid (essential oils, oleoresin, and water extracts), dried, or encapsulated forms.

Essential oils are obtained by water distillation, steam distillation, water-steam distillation or cold pressing of ground, chopped, crushed leaves, seeds, stems, roots and bark of ground, chopped, crushed leaves, seeds, stems, roots, or barks. The essential oils are about 75–100 times more concentrated than the fresh herbs and spices (Uhl 2000). They are easily soluble in alcohol or ether, but only sparingly soluble in water.

The non-volatile components of herbs and spices, known as oleoresins are recovered by solvent extraction of dried ground herbs and spices. After extraction, the solvent is removed giving both essential oil and desirable non-volatile compounds (Reineccius 2006). Oleoresins are available as viscous oils and thick pastes and are more difficul to handle than essential oils. But they are highly concentrated and have greater stability than essential oils (Uhl 2000).

Compositions

The herbs and spices are rich in volatile oils giving pleasant aromas. They may also contain alkaloids and glycosides, which are of greater interest to pharmacologists. Other compounds such as coumarins and fl vones have been known for their antibacterial and anti-inflammator properties, respectively (Brown 1995; De Guzman and Siemonsma 1999).

Table 18.1 Parts, form, and bioactive compounds of selected herbs and spices

Latin name	Common name	Parts used[a,b,c]	Form[a]	Bioactive compounds[b,c,d]
Elettaria cardamomum; *Amomum subulatum*	Cardamom	Fruit, seed	Dried whole, ground seed	Limonene, caffeic acid
Carum carvi	Caraway	Fruit, seed, root	Dried whole, ground fruit/seed	Carvone, limonene, α-pinene, kaempferol
Capsicum annum	Chili pepper	Fruit	Fresh whole, sliced, pureed; dried whole, crushed, ground	Capsaicin, α-tocopherol, lutein, β-carotene, ascorbic acid, vitamin E
Cinnamomum sp.	Cinnamon	Bark, leaf	Dried whole bark, chunk, ground	Cynnamic aldehyde, 2-hydroxycynnamaldehyde, eugenol
Syzigium aromaticum	Cloves	Flower bud	Dried whole, ground; oil	Eugenol, isoeugenol, gallic acid
Coriandrum sativum	Coriander	Leaf, seed	Dried whole ground seed; fresh leaf, fresh root	Quercetin, caffeic acid, cineol, geraniol, borneol, 1,8-cineole, α-terpinene, β-carotene, β-pinene, β-sitosterol, cinnamic acid, ferrulic acid, γ-terpinene, p-cymene, quercetin, rutin, vanillic acid
Cuminium cyminum	Cumin	Seed	Dried whole, ground	α-Pinene, β-pinene, γ-terpinene, p-cymene, cuminaldehyde, carvone, 1,8-cineole, β-carotene, β-sitosterol, caffeic acid, carvacrol, carvaol, geranial, kaempferol, limonene, p-coumaric acid, quercetin, tannin, thymol
Anethum graveolens	Dill	Fruit, leaf, top	Dried whole, crushed, ground fruit; fresh and dried whole, chopped, ground leaf	Carvone, limonene, isorhamnetin, kaempferol, myricetin, quercetin, catechin
Foeniculum vulgare	Fennel	Leaf, twig, fruit	Dried whole, ground seed	α-Pinene, β-carotene, limonene, quercetin, benzoic acid, β-sitosterol, caffeic acid, cinnamic acid, ferulic acid, fumaric acid, kaempferol, myristicin, 1,8-cineole, p-coumaric acid, quercetin, rutin, vanillic acid, vanillin
Allium sativum	Garlic	Bulb	Fresh whole clove, crushed, sliced, minced, chopped, roasted; dried powdered, granulated, fla ed, diced, ground, minced, chopped, sliced	Allicin, diallyl disulfide allyl isothiocyanate

(*Continued*)

Table 18.1 (*Continued*)

Latin name	Common name	Parts used[a,b,c]	Form[a]	Bioactive compounds[b,c,d]
Zingiber officinal	Ginger	Rhizome	Fresh whole (unpeeled), sliced, chopped, crushed, grated; preserved in syrup, pickled, dried bruised, sliced, powdered	Zingiberone, zingiberene, ingerol, paradol, curcumin, shagoal
Cymbopogon citratus	Lemongrass	Stalk	Fresh whole, bruised, sliced, chopped, coarsely pureed; dried chopped, ground; frozen whole	Farnesol, geraniol
Origanum majorana	Marjoram	Leaf, flora bud	Fresh whole, chopped; dried whole, broken, ground	Eugenol, limonene, ursolic acid, 1,8-cineole, α-pinene, α-terpinene, carvacrol, farnesol, geraniol, p-cymene, rosmarinic acid, sterols, thymol, apigenin
Brassica sp.	Mustard	Leaf, seed	Dried whole, crushed, ground, powder; paste	Allyl isothiocyanate, β-carotene
Myristica fragrans	Nutmeg	Seed, kernel	Fresh kernel, preserved in syrup; dried whole, ground seed	Caffeic acid, catechin
Allium cepa	Onion	Bulb, leaf	Fresh chopped, sliced, diced; roasted, grilled, fried, pickled; dried granulated, powdered, ground, minced, chopped, toasted	Quercetin, dipropyl disulfide
Origanum vulgare	Oregano	Leaf, fl wer	Fresh whole, chopped, minced leaf; dried whole, fla ed, ground	Apigenin, luteolin, myricetin, quercetin, caffeic acid, p-coumaric acid, rosmarinic acid, carvacrol, thymol
Capsicum annum	Paprika	Fruit, seed	Fresh whole fruit; ground seed	α-Tocopherol, capsaicin, dihydrocapsaicin, lutein, β-carotene, ascorbic acid, vitamin E
Petroselinum crispum	Parsley	Leaf, seed, root	Fresh, dried whole, fla ed, chopped, minced, pureed leaf. Fresh seed, root.	Apigenin, luteolin, kaempferol, myricetin, quercetin, caffeic acid
Piper nigrum	Pepper, black	Fruit berry	Dried whole, cracked, ground berry	Piperidine, piperine, limonene, α-pinene, β-pinene
Mentha piperita	Peppermint	Leaf, terminal shoot	Fresh or dried whole, fla es, chopped, crystallized leaf	Limonene, menthol, eriodictyol, hesperitin, apigenin, luteolin

Table 18.1 (*Continued*)

Latin name	Common name	Parts used[a,b,c]	Form[a]	Bioactive compounds[b,c,d]
Rosmarinus officinali	Rosemary	Terminal shoot, leaf	Fresh or dried whole, minced, chopped, crushed, rubbed, ground leaf	Carnasol, carnosic acid, cineole, geraniol, α-pinene, β-carotene, apigenin, limonene, naringin, luteolin, caffeic acid, rosmarinic acid, rosmanol, vanillic acid
Salvia officinali	Sage	Terminal shoot, leaf	Fresh or dried whole, minced, chopped, crushed, rubbed, ground leaf	α-pinene, β-sitosterol, citral, farnesol, ferulic acid, gallic acid, geraniol, limonene, cineole, perillyl alcohol, β-carotene, catechin, apigenin, luteolin, saponin, ursolic acid, rosemarinic acid, carnosic acid, vanillic acid, caffeic acid, thymol, eugenol
Artemisia dracunculus	Tarragon	Leaf	Fresh whole, chopped, minced; dried whole, chopped, ground	Luteolin, isorhamnetin, kaempferol, quercetin, caffeic acid
Thymus vulgaris	Thyme	Terminal shoot, leaf	Fresh, dried whole, minced, ground leaf	Thymol, carvacrol, cineole, α-pinene; apigenin, β-carotene, eugenol, limonene, ursolic acid, luteolin, gallic acid, caffeic acid, rosmarinic acid, carnosic acid, hispidulin, cismaritin

[a]Uhl (2000).
[b]Shylaja and Peter (2004).
[c]Ravindran and Pillai (2004).
[d]Kaefer and Milner (2008).

The functional properties of herbs and spices come from their bioactive components. Generally, these compounds work synergistically for specifi actions such as antimicrobial, anti-inflammation or antidiabetic.

Functional Properties of Herbs and Spices

Medicinal and Nutraceutical Properties

Herbs and spices are well recognized for their medicinal properties. Accordingly they have been investigated for antidiabetic, antioxidant, anti-inflammator , antihypercholesterolemic, and anticarcinogenic effects.

Antihypercholesterolemic Properties

Some herbs and spices have been investigated for their effica y in lowering serum cholesterol in relation to atherosclerosis and coronary heart diseases. Ginger, garlic, fenugreek, chilli, turmeric, garlic, and onion were found to be effective as hypocholesterolemic agents both in humans and in animals. Ginger and its active compound, shogaol, were shown to have positive effects on blood pressure (Suekawa et al. 1984). Further, reduction in

blood glucose and total serum cholesterol, and an increase in high-density lipoprotein (HDL) cholesterol were observed when ginger extract was administered to male rats (Ahmed and Sharma 1979). These actions were also observed with the intake of fenugreek seed powder (Sharma et al. 1996; Amrithaveni and Thirumanidevi 2004). In human studies, the consumption of dried ginger inhibited platelet aggregation (Verma et al. 1993). Similar action of platelet inhibition was found due to high intake of aged garlic extract (Liu and Yeh 2001) which contained water-soluble and lipid-soluble organosulfur compounds and fl vonoids. Further, the aged garlic extract was reported to be more effective than fresh or other preparations (Steiner and Li 2001). Curcumin and capsaicin, the bioactive components of turmeric and chilli, respectively, were shown to have hypocholesterolemic effects (Suzuki and Iwai 1984; Govindarajan and Satyanarayana 1991; Surh and Lee 1995; Srimal 1997).

Antidiabetic Property

Turmeric and its active constituent, curcumin, were reported to decrease blood sugar level and prevent galactose-induced cataract formation (Arun and Nalini 2002; Suryanarayana et al. 2005). In other studies, dietary intake of turmeric and onion was reported to impart beneficia hypoglycemic effects (Tank et al. 1990; Babu and Srinivasan 1998, 1999). Ginger and gingerol also induced production of antihyperglycemic effects in diabetic rats (Sekiya et al. 2004; Bhandari et al. 2005). Fenugreek seed is widely used for the treatment of diabetes. It exhibited significan action against hyperglycemia, hypoinsulinemia, and glycoselated hemoglobin in rats (Devi et al. 2003), and stabilized glucose homeostasis in rat liver and kidney (Raju et al. 2001). The hypoglycemic actions of garlic and onion have been attributed to their sulfur compounds (2-propenyl disulfid and 2-propenylpropyl disulfide (Augusti and Sheela 1996).

Antioxidant Properties

Rosemary, thyme, oregano, sage, capsaicin, curcumin, ginger, basil, black and red pepper, clove, basil, marjoram, caraway, peppermint, fennel, nutmeg, cinnamon, coriander, dill, parsley, garlic, cumin, and many other herbs and spices have been widely investigated for their antioxidant capacity. The antioxidant properties have been attributed to fl vonoids, phenolic acids, and diterpens, which have the ability to scavenge free radicals, donate hydrogen atoms or electron, or chelate metal cations (Pietta et al. 1998).

Some herbs have antioxidant activity in vegetable oils and lard, but others are effective in emulsion, water, sausage, or minced meat. For example, rosemary and sage are effective antioxidants in lard (Palitzsch et al. 1969), but their activity is relatively low in oil-in-water emulsion as compared to clove (Al-Jalay et al. 1987).

Antimicrobial Properties

Herbs and spices can be a natural means to inhibit microbial growth and spoilage of foods. Their inhibitory properties have been ascribed to the naturally present phenols and phenolic acids, coumarins, terpenoids, and alkaloids (Cowan 1999; Bergonzelli et al. 2003). The phenolics break down bacterial cell membranes, resulting in leakages of intracellular components or destroying bacterial enzyme system. It is reported that the gram-positive bacteria are more susceptible to phenolics than gram-negative bacteria as the phospholipid membranes of the latter bacteria are impermeable to lipophilic compounds providing barrier for antibacterial action (Shelef et al. 1980; Farag et al. 1989; Russell 1991).

Methanolic extract of cinnamon, clove, and oregano have been shown to inhibit the

growth of *Staphylococcus aureus*, *Bacillus cereus*, *Listeria monocytogenes*, *Salmonella anatum*,, and *Escherichia coli* (Shan et al. 2007). Rosemary, sage, and thyme also exhibited antimicrobial properties against *S. aureus*, *B. cereus*, *L. monocytogenes*, and *S. anatum* but did not show any inhibitory effect on gram-negative bacteria *E. coli* (Shan et al. 2007; Oyedemi et al. 2008). However, the latter bacteria are susceptible to water extracts of cinnamon and mustard (Sofi et al. 2007). The antimicrobial properties of the selected herbs and spices are summarized in Table 18.2.

Herbal Extract Processing

In comparison to fresh and frozen forms, dried herbs and spices dominate the home and industrial use market. However, the extractive forms are mainly used industrially.

Drying

The herbs and spices contain about 75–80% moisture; drying is commonly employed to lower the moisture content to less than 15%. In addition, there is a substantial reduction in weight, reducing packaging, storage, and transportation costs. However, drying of herbs and spices can cause some changes in aroma and appearance but the effect of a particular drying on the volatile compounds is not easily predictable and would depend on the stability of aroma compounds and the spice source.

Sun-drying is the oldest form of drying to make dried herbs and spices in many parts of the world. As a natural source of solar energy, it is abundant and free, and unlike other forms of energy, it is nonpolluting and environmentally friendly. However, there are some limitations with sun-drying, such as the relatively longer drying time, exposure to environmental contaminations (dust, insects, etc.), dependent on weather conditions (solar radiation, ambient temperature, relative humidity, and wind speed), and there is relatively more manual labor requirement. Besides, sun drying can have adverse effect on the desirable color pigments. Akpinar (2006) showed that during the sun drying of mint, parsley, and basil leaves, moisture decreased continuously with time. The wire basket solar dryer can be used directly in the fiel to avoid transportation of large quantity of the wet crops (Balladin et al. 1996). Using wire solar basket dryers, drying of thyme reached equilibrium moisture after 12 hours of drying at 50°C (Balladin and Headley 1999).

Freeze-drying, a relatively expensive form of drying, caused less pronounced changes in the characteristic appearance and aroma of herbs and spices. Abascal et al. (2005) indicated losses of monoterpens during freeze-drying. However, many volatiles were reported to be retained in freeze-dried bay leaves (Diaz-Maroto et al. 2002a), spearmints (Diaz-Maroto et al. 2003), dill (Huopalahti et al. 1985), sage and thyme (Venskutonis 1997), and oregano (Yousif et al. 2000). Freeze-drying is a very expensive technique; therefore, the cost of product should be acceptable to the market.

Although, drying prolongs shelf life, it can also affect fl vor and appearance. The changes in volatile profil of herbs and spices dried by various forms of drying are shown in Table 18.3. The changes in concentrations of the volatile compounds during drying depend on several factors, such as the drying method, the biological characteristics of the plants, and their volatile composition (Diaz-Maroto et al. 2004).

Extraction

The spice extracts such as essential oils and oleoresins from leaves and fl wer tops of various herbal spices can be recovered using steam distillation, water and steam distillation, supercritical carbon dioxide extraction, and solvent extraction using low-boiling organic solvents. In steam distillation, the plant material is exposed to high temperatures,

Table 18.2 Antimicrobial properties of selected herbs and spices

Systematic name of herbs and spices	Common name	Extraction technique	Microbial inhibitory	References
Cinnamomum cassia Presl.	Cinnamon	Methanolic	*Staphylococcus aureus* > *Bacillus cereus* > *Listeria monocytogenes* > *Salmonella anatum* > *Escherichia coli*	Shan et al. (2007)
Cinnamomum burmannii L.	Cinnamon stick	Methanolic	*S. aureus* > *B. cereus* > *S. anatum* > *L. monocytogenes* > *E. coli*	Shan et al. (2007)
Eugenia caryophylata Thunb.	Clove	Methanolic	*S. aureus* > *B. cereus* > *S. anatum* > *L. monocytogenes* > *E. coli*	Shan et al. (2007)
Origanum vulgare L.	Oregano	Methanolic	*S. aureus* > *L. monocytogenes* > *B. cereus* > *S. anatum* > *E. coli*	Shan et al. (2007)
Rosmarinus officinali L.	Rosemary	Methanolic	*S. aureus* > *B. cereus* > *L. monocytogenes* > *S. anatum*	Shan et al. (2007)
		Hydrodistillation	*Streptococcus pyogenes* = *Bacillus subtilis* = *Proteus vulgaris* = *Shigella fl xneri* = *Pseudomonas fluo escens* > *L. monocytogenes* = *B. cereus* = *E. coli* = *Klebsiella pneumoniae* = *Alcaligenes faecalis*	Oyedemi et al. (2008)
Salvia officinali L.	Sage	Methanolic	*S. aureus* > *B. cereus* > *L. monocytogenes* > *S. anatum*	Shan et al. (2007)
Thymus vulgaris L.	Thyme	Methanolic	*B. cereus* > *S. aureus* > *L. monocytogenes* > *S. anatum*	Shan et al. (2007)
Ocimum basilicum L.	Sweet basil	Methanolic	*S. aureus* > *B. cereus*	Shan et al. (2007)
		Hydrodistillation	*B. cereus* > *S. pyogenes* > *P. vulgaris* > *L. monocytogenes* = *B. subtilis* = *P. fluo escens* = *K. pneumoniae* > *S. fl xneri* = *E. coli* = *A. faecalis*	Oyedemi et al. (2008)
		Ethanol, methanol, hexane extraction	*Acinetobacter calcoaceticus* > *E. coli* > *Staphylococcus epidermidis* > *Bacillus macerans* > *S. aureus*	Adiguzel et al. (2005)
Allium sativum	Garlic	Water extraction	*B. cereus* > *S. aureus* > *E. coli*	Sofi et al. (2007)

Table 18.2 (*Continued*)

Systematic name of herbs and spices	Common name	Extraction technique	Microbial inhibitory	References
Zingiber officinal	Ginger	Water extraction	*S. aureus* > *B. cereus* > *E. coli*	Sofi et al. (2007)
Mentha piperita	Mint	Water extraction	*S. aureus* > *B. cereus* > *E. coli*	Sofi et al. (2007)
Syzigium aromaticum	Clove	Water extraction	*E. coli* > *B. cereus* > *S. aureus*	Sofi et al. (2007)
Cinnamomum zeylanicum	Cinnamon	Water extraction	*E. coli* > *S. aureus* > *B. cereus*	Sofi et al. (2007)
Brassica jance	Mustard	Water extraction	*E. coli* > *S. aureus* > *B. cereus*	Sofi et al. (2007)

leading to the degradation of important components of essential oils, while extraction with organic solvents leaves residues of the solvent in spice extracts. Extraction using compressed carbon dioxide gas or supercritical flui is an effective method as the extracts are free of solvent and there is no thermal and hydrolytic degradation of important components (Diaz-Maroto et al. 2002b; Perakis et al. 2005; Araus et al. 2009).

Microwave extraction is another technique of extraction offering relatively low-energy consumption, low cost, less emission of CO_2, and good quality (Sahraoui et al. 2008).

Microencapsulation of Herb Extractives

Herb and spice extractives including essential oils, oleoresins, and water extracts are easily

Table 18.3 Changes in volatile profiles of selected herbs dried by techniques of drying

Herbs and their major constituents	Concentration (μg/g, db) of SDE extract				References
	Fresh	Air-dried (ambient temperature)	Freeze-dried (−18°C)	Oven-dried (45°C)	
Spearmint					
- 1,8 cineole + limonene	6,488	7,909	7,492	8,319	Diaz-Maroto et al. (1988)
- Cis-dihydrocarveol	736	672	622	565	
- Dihydrocarvone	1,733	1,434	1,109	1,561	
- Carvone	14,399	14,702	14,229	15,324	
Parsley					
- β-phellandrene	518	476	308	204	Diaz-Maroto et al. (2002c)
- p-mentha-1,3,8-triene	315	482	252	154	
- Myristicin	264	191	112	192	
- Apiole	810	491	480	382	
Bay leaf					
- Sabinene	448.4	478.5	534.2	295.3	Diaz-Maroto et al. (2002a)
- 1,8-cineole	2515.8	2172.2	2349.4	1621.2	
- Linalool	1822.6	1708.3	1522.3	339.1	
- Terpinyl acetate	602.5	318.6	353.8	343.0	
Basil					
- Linalool	4886	3158	3628	3091	Diaz-Maroto et al. (2004)
- Eugenol	1780	1360	1703	1464	
- β-elemene	423	356	493	377	
- Trans-cadinol	336	211	252	225	

subjected to adverse effects of environmental conditions such as heat, moisture, light, oxygen, or other reactive substances. In the form of liquid, the extractives are also difficult to handle. Microencapsulation technology provides protection to active materials against harsh processing and storage conditions. The active materials are packed and sealed in tiny capsules (2–5000 μm) so that they have longer shelf life and better stability (Bakan 1973; Sparks 1981; King 1995). Microencapsulation converts the active materials into solid or free-flowing powder form providing easy handling. In addition, controlled release properties are other advantages of encapsulated extractives. Various techniques and encapsulating materials can be used for the encapsulation herbs and spice extractives.

The choice of microencapsulating technique and the encapsulating materials depends upon the end use of the flavor material and the processing conditions involved in the manufacturing of the product.

Spray Drying

Spray drying is the most common and cheapest method to produce encapsulated flavors or volatiles. More than 90% of the encapsulated flavorings are produced by this method (Reifsteck and Jeon 2000). The spray drying process involves three basic steps: (1) preparation of the emulsion or dispersion; (2) homogenization of the dispersion; and (3) finally, drying by atomizing into a spray drying chamber (Dziezak 1988). The carriers commonly used in spray drying are starch, modified starches, dextrins, succinylated gelatin, and gum arabic (Anandaraman and Reineccius 1980).

Spray-dried encapsulated flavors have a shelf life of about 6 months. The stability of the encapsulated flavors depends on the type of flavor compounds, encapsulating material used, absence of surface oil (which oxidizes rapidly), moisture content of the powder, and moisture absorption during storage (Bhandari and D'Arcy 1996). Spray-dried products typically have a small particle size (generally less than 50 μm) and the carrier materials used are water-soluble, which makes the microcapsules hygroscopic and soluble in water (Shahidi and Han 1993). The application of spray drying for encapsulating oleoresins have been reported elsewhere with the load of 2.5–10% (based on encapsulating materials) for black pepper (Shaikh et al. 2006), cardamom (Krishnan et al. 2005), cinnamon (Vaidya et al. 2006), and ginger. Examples of encapsulated black pepper oleoresin products are presented in Figure 18.1.

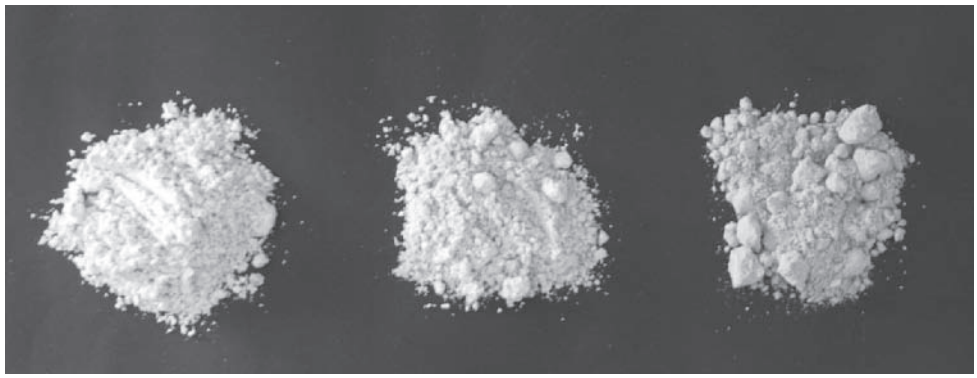

Figure 18.1 Black pepper oleoresin encapsulated in (a) soy milk powder; (b) gelatinized soy starch; (c) soy flour (Courtesy, Indonesian Centre for Agricultural Postharvest Research and Development, Bogor, Indonesia).

Extrusion Encapsulation

Extrusion is the second largest encapsulation method in terms of volume for production of encapsulated powders. In this case, the temperatures and pressures are normally less than 115°C and 690 kN/m, respectively (Reineccius 1989). Extrusion involves forcing a fla vor material dispersed in a carbohydrate mass through a die into a bath of dehydrating liquid (e.g., isopropanol). The coating material hardens on contact with the liquids, forming encapsulating matrix to entrap the core material. The extruded filament are separated from the liquid bath, dried, and sized (Shahidi and Han 1993). The encapsulating material used may be composed of more than one ingredient such as sucrose, maltodextrin, glucose syrup, glycerine, and glucose (Arshady 1993). The advantage of this method is that the material is completely surrounded by the wall material (true encapsulation) and any residual oil or core material is removed from the surface in an alcohol bath (Risch 1995; Gibbs et al. 1999). This gives stability against oxidation and prolongs shelf life. The encapsulated herbs and spices can be kept for 1 to 2 years without any substantial loss of quality (Risch 1988).

Fluidized Bed Coating

Fluidized bed coating is used to create a continuous coating of a polymer fil onto solid powders. The process involves spraying a polymer solution onto a fluidize powder and evaporating the solvent to obtain a polymer fil covering the powder particles. This technique is commonly used for encapsulating drugs, agrochemical compounds, or food ingredients (Ubbink and Schoonman 2003). The method can also be used to coat fla vors to prevent oxidation. The capsules release their contents by increasing the temperature or physical breakage and by water solubilization (Gibbs et al. 1999). Fluidized bed coating can be also used to encapsulate larger particles.

Coacervation

Coacervation, often called "phase separation," is considered as a true microencapsulation technique because the core material is completely entrapped by the encapsulating material. This technique involves the precipitation or separation of a colloidal phase from an aqueous phase (Dziezak 1988). The complex coacervate is produced when the two opposite charges neutralize each other (Soper 1995). The polymer–polymer complex should have hydrophobic properties to form a continuous shell around the hydrophobic substance. Coacervation is usually used to encapsulate water-insoluble essential oils (Anandaraman and Reineccius 1980). Various polymers can be used for complex coacervation such as gum acacia, pectin, carboxymethyl cellulose, and alginate as anionic polymers, and gelatin as a cationic polymer.

Spray Chilling

Spray chilling is similar to spray drying; however, in spray chilling, the air is cooled to below the solidificatio point of the molten fat used for coating (Shahidi and Han 1993). The process involves heating the encapsulating material at above the melting point, mixing the core material, and atomizing into a cooled chamber (Ubbink and Schoonman 2003).

Lipids (typically low melting point fractionated or hydrogenated vegetable oils, melting point of 32–42°C) are often used as the encapsulating material. Thus, the capsules produced are insoluble in water and primarily used for encapsulating water-soluble core materials such as spray-dried fl vors (Shahidi and Han 1993). The fl vor release mechanism of the capsules is mainly by melting the wall material during heat treatment.

Molecular Inclusion

In this method, the fl vor compounds are entrapped inside the hollow center of a

β-cyclodextrin molecule. β-cyclodextrin is a cyclic derivative of starch made up of seven glucopyranose units. The external part of the cyclodextrin molecule is hydrophilic, whereas the internal part is hydrophobic. The guest molecules, which are hydrophobic, can be entrapped into the hydrophobic internal cavity through a hydrophobic interaction (Pagington 1986). This internal cavity is about 0.65 nm in diameter and permits the inclusion of essential oil compounds. The internal cavity can take up one or more fl vor volatile molecules (Dziezak 1988).

Flavor-β-cyclodextrin complex is produced by mixing β-cyclodextrin with water to form an aqueous suspension or a paste, and the fl vors are added to form an inclusion complex. The fl vor inclusion reduces the solubility of β-cyclodextrin and the inclusion complex is precipitated in crystalline form. The crystals are separated from the mixture and dried. The inclusion capacity of 1 g of β-cyclodextrin is about 97 mg of lemon oil (Bhandari et al. 1999).

β-cyclodextrin-fl vor complexes can withstand up to 200°C heating (Pagington 1986; Reineccius and Risch 2006; Szente and Szejtli 1986). In the complexation of garlic oil, the volatile loss was only 2–3% after heat treatment at 85–90°C, while the loss of volatiles of uncomplexed garlic oil was up to 94% (Szente and Szejtli 1988). Similar results were observed for complexed and uncomplexed caraway, onion, and dill oil; the volatile loss ranged from 3–5% and 88–96%, respectively. Complexed D-limonene was reported to be stable under extrusion of cornstarch at 133–167°C with oil recovery up to 92.2% (Yuliani et al. 2006a). Without complexation, the recovery of D-limonene after extrusion was only 8.0% (Yuliani et al. 2009).

Protein Precipitation

This novel technique was developed by Begum (2005). In this technique, the fl vor volatiles are encapsulated in a milk protein system at the isoelectric point of the protein. The technique involves the emulsificatio of fl vor oil in the aqueous solution of sodium caseinate. The system is then brought to the isoelectric point and the precipitate obtained is dried and ground to form a free-fl wing powder. The capsules provided moderate protection against volatile losses under extrusion conditions (Yuliani et al. 2006b).

Microbial Control

Herbs and spices, like other agricultural products, are exposed to microbial contamination during postharvest handling, storage, distribution, and marketing (McKee 1995). As about 90% samples of "ready-to-use" dried herbs and spices were shown to have microbial contamination (*Salmonella* spp., *B. cereus*, *Clostridium perfringens* and/or *E. coli*) (Sagoo et al. 2009), it is important to use hygienic and good manufacturing practices (GMP) during growing, harvesting, postharvest handling, processing, packaging and storage, and monitor the finishe products for microbial safety (Codex Alimentarius Commission 1995). Several methods commonly used for controlling insects and microbes include fumigation, irradiation, and steam sterilization. Chemicals normally used in spice fumigation to control insect include methyl bromide, formaldehyde, carbon disulfide chloropicrin, or phosphine (aluminium phosphate). Ethylene oxide and propylene gas are also used for controlling microbes. These chemicals have minimal impacts on fl vor and aroma but impart color changes and vitamin decomposition. However, they have been banned in a number of countries as they are considered toxic materials. Steam sterilizations have been practiced for many years and are commonly used in Japan (Uhl 2000). Although steam treatment is widely used, this method of decontamination suffers from drawbacks such as difficult in handling of ground products, degradation of light-weight leafy herbs, effect on active

compounds, changes in color and aroma (Pfeiffer and Dunkelberg 1980; Waje et al. 2008).

Irradiation for sterilization of herbs and spices provides a practical alternative to fumigation or steam decontamination. The use of irradiation through gamma rays generated from cobalt-60 and cesium-137, X-ray radiation and high-energy electron produced by electron accelerator is considered as safe and well proven method for microbial decontamination (Sadecka 2007). Irradiation doses of 7–10 kGy are normally recommended for microbial decontamination (Uhl 2000).

Irradiation of Korean red pepper powder at doses up to 7 kGy was shown to reduce the population of mesophilic bacteria and fungi effectively without significan quality changes (Lee et al. 2004). Irradiation provides better decontamination of ground black pepper than steam treatment with minimal effects on the proximate composition, functional components, color, and sensory attributes (Waje et al. 2008). After 6 months storage, irradiated ground black pepper had a better quality than steamed treated which had darker color and lower piperine content. Irradiation followed by low temperature (4°C) storage provided minimal microbial contamination and piperine losses of ground

Packaging and Storage

Fresh green herbs are susceptible to discoloration and decay due to their high rate of metabolism. Prevention of water loss during storage (through use of high humidity and low temperature) is important to maintain the freshness of harvested herbs. Storage conditions of selected fresh herbs are presented in Table 18.4. Fresh herbs are normally bunched and tied with rubber bands or twist-tie, packaged in plastic bags and packed in corrugated carton box. Bulk packaging of herbs such as watercress, chives, chervil, sorrel, coriander, dill, or parsley in perforated polyethylene (PE)-lined cartons can noticeably reduce water loss, but not the yellowing and decay (Aharoni et al. 1989). Nonperforated PE-lined carton, on the other hand, provides retardation of both yellowing and decay. This is attributed to the presence of CO_2 (minimizes the influ ence of ethylene) within the package which can delay chlorophyll degradation (Aharoni et al. 1989). Typically, herbs have low ethylene production but they are highly sensitive. It was reported that fresh parsley (which without packaging can be kept for about 2 days at 2°C) had a shelf life of up to 3 weeks at 2°C packaged in non-PE plastic bags (Umiecka 1973).

Controlled atmosphere storage with 5% CO_2 and 21% O_2 can be applied for delaying

Table 18.4 Storage conditions of selected fresh herbs and their shelf life

Herbs	Storage temperature (°C)	RH (%)	Shelf life (week)	References
Chives, mints	0	95–100	1–2	Hruschka and Wang 1979; Cantwell 2001
Marjoram, oregano, tarragon	0	90–95	1–2	Hruschka and Wang 1979; Cantwell 2001
Rosemary, sage, thyme	0	90–95	2–3	Hruschka and Wang 1979; Cantwell 2001
Coriander	8	90–92	6–7 days	Waskar et al. 1998
Fennel	0	90–95	14–28 days	Mercantila 1989
	0–1	95	1–2 weeks	Snowdon 1991
Parsley	0–1	95–100	1–2 months	Snowdon 1991
Mint	0–1	95–100	2–4 weeks	Snowdon 1991

chlorophyll degradation of parsley (Aharoni et al. 1989). A modifie atmosphere (MA) storage in 200 gauge polyethylene bags with 2% ventilation was recommended by Waskar et al. (1998) to extend the shelf life of coriander leaves.

Refrigeration slows microbial growth in ground or whole spices. Colder temperatures also help preserve volatile oil's fl vor and aroma, freshness, and sanitary quality. Some spices need cooler refrigeration temperatures to prevent mold infestation, color deterioration, and rancidity. Water activity and temperature plays important roles in determining the shelf life of stored herbs and spices. *Aspergillus flavu* contamination were observed in 10 herbs with water activity above 0.81 and stored at temperatures of 25–40°C. At a water activity below 0.81, herbs stored at 25–40°C did not contain *A. flavu* . The *A. flavu* was also not found in herbs with water activity above 0.81 and stored at 10°C (Kulshrestha et al. 2008).

Dried herbs and spices or their extractives should be stored in tightly closed containers in cool, dark, dry conditions below 20°C and 60% humidity. Dried herbs such as dill, marjoram, and basil are best stored in vacuum packages. In the air-tight packages, the quality of the herbs can be maintained for 2 years at room temperature (23°C) (Paakkonen et al. 1990). Freeze-dried herbs showed better odor and taste than air-dried herbs (Paakkonen et al. 1989). Microbes were shown to be present in dried herbs packed in oxygen-containing packages (Malmsten et al. 1991).

A combination of processes involving gamma irradiation (60 kGy) and low-density polyethylene packaging was reported to extend the shelf life of fresh ginger rhizomes for up to 2 months at ambient temperatures (25–30°C) (Mukherjee et al. 1995).

Conclusion

This chapter highlighted composition, processing, and quality aspects of various herbs and spices. The use of herbs and spices for foods, pharmaceuticals, or cosmetics is increasing in line with the popularity of "back to nature" lifestyle. Newer processing and preservation techniques and structure–function relationship will play a role in better utilization of herbs and spices in various foods and supplements.

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Chapter 19

Processing and Computer Technology

Gokhan Bingol and Y. Onur Devres

Introduction

The last 20 years have seen increasing use of computers in the food industry for various process controls, and data recording and monitoring. The employment of computers beyond personal usage can be classifie as: (1) process modeling; (2) process control; and (3) process/postprocess operations. In this chapter, these topics are discussed with novel applications in vegetable processing in order to analyze future trends.

Modeling of Processes

Food processing plants simultaneously look for maximizing production capacity while minimizing production costs. Analyzing processes with modeling at every individual step with respect to resources can help achieve these targets. Regarding resources, raw material, finance process line equipments and devices, work force, energy should be taken into consideration in the framework of safety and liability issues (Mahalik and Yen 2009).

According to Datta and Sablani (2006) a model is an analog of a physical reality and can be physical or mathematical. A mathematical model is a mathematical abstraction of a real process and a physical model can be the laboratory version of an industrial scale piece of equipment. Mathematical models use mathematical language to describe a system and are extensively used in the natural sciences and engineering disciplines such as physics, biology, earth science, meteorology, etc. Thus, in this section, emphasis is given to the role of mathematical models in simulation of industrial processes. Seborg et al. (1989) list the possible usage of mathematical models as follows:

1. *To improve understanding of the process*: Process models can be analyzed or used in a computer simulation of the process to investigate the process behaviors without the expense of operating the real process.
2. *To train plant operating personnel*: Plant operators can be trained to operate a complex process by use of process simulator.
3. *To design the control strategy for a new process*: A mathematical model allows alternative control strategies to be investigated such as the selection of the new variables that are to be measured or manipulated.
4. *To select controller settings*: A dynamic mathematical model of the process might be used to develop suitable controller settings either by computer simulation or by direct analysis of the dynamic model.
5. *To optimize process operating conditions*: In order to minimize costs and maximize profits most processing plants adjust the operating conditions periodically.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Depending on the derivation of the model, mathematical models can be classifie as follows:

1. *Theoretical models*: These models are developed by using the core principles of chemistry and physics.
2. *Empirical models*: They are obtained from a statistical analysis of process operating data. They have no physical connection with the process.
3. *Semiempirical models*: These models are a compromise between theoretical and empirical models in which some of the coeffi cients of the model are evaluated from the physical experiments or from process data.

Solution of the aforementioned mathematical models by computers requires adequate numerical methods to be used. Wang and Sun (2003) pointed out that numerical modeling technology can offer an efficien and powerful tool for simulating the processes in the food industry. Among the many merits of numerical analysis are the following: analysis of the processes for better understanding of the underlying complex physical mechanisms, evaluation of processes for ensuring the safety and quality of food products, design and optimization of food processes and systems, and so on.

In food processes, the underlying physical mechanisms of the processes are governed mostly by partial differential equations (PDEs). Pham (2006) recommends a two-step numerical solution technique: (1) discretizing the space domain to obtain a set of ordinary differential equations (ODEs) relating a finit number of nodal properties; and (2) solving this set of ODEs. There are three commonly used methods for discretizing the space: (1) finit difference (FDM); (2) finit element (FEM); and (3) finit volume (FVM).

Finite Difference Method

FDM is relatively simple to formulate a set of discretized equations from the transport differential equations. The main idea of solving PDEs with FDM is to replace spatial and temporal derivatives of the equation with their discrete approximations thereby breaking up one large problem into many smaller problems. FDM is considered to be the oldest method and is the most convenient and efficien for problems involving simple geometries such as slabs, cylinders, or brick-shaped objects (Wang and Sun 2003; Regier and Schubert 2005; Pham 2006). However, for foodstuffs with irregular shapes, FDM does not yield satisfactory results due to geometric simplifications

There are several studies in literature pertinent to the use of FDM: Esmaiili and Sotudeh-Gharebagh (2006) analyzed the diffusion equation during drying of spherical shaped grapes using 90 grid points and a time step of 10 seconds. The authors found good agreement between experimental data and the proposed model, especially during the end of drying. Marizy et al. (1998) simulated the freezing process of mashed broccoli on a continuous drum freezer. The authors used the Crank–Nicolson scheme to discretize the related heat transfer equations. They tested the model with the analytical solution and experimental data and found good agreement. Among many others, some of the recent studies are as follows: Sarang and Sastry (2007) determined the apparent diffusion coefficien of Chinese water chestnut; Gil et al. (2006) simulated inactivation kinetics of microorganisms on the surface of the foods during dry and wet pasteurization; Rodriguez et al. (2005) evaluated the effective diffusivity coefficien during microwave-vacuum and freeze-drying of mushrooms.

Finite Element Method

FEM was firs developed in 1943 by R. Courant (Courant 1943). For shapes that cannot be represented by a regular orthogonal grid, FEM and FVM are more fl xible than FDM, and FEM may perform better

than FDM for these types of irregularities, complex boundary conditions, and heterogeneous materials (Wang and Sun 2003; Pham 2006). Among many others, some of the most popular commercial software that uses FEM method are the following: Abaqus, Ansys, Comsol, Fluent, and MATLAB FEM Toolbox. According to Vidas (1997), there are generally two types of analysis that can be done with FEM: 2-D modeling, and 3-D modeling. Generally 2-D modeling conserves simplicity and allows the analysis to be run on a relatively normal computer; however, it tends to yield relatively less accurate results. On the other hand, 3-D modeling produces more accurate results while sacrificin the ability to run on all but the fastest computers effectively.

There are several studies relevant to FEM: Sanga et al. (2002) simulated the heat and mass transfer during microwave assisted convective drying of carrots by taking shrinkage into account. The authors found good agreement between the model and the experimental data; Martens et al. (2001) studied coupled 3-D heat transfer and enzyme inactivation kinetics problems, and solved the governing model equations using FEM by means of a research finit element package, namely CHAMPSPACK; Markowski (1997) predicted water diffusion coefficien in cylinder-shaped carrot slices during air drying; Verlinden et al. (1993) modeled starch gelatinization in potatoes during cooking, and Lomauro and Bakshi (1985) used FEM to describe moisture diffusion in freeze-dried turnip during adsorption.

Finite Volume Method (FVM)

Although the terminology is new, FVM is derived from the FDM. FDM is suitable for regular geometries; however, FVM is suitable for irregular geometries. In FVM, the domain is subdivided into discrete control volumes. The key step of FVM is to integrate transport equations over a control volume to yield a discretized equation at nodal points. The control volumes and nodes do not have to be in a regular array; thus, similar to FEM, there is great fl xibility in dealing with complex shapes. Among several studies relevant to FVM, the ones pertinent to vegetables are: Ranjan et al. (2002) modeled the temperature, moisture, and pressure profile inside a potato slab during infrared heating using coupled heat, mass and pressure transfer equations; Do Carmo and Lima (2005) studied drying of lentil using 2-D diffusion equation by taking into account shrinkage and obtained good agreement with the experimental data.

The softwares tabulated in Table 19.1 can be used for widespread applications in heat and mass transfer simulations and thermal process designs such as canning, freezing, and drying.

Thermal Processing

Thermal processing, conventionally called canning, involves heating foods in hermetically sealed containers for a specifi time at a specifi temperature in order to eliminate microbial pathogens that endanger public health, and microorganisms and enzymes that deteriorate food during storage (Ramaswamy and Marcotte 2006). According to Teixeira (2006) two distinct bodies of knowledge are required to understand the basic principles of thermal process calculations: thermal inactivation kinetics of spoilage-causing organisms and heat transfer phenomena that govern the temperature profiles Welt et al. (1997) pointed out that since thermally labile factors are usually dispersed continuously throughout the volume of a packaged product, acquiring the temporal and spatial dependent thermal profile in foods is only half the task in thermal process design. To predict the extent of any reaction, it is required to integrate the temperature-dependent kinetic function over the thermal profil throughout the whole volume of the product.

Table 19.1 General purpose commercial softwares

Name of the software/company	Objectives
Abaqus Multiphysics by Simulia	The Abaqus Unifie Finite Element Analysis product suite offers broad physical modeling capabilities for multiphysics problems such as fluid thermal, mechanical, and electrical couplings.
ANSYS FLUENT by Ansys	It contains the broad physical modeling capabilities needed to model fl w, turbulence, heat transfer, and reactions for industrial applications ranging from combustion in a furnace to bubble columns, oil platforms, and clean room design to wastewater treatment plants.
ANSYS Multiphysics by Ansys	It offers solution for both multiphysics and single-physics analysis such as structural, thermal, fluid and both high- and low-frequency electromagnetic analysis.
COMSOL Multiphysics by The COMSOL Group	The COMSOL Multiphysics® simulation environment has predefine modeling interfaces for applications ranging from flui fl w and heat transfer to structural mechanics and electromagnetic analyses. Material properties, source terms, and boundary conditions can all be arbitrary functions of the dependent variables.
MATLAB by Mathworks	MATLAB is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation.
MATHEMATICA by Wolfram Research	Mathematica is a computational software program used in scientific engineering, and mathematical field and other areas of technical computing. Similar to MATLAB, it can be used for algorithm development, data visualization, data analysis and numeric computations.

In the presence of an analytic solution of the heat transfer equation, the temperature profil at spatial and time coordinates can be obtained. However, in the absence of an analytic solution, one should recourse to numerical techniques. This is where the computer programs play significan role.

Weng (2006) lists the process calculation methods as follows:

1. The general method using physically measured time–temperature data.
2. The semiempirical mathematical methods using a constant heating or cooling temperature, such as the Ball formula method.
3. The theoretical models, such as pure conduction- or convection-heating models and computational flui dynamic models, which are based on Navier–Stoke's equations.
4. The innovative models for handling the variable retort temperatures.

Some of the softwares that are developed either for commercial or scientifi use are given in Table 19.2.

A remarkable application of a commercial computational flui dynamic software, namely PHOENICS™ (CHAM Ltd., Wimbledon, UK), which uses FVM for discretization, is revealed by Abdul-Ghani et al. (2002), who investigated the effects of changing the position of can from vertical to horizontal on the temperature and location of the slowest heating zone (SHZ). The authors solved the governing energy and momentum equations in vertical and radial directions using a nonuniform grid system of 105,000 cells. The solution was obtained in 17 hours of CPU time on the UNIX IBM RS6000 workstation. The authors found that when the can was horizontally positioned in the retort, the SHZ covers about 20% of can volume, whereas the corresponding SHZ value for a vertical position was only 10%. Thus, reducing the SHZ volume increased the number of pathogens eliminated and enzymes inactivated, thereby reducing the health risks. Another merit of this findin could be the reduction of energy consumption due to reduction in heating time, which also eliminates the risk of overprocessing of foodstuffs.

Table 19.2 Softwares that can be used for thermal processing of foods

Name of the software/ company or developer	Objectives
TPRO by Norback, Ley & Associates LLC	This is a Microsoft® Windows® based PC software for thermal process industry. It can be used to perform heat penetration calculations and produce graphic output.
NumeriCAL™ by FMC Technologies	It is proprietary software, which enables food processors to calculate the lethality accumulated during process come up and cooling stages. It is a finit difference base model that provides general Method accuracy by using Ball Formula-type heating factors.
CALSoft™ by TechniCAL	It was designed for conducting heat penetration and temperature distribution testing, evaluating the collected data, and calculating a thermal process or vent schedule/come-up time. After the data is evaluated, a thermal process can be generated using the Ball Formula Method.
Can-Calc Analysis by Engineering & Cyber Solutions Company by the author Balaban (2009)	This is a Microsoft® Windows® based PC software for thermal process analysis. It can be used to analyze, plot and fi First Order, Peleg, Weibull and Sapru isothermal kinetic data. Effect of time and temperature data on inactivation kinetics can be investigated either through experimental data or by heat transfer analysis in slab, cylinder and sphere geometries.
STERILMATE by the authors Kim et al. (1993)	It solves the Fourier equation numerically by using a Finite Difference method as an input for the calculation of the process lethality by numerical integration. The software can also compute lethality rates from time varying retort temperature profiles
SIM by the authors Chen and Ramaswamy (2007)	It is a graphic computer simulation program for retort thermal processing developed using the Microsoft Visual Basic. The software can be applicable to different retort thermal processing systems such as constant and variable retort temperature with different types of foods of different shapes and sizes.

It should be noted that there is no software existing to solve a number of complex processes in one package. However, some of the commercial software enables users either to write their own scripts or to interface with a programming language via application programming interface in order to extend the capabilities and to meet particular needs. As an example to this, Halder et al. (2007) developed software that was interfacing with COMSOL™ Multiphysics in order to predict microbiological growth in foodstuffs. It is known that the composition of foodstuff plays an important role in growth rate of microorganism. Therefore, the amount of macro- and micronutrients in the food was obtained from the USDA database that contains approximately 7,412 foods. Knowledge of composition of a food commodity also enables calculation of thermal properties of the respective product through predictive equations. Thermal death and the growth model of microorganisms were assumed to be a first-orde model. Meshing the food geometry, solving the particular problem and post-processing the obtained data were done by COMSOL™ Multiphyics.

Another approach for modeling a heat transfer problem could be the use of MATLAB program to develop a script. A relatively short script code published by Balaban and Ural (1996) calculates the transient heat conduction in a cylinder, which, to some extent, might be helpful to calculate lethality rates with the integration of thermal inactivation kinetics equations into the code.

However, the programming languages, wherein Visual BASIC, C++, Java, FORTRAN are among the popular, can also be used to develop code to meet the particular needs. It should be noted that selection of a correct algorithm plays vital role in execution speed, accuracy, and stability of the program. Mohamed (2003) used direction implicit FDM, which alternates between explicit and implicit FDMs at different time steps, and was firs introduced by Peaceman and Rachford (1955) for the solution of parabolic and

elliptic differential equations, to solve the 2-D heat conduction equation in finit cylindrical can geometry. The FORTRAN-based computer program showed remarkable agreement with the experimental data for tomato sauce in cans, which was retorted at a constant heating temperature of 121.1°C.

Drying

In the realm of vegetable drying, the term drying means the removal of water from the produce to reduce the water content to an acceptably low level, which will increase its shelf life by preventing deteriorative reactions. There are numerous types of dryers meant to achieve a suitable drying operation for a particular foodstuff. This brings about a continuing interest in the development or in the improvement of drying technologies that will take into account not only the product safety and quality but also the reduction of energy consumption and cost. The reduction of energy demand for drying will result in reduced utilization of fuels, natural gas and heavy oil, and to a lesser extent electricity, and as a consequence, would lead to a significant reduction of greenhouse gas emission (Ramaswamy and Marcotte 2005).

According to Menshutina and Kudra (2001), the main problems with the existing dryers are the lack of optimization in terms of energy consumption, product quality, and safety in operation, the ability to perform with large changes in throughput, feed rate, and material characteristics due to the empirical development of these dryers. The efficien y of a drying operation can be improved by better design, optimization, control of drying parameters, use of renewable energy sources, and reduction in size of industrial equipments without compromising from the throughput of the process that can be achieved with the aid of effective computer technologies (Menshutina and Kudra 2001; Mujumdar and Zhonghua 2008).

Selected drying models from Mujumdar and Zhonghua (2008) are tabulated in Table 19.3.

Although not as complicated as the models given in Table 19.3, the thin-layer models have found widespread use in literature due to its simplicity in describing the drying curves. The thin-layer drying models can be distinguished in three main categories, namely the *theoretical*, the *semitheoretical*, and the fully *empirical* ones (Sharaf-Eldeen and Hamdy 1979). The major difference between these groups is that the theoretical models suggest that the moisture transport is controlled mainly by internal resistance mechanisms, while the other two consider only external resistance. The semitheoretical models are derived directly from the general solution of Fick's law by simplification The empirical models are derived from statistical relations and they directly correlate moisture content with time, having no physical connection with the drying process itself (Babalis et al. 2006). Several authors used the semitheoretical thin-layer equations to describe the drying curves of fruits and vegetables, for example: Ozdemir and Devres (1999) for hazelnuts, Margaris and Ghiaus (2007) for Sultana grapes, Doymaz (2006) for black grapes, Ertekin and Yaldiz (2004) for eggplants, and Midilli et al. (2002) for pollens, pistachios, and mushrooms.

Kemp et al. (2004) classifie drying related programs into four broad categories:

1. *Calculation programs* which fall into the category of dryer models or auxiliary programs such as psychrometric software (Figure 19.1), particle size analyzers, or experimental data processors. Dryer models can be distinctively categorized into two groups:
   (a) The purpose or mode of calculation such as design of a new dryer, analyzing performance of an existing dryer, or scaling up a laboratory-scale dryer to a full scale.

Table 19.3 Simulation models for drying

Model name	Concise description	Example applications
Lattice Boltzman simulation	Simple, powerful method for simulating fl w in porous media. Efficien for parallel programming.	Few applications in drying
Discrete element Model	Tracking the motion of individual particles. Computationally intensive.	Spray bed drying and particle mixing in a drum
Pore network model	Simulation of fl w in porous bodies; influenc of pore structure on drying kinetics and microscopic description of transport phenomena.	Drying of porous materials
Thermomechanical model	Simplifie drying models based on the diffusion equations.	Shrinkage, capillary forces and thermal tensions caused stresses in dried bodies
Multiscale model	Two scales: microscopic description of transport phenomena and macroscopic description of flui dynamics.	Potential application in drying of porous materials
Response surface methodology	A statistical technique to develop a relationship between input and output parameters.	Process optimization and identificatio of significan factors
Neural networks	An interconnected group of functions that can represent complex input-output relationships.	Wide applications such as process control and product quality
Genetic algorithms	Search algorithms in a combinational optimization problem.	Parameters optimization and process control method
Fuzzy logic	Allows gradual assessment of the membership of elements.	Dryer selection; control

(b) The level of complexity of calculation such as *Level 1* for simple heat and mass balances; *Level 2* for scoping and approximate calculations that give rough sizes and throughputs such as the DRYSCOPE™ software; *Level 3* for scaling calculations to obtain overall dimensions of a dryer such as FLUBED™; *Level 4* for detailed methods in order to track the local conditions of the solids as drying progresses such as the NIZO-DrySim software developed by Straatsma et al. (1999). Among the four levels, level 4 possesses the highest complexity in calculations.

2. *Process simulators* allow the dryer to be set in the overall process fl wsheet and link with the general heat and mass balance such as Aspen Plus and Aspen HYSYS manufactured by AspenTech or DryerDesigner developed by Kiranoudis et al. (1994). It should be noted that all simulators use simplifie models at levels 1 or 2.
3. *Expert systems*, which according to Linko (1998), are efficien and reliable tools to make decisions on the basis of knowledge that can deal with uncertainties and imprecise information. The process of constructing an expert system is called as "knowledge engineering."
4. *Information delivery systems*, which are online libraries or knowledge bases, such as Aspentech: Process Manual (http://www.aspentech.com/) which is a collection of chemical engineering knowledge and information that has 100 volumes on 9 technical areas and is a web-based knowledge management tool for the process industries.

Mujumdar and Zhonghua (2008) pointed out that in the foreseeable future, the interest in research and development in drying technologies will not decrease not only because of increasing energy costs and increased consumer demand for high-quality products but also due to necessity to reduce greenhouse gas

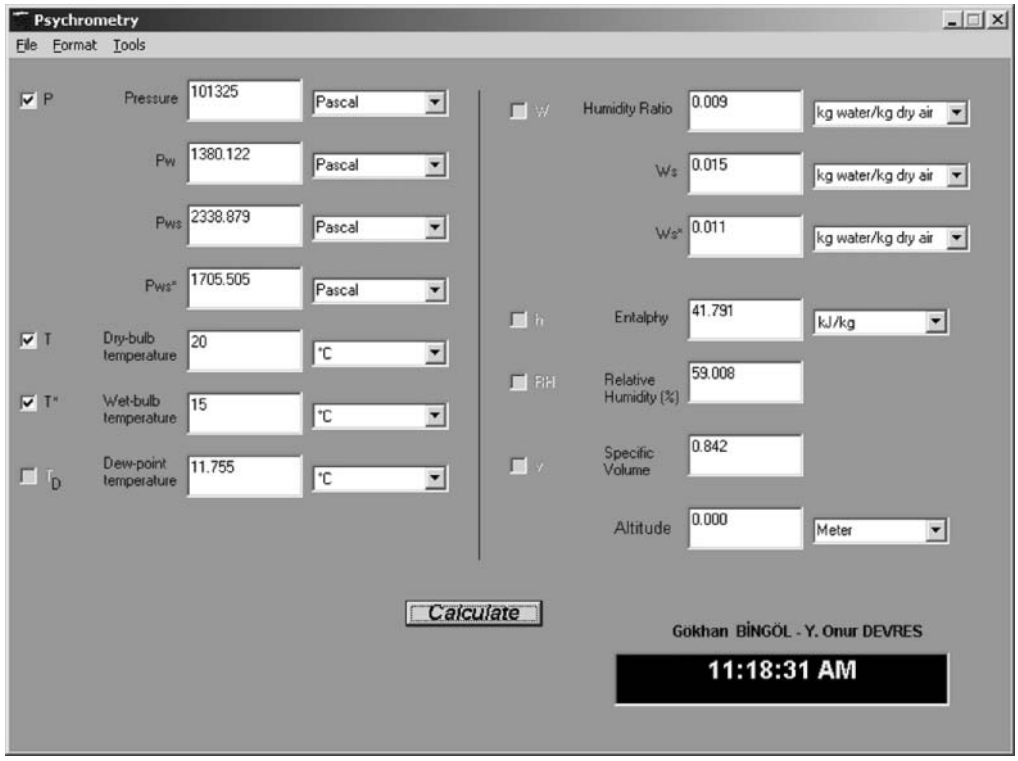

Figure 19.1 An auxiliary software for air drying processes to calculate psychrometric properties at different pressures.

emissions contributing to climate change which, with the Kyoto Protocol, will put pressure on manufacturers to search for more energy efficien technologies or to improve the efficien y of the existing ones.

Computer Vision

Computer vision, or machine vision, is a novel technology for acquiring and analyzing the image of a real object/scene by computers in order to obtain information or to control machines or processes (Sun 2004). Computer vision provide accurate, fast and objective quality determination techniques, possibly alternative to current practices, for an automated, nondestructive and cost-effective technique to meet the increased expectations for food products of high quality and safety standards (Brosnan and Sun 2004).

Computer vision can be define as the acquisition and processing of visual information by computer which is comprised of two primary component types: hardware and software. The hardware components can be divided into the image acquisition subsystem, the computer itself, and the display devices. The software allows manipulating the image and performing any desired processing on the image data (Umbaugh 1998). An exemplary system, developed by Engineering & Cyber Solutions Company, is shown in Figure 19.2.

The computer system shown in Figure 19.2 is capable of grabbing the frames, taken by the CCD camera, and storing the frames in bitmap fil format (device-independent bitmap, uncompressed image format). The image is then analyzed by the LensEye^{TM} software to get both color information and number of

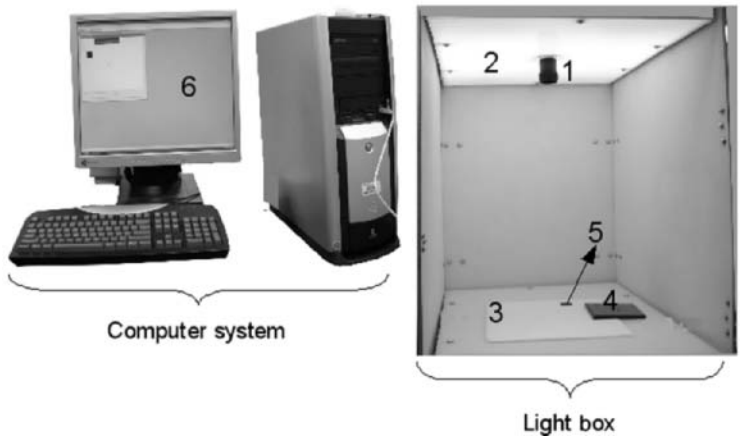

Figure 19.2 Computer vision system (1) CCD Camera; (2) D_{65} illuminant; (3) Sample plate; (4) Color calibration plate; (5) 1 inch^2 cardboard plate; (6) LensEye^{TM} Software.

objects placed on the sample plate. Individual or average color information of the objects in L*a*b* color space, which is an international standard adopted by CIE (International Commission on Illumination) and is widely used to quantify the colors of foodstuffs, can be obtained. By means of the 1 inch^2 cardboard plate, the visual area of the objects can also be acquired. The software is also capable of analyzing the volume and visual texture of the food materials (Balaban 2009).

For further technical information about the system shown in Figure 19.2, the reader is recommended to refer to the study of Luzuriaga et al. (1997). A conceptually similar system was used by Yadollahinia and Jahangiri (2009) to evaluate the shrinkage of potato slices during drying. The work was realized by integrating the dryer and the image recording system, which included a digital camera, an illumination chamber, computer hardware and software.

Brosnan and Sun (2004) list the cons and pros of machine vision system as tabulated in Table 19.4.

It is seen from Table 19.4 that the advantages of machine vision outnumbers its disadvantages. Although artificia lightning was considered to be a disadvantage for computer vision applications, it is worth mentioning that this so-called disadvantage might be overcome with a suitable lamp at a low cost. Another interesting advantage of machine vision over surface colorimeters, such as Minolta, was revealed by the study of Yagiz et al. (2009). The authors compared the L*,a*,b* values obtained from a machine vision system, similar to Figure 19.2, with a hand-held Minolta CR-2000 Chroma Meter (Minolta Camera Co., Osaka, Japan) for Atlantic salmon fillets Both systems were illuminated with average daylight illuminant, namely D_{65}.

Table 19.4 Advantages and disadvantages of machine vision

Advantages	Disadvantages
Generation of precise descriptive data,	Object identificatio might be considerably difficul in unstructured scenes,
Quick and objective	Artificia lightning needed for dim or dark conditions.
Reduces tedious human involvement in processes,	
Consistent, efficien and cost effective,	
Nondestructive and undisturbing.	

The authors found significan difference between the readings of two instruments, where color represented by Minolta readings was purplish, while that measured using the machine vision system was much closer to the average real color of Atlantic salmon fillets

A consumer firs judges the visual appearance of foods, hence color is one of the most important visual attribute because of its influenc on consumer acceptability (Maskan 2001). Quantitative analysis of surface color of foodstuffs is aimed at reducing the variability caused by subjective analysis and providing numerical specificatio (Brimelow and Joshi 2001; MacDougall 2001). Yam and Papadakis (2004) investigated the bottom surface color of microwaved pizza using a 2 megapixel digital camera for capturing the image under a lightning provided by two CIE source D_{65} lamps to simulate the daylight conditions. The images were then analyzed with a commercially available software, namely Adobe Photosop™, in order to obtain the color values in L*a*b* color space. A substitute for the Adobe Photosop™ software could be the GIMP software, acronym for GNU Image Manipulation Program, which is distributed under GNU General Public License. GIMP can be downloaded from its officia website (http://www.gimp.org) at no cost and new features can be added by writing own codes to meet the specifi needs.

Computer vision has been widely used for quality evaluation. Aguirre et al. (2009) modeled the browning of closed cup mushrooms during storage using image processing technique. The authors monitored the mushrooms using an inexpensive webcam (Logitech® QuickCam® Express, Logitech Europe S.A., DE) under controlled illumination conditions that is provided by a 40 W fluorescen lamp. The browning kinetics of mushrooms was followed by a gray value parameter, which was expressed as an average of RGB (red, green, blue) values. Luzuriaga et al. (1997) studied the melanosis levels and developed predictive relationships of view area versus weight of white shrimps using a machine vision system.

In the aforementioned machine vision systems, the images were acquired either using a camera or a webcam. However, the study by Romani et al. (2009) showed that a desktop flatbe scanner (Agfa Snapscan™ E40, Agfa-Gevaert N.V., Mortsel, Belgium) can also be used to obtain images that are congruent to image processing. The authors scanned deep-fried potato chips and processed the acquired images using a custom-developed MATLAB code. The authors found that the proposed machine vision system was able to detect color modificatio incurred by the frying process in terms of frying time and temperature.

In the image processing terminology, the term texture is totally different than its regular definition Image texture can be define as the variation of intensity in an image at various wavelengths. It may prove to be helpful to differentiate characteristics of an object that can be hardly distinguished visually. The study by Mendoza et al. (2007) aimed correlating image texture information (energy, entropy, contrast, and homogeneity) with potato chip preferences of a group of consumers. The authors used a digital camera to obtain high resolution (1024 × 768 pixels) images which were saved in JPEG format. The images were analyzed by a code written in MATLAB. The authors reported that by means of the image texture features, different quality categories of potato chips can be objectively distinguished.

It is reported by Gunasekaran (1996) that the food industry is ranked among the top 10 industries using machine vision technology and according to Sun (2000), it will be used increasingly as it provides suitably rapid, economic, consistent, and objective assessments. It is foreseen by Brosnan and Sun (2002) that the adaptation of machine vision for quality evaluation of processed foods is the area for the greatest potential of this technology and techniques such as 3D and color vision will ensure its continual development.

Automatic Control

During investment and running phases of an industrial plant, it is aimed to convert raw materials into products using the available resources in the most feasible patterns. During this operation, some requirements should be fulfille such as safety, traceability, production specifications environmental regulations, operational constraints, and economics. All these necessities enforced the need for continuous controlling of the process in a systematic method (Stephanopoulos 1984). Therefore, analog devices have been employed as a means to control processes in the industry since the beginning of industrial age. First usage of such equipment was for steam engines by James Watt as a speed control system in 1788. For this reason he has been named as "firs control engineer" in his era. Watt's centrifugal, or flyball governor, which had been previously used to control the speed of waterwheels and windmills, was one of the firs examples of linking the output of a mechanism to its input. This approach was define as feedback (closed loop) control and it provides the basic idea of automation (Anderson 2008).

Control Loops

Every system to be controlled has a mathematically describable transfer function, which has inputs viz. *disturbances*, *manipulated variables*, and outputs viz. *controlled variables*. Disturbances affect system's operation and can be internal (stationary-changing) and/or external (ever-changing). Internal disturbances are known and measures against them should be taken initially. Manipulated variables can be adjusted manually or automatically. Controlled variables are a response of the control operation and can be measured for further evaluations. Evaluations of inputs and outputs realized in a loop approach and control loop can be designed as open or closed respect to system's requirements (Stephanopoulos 1984).

In an open loop, input signal is fed to the system directly according to predefine conditions. In general, system works in stable conditions and there is no need to compare the output signal with set point. Washing of vegetables prior to processing in a certain time period in the plant can be given as an example for this type of control. The control system does not check the fina cleanness of every individual product but the operator decides washing duration with regard to initial product quality at the beginning. Such and similar systems are simple and they should be kept like that. Remaining in simplicity, as much as possible, is always preferable in control theory.

In a closed loop, however, the output signal generated by the system's response is compared with the reference or set point by the controller and the resulting modifie input signal is fed to the system. This adjustment continues until the output signal is equal to the set point. Temperature control during sterilization of canned beans by calculating the F-value can be shown as an example of such control. Closed loop controls are also called feedback control and its fi e components should work in harmony. These are as follows (Stephanopoulos 1984):

1. *System*: An equipment, device, controlled volume, etc. to be controlled are define as system.
2. *Controller*: Controller regulates the process and it should stabilize system which operates under disturbances. Controllers can be either analog or digital. Most of the current controllers in the industry are analog. They follow a predefine function having a relationship with error, which is a difference between the output and set point. The functions can be define as proportional (P controller), proportional-integral (PI controller), proportional-integral-derivative (PID controller), proportional-derivative (PD controller). In addition to these control forms, on-off and time proportioning controls can

be employed regarding simplicity and economics aspects.

3. *Sensors*: Output of the system is measured in analog signals by sensing devices such as thermocouples, fl w meters, etc. in order to be fed to controller.
4. *Final control element*: The signal produced by the controller is fed to this component in order to have the desired controlled variable of the process. Valves, motors, and switches are used for this purpose.
5. *Transmission lines*: Communication lines between controllers, sensors, and fina control elements are define as transmission lines. They can be either pneumatic (compressed air) or electrical. In the 1940s, in transmission lines, pressure signals of 3–15 psi for the monitoring of control devices had been employed. In the 1960s, however, the 4–20 mA analog signal standard was introduced for instrumentation.

Measurements of sensors should be converted to suitable physical quantities such as to an electric voltage or current, or to a pneumatic signal by transducers. Together with them, recorders can be employed during the control process for smooth operations.

Digital Computer Control Loops

Feedback control systems referred to above consist of analog devices. A set of feedback control systems can be employed by a single process and manual settings are satisfactory to manage them. On the other hand, current processes operated in the industry require multiple data controls and analog devices run by manual settings cannot be easily manageable for required safety, quality, quantity, and economical aspects. Therefore, computer technology has been started to be used in the plants with introduction of new devices since the 1990s. They can be employed in single or multiple loops like in analog control loops.

In those loops, sensors and fina control elements work with analog signals such as mA or mVs. Digital controllers/computers are however run by digital data. Therefore, interfaces between analog and digital signals should be converted to each other through devices called analog–digital-converters (ADC) and digital–analog-converters (DAC). Another obstacle to be handled was analog and digital signal's continuity on time basis. Analog signals are continuous but digital signals are discrete. For this reason, in order to carry signals through digital–analog and analog–digital interfaces, two separate devices are being employed:

1. Sensor measurement in analog signal at a certain time period is taken by a sampler and sent to digital controller/computer for calculations.
2. Conversely, computer-generated data to operate the fina control element are discrete time signals, but the element should run in continuous signals. For this reason, a holder is employed to fi the signals at a stepwise-stationary position until the next calculation sent by the computer.

All these efforts can be realized in SCADA (supervisory control and data acquisition) system in order to control and monitor the process and this system is widely used in the food industry. In this system, generally, controller's duty is accomplished by remote terminal unit (RTU) or programmable logic controller (PLC).

Fieldbus, which is a control networking system, is used for connecting control components such as sensors, controllers, fina control element, and man–machine interfaces. It introduces distributed control strategy by minimizing wiring costs and replacing the existing 4–20 mA analog signal. Despite its many merits, it was found that about 98% of approximately 200 food processing industries are still employing conventional

non-field us-based automation systems (Mahalik and Yen 2009).

Control Applications in the Food Industry

Automation is vital to the food industry due to today's rapidly changing environment. Dahm and Mathur (1990) list the factors that are pushing the food industry to implement automation practices as follows:

1. Increasing competition from globalization and mergers;
2. The consumer demand for higher and consistent quality foods;
3. The laws on food safety that must be complied;
4. The need for fl xibility in manufacturing for more diversifie product lines.

A survey by Caro and Morgan (1991) showed that the food industry has been slow to adopt automation in manufacturing technology due to the required capital expenditure. However, as pointed out by Ilyukhin et al. (2001), other manufacturing sectors, such as petroleum and chemical industries, have employed computer automation to improve their productivity. A survey carried out by Ilyukhin et al. in 2001, a decade after Caro and Morgan (1991), revealed that 59% of the food manufacturer's plant was mostly automated and the majority of these companies were using microprocessor-based technologies. The authors found that among the major obstacles that hindered the use of automation-based technologies were technical skills of support staff, cost, and management commitment. However, the improvement of product quality, the decrease in production cost, and the ability and convenience to access and process information were listed among the motivational factors for the implementation of an automation-based technology.

In the canning industry, public safety is an important consideration and processors must operate in strict compliance with the US Food and Drug Administration's Low-Acid Canned Food (FDA/LACF) regulations, which strictly require documentation and record-keeping (Simpson et al. 2007). Deviations are an inherent part of the processes and processors should correct them to compensate for the lost lethality or end-product quality. Computer-based control systems can acquire and analyze real-time data to compute the accumulated lethality in order to compare with the target value and can, therefore, provide online correction factors, which in this case would be by delaying the cooling phase until the target lethality is achieved. Therefore, online correction of the process is accomplished without operator intervention and without compromising the food quality due to unnecessary overprocessing (Teixeira and Tucker 1997; Simpson et al. 2007).

Food grading is a labor-intensive process and it economically puts pressure on manufacturers with the increasing labor costs. Considering among its many benefits integration of a nondestructive automatic grading system has the potential of improving efficien y and reducing costs. Such a system was developed by Lee et al. (2008) to sort the dates into four grades on the basis of size and skin delamination. Among its many parts, the proposed automatic date grading system, namely QuickSort, consisted of NIR-extended CCD cameras, which allowed image acquisition between 750–1200 nm wavelength region and a computer vision software to process the acquired digital images to determine the grade of the date. Contrary to its counterparts, the system allowed 20 pieces of dates to be graded within an accuracy range of 74–79%, which is higher than the human grading system that ranges from 60 to 72%. The authors claimed that although the system is developed for dates, it can be adapted to other fruits and vegetables.

In the literature, many papers emphasizing the merits of automation-based manufacturing can be found. Although the implementation of automation-based manufacturing

requires capital investment and a transition time in manufacturing, in the long term, as seen from the aforementioned examples, the computer-controlled automation systems can reduce the direct costs such as labor cost and can also alleviate indirect costs by improving the quality and consistency of the end product.

Postprocess Operations

Barcodes are optical machine-readable data, which defin the product information and are employed since the 1950s. Their convenient nature in connecting analog and digital medium makes them applicable for computer transactions taking place in inventory, selling, identification etc. Automation in supermarket systems pushed to use packed products and also influence packaging of food products in compliance with food safety regulations. Herewith, barcodes have been applied to packed food products with the infrastructure of computer systems, softwares, barcode printers, readers, and also hand-held readers built by various producers. Nowadays a rival is trying to take place of barcodes namely RFID (Radio frequency identifica tion). Although the theory of RFID technology has been available since the 1950s, like microwaves as a consequence of radar and radio research undertaken during the World War II, its broad applications in the industry could not be realized until the late 1980s due to high application costs and those days' incapable digital technology. One of the firs applications was tag detecting of attached item through security gates of retail stores against shoplifters in the 1970s which is still in use.

RFID system consists of tags and readers with antenna and transceiver. Embedded information inside the tags is transmitted to a reader in a certain distance by radio waves. Tags can be with battery, which are read/write devices and called as active tags and the tags without batteries are called passive ones and are read-only. The data transmitted by the tags included: (1) an operating system; (2) data storage; and (3) an electronic product code (EPC) which is the successor to the barcode. Tag reader is connected to company computer system for further related bidirectional data processing (Roberts 2006).

Biosensors are based on microelectronics and biology. Its architecture consists of a specifi biological identificatio component, which has certain sensitive and selective properties together with a transducer for signal processing. The most typical techniques employed in functioning of transducers are electrochemical (potentiometric, amperometric, and conductometric), optical (absorbance, fluorescence chemiluminescence, surface plasmon resonance, and changes in light reflect vity), and piezoelectric. Electrochemical biosensors are most suitable to miniaturization and hand-held usage (Luong et al. 2008) which is a practical need.

The future trend aims interaction with wireless technology such as RFID or similar infrastructure, miniaturization of biosensors with the improvement of integrated circuits. In this framework Johnson et al. (2008), states that they developed a bacteriophage genetically engineered to bind *Bacillus anthracis* spores generating a shift in the resonance frequency which can be detected by a wireless scanning device. For real-time wireless detection of *Escherichia coli* O157:H7, Huang et al. (2008) described a magnetoelastic sensor with an initial detection limit of 2×10^2 to 3×10^6 cells/mL. Serra et al. (2007) and Rocchitta et al. (2007) used AM transmitter to send data measured by glucose biosensor up to 30 m and FM transmitter up to 200 m respectively. Wu et al. (2007) designed a wireless α-amylase biosensor based on the surface immobilization of starch gel on a mass sensitive magnetoelastic sensor.

During manufacturing and postprocess operations like customer and supplier relationship management (CRM, SRM), enterprise resource planning (ERP), various softwares (Oracle, SAP, etc.) are available to plan and analyze resources. In addition to these

software infrastructures, the advances in RFID technology will help to integrate and combine RFID to quality assurance and resource planning systems to improve their effectiveness (Lyu et al. 2009).

Conclusion

Computers are an ever-increasing integral part of daily life in today's academic and industrial world. Among the many countless uses of computers, modeling and automation of processes and storage of process or experimental information for further evaluations and traceability studies are vital to both academia and industry. Efficien use of computer technology can lead to improvements in machine and process efficien y, which directly reduces energy consumption and thus the cost of respective operations, as well as leads to improvements in quality of the end product.

The continuing development in computer technology, in terms of hardware and software, enabled the efficien individual or simultaneous use of other emerging technologies such as RFID and biosensors in real-time applications. Integration of computer technology with microelectronic circuits and biological sciences provided remarkable real-time information on phenomena occurring in microscales that might further pave the way for other notable innovations.

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Chapter 20

Packaging for Fresh Vegetables and Vegetable Products

Melvin A. Pascall

Introduction

The main objectives of vegetable packaging are shelf-life extension, maintenance of natural color, texture, fl vor, and nutrients; reduction in moisture loss and subsequent wilting; limiting disease, infections and infestation; cushioning as a preventative measure against injury during handling and shipping; aid in processing, facilitating transport and help in labeling, advertisement, and marketing.

The types of packaging used to package fresh vegetables are wood crates, corrugated shipping cartons polymeric films pouches, bags, baskets, crates, and trays; paper sheets, pouches, etc. Packaging technologies and systems used to protect fresh vegetables are methods used to create permeable films fil microperforation, antimist fil coatings, modifie and controlled atmosphere (CA) packaging, and active packaging systems. The types of packaging used to package vegetable products are thermoformed cups, trays, and other containers; bottles, form-fill-sea polymeric pouches, cups, trays, and other containers; metal cans, drums, and other containers; glass bottles and jars; composite packages such as Tetra Pak® and Combibloc® brick-type boxes, paper-based packages of various types (sometimes waxed or protected with selected films)

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Figure 20.1 shows a sampling of selected fresh-packaged vegetables. At the retail level, packaged salad is the top most category in the produce department (Figure 20.2; Campuzano 2009), as shoppers seek convenient and healthy options for lunch and side dishes

In this chapter, various packaging technologies of fresh vegetables and vegetable products are reviewed.

Postharvest Bulk Packaging of Fresh Vegetables

Cushioning as a Shelf-Life Extension Tool

Proper packaging helps in reducing the potential for injury and a resultant loss in shelf life. Various types of packaging materials are used to provide cushioning for vegetables. One of the main material types used to perform this function is foam polystyrene. It can be used to completely or partially wrap the produce or form dividers between them. An example of this could be seen in the packaging of fresh fruits and vegetables (Figure 20.3). Some commodities are usually packaged in a netted design device made of foam polystyrene. In some cases, the protective packaging is in the form of small nuggets, as in the case of grapes, for instance, when the material could be wood shavings. The tertiary packaging for these items is usually wooden crates or corrugated cartons, since they offer rigidity.

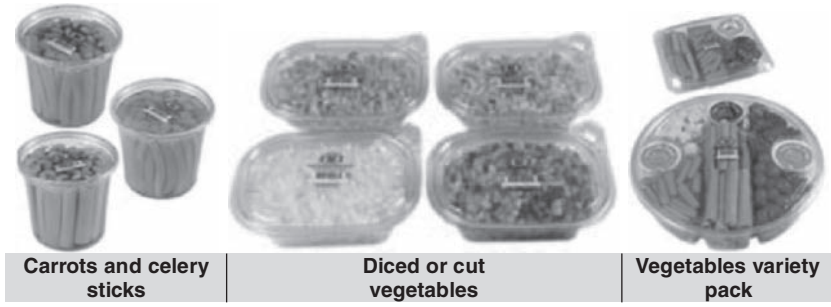


Figure 20.1 A sampling of selected fresh-packaged vegetables.

Control or Reduction of Moisture Loss

Moisture loss is a serious problem with harvested produce. This causes wilting in vegetables and loss of firmness Packaging used to reduce moisture loss can be from a selected category called edible packaging. Examples of these can be seen in the use of various types of waxing. In addition to moisture loss minimization, Barbosa-Cánovas et al. (2003) reported that waxing provides the following benefits

- Seals small cracks and dents in the rind or skin.
- Provides a protective coating over the entire surface.
- Seals off stem scars or base of petiole.
- Reduces moisture loss.
- Permits natural respiration.
- Extends shelf life.
- Enhances sales appeal.

Although this chapter discusses the packaging of fresh vegetables, the waxing of fruits provides examples of the advantages to be gained from it. This is discussed in detail later in the chapter. Another method of reducing moisture loss is by shrink-wrapping of vegetables.

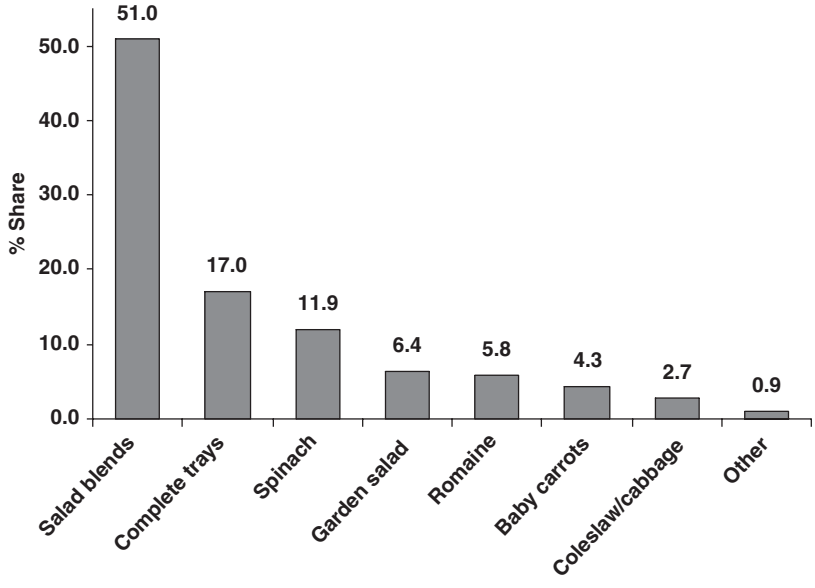


Figure 20.2 Total US Packaged Salad Share (Campuzano 2009).

Figure 20.3 Packaging used to cushion fresh fruits and vegetables.

Figure 20.4 shows an example of shrink-wrapped short cucumbers.

Ease of Transport

Convenience is one of the factors driving consumers' choice of one product over another. It is well known that packaging plays a key role in the convenience of a product. In this function, it aids the consumer in ease of transport. Fresh vegetables can be bulk packaged in crates made from polymeric materials such as Polyvinyl chloride (PVC) or polypropylene (PP) or from wood. If the package is least likely to be exposed to high moisture, the crates can be made from paperboard. In such cases, corrugated materials are used to fabricate the package. Large bags or baskets can also be used to transport vegetables. These can be made from polymeric materials or from bio-based sources such as jute, hemp, or flax Packaging at this stage should facilitate the free circulation of air through the produce so that shelf life is not shortened.

Figure 20.4 Shrink-wrap packaging used to reduce moisture loss and preserve the freshness of cucumbers.

Marketing Considerations

Packaging can be used to increase the visibility and sales of a particular produce item, which can be done by packaging convenient portion sizes. For example, a consumer is inclined to purchase the exact quantity of a vegetable that he or she needs. However, if portioned and packaged together, this could influenc a higher selling volume of the product. Packaging also gives the option of combining various varieties of produce that may not be purchased separately by the same consumer.

Disease, Infections, and Infestation Control

Postharvest losses due to diseases could be a significan problem in fresh and fresh-cut vegetables. In one study, postharvest losses due to diseases were estimated to vary between 10 and 30 % on an annual basis, despite the use of modern storage facilities and techniques (Gersbro and Rolle 2009).

All vegetables are susceptible to infections caused by bacteria and fungi during the growing season at or after harvesting, during handling, storage, transport, and marketing (McGrath 2005). It could also occur at the home of a consumer after the purchase of the

item. Many decay-causing organisms (bacteria and fungi) cannot invade sound, undamaged tissue, but as the tissue becomes older, it becomes weaker and more subject to invasion (Reiners and Petzoldt 2009). Packaging could be used to limit such occurrence by forming a physical barrier to decay organisms, infestation, or chemical treatment, by helping to keep the compound in contact with the produce. For example, in an attempt to control infestation of various seeds, the application of gaseous chemicals is best controlled if applied to the product within a package by a process known as fumigation (D'Aquino et al. 1997).

Storage and Relevant Packaging Technologies

Temperature Control

The influenc of temperature is the most important factor that impacts upon the shelf life of freshly harvested vegetables. Optimum refrigeration temperature, relative humidity, and shelf life for various vegetables is given in Table 20.1. This is so because temperature has a profound effect on metabolism and respiration. Over the physiological range of most crops, i.e., 0–30°C (32–86°F), increasing temperatures can cause an exponential increase in the respiration rate of fresh produce (D'Aquino et al. 1997).

Temperature abuse is one of the main factors known to hasten the loss of shelf life for harvested vegetables. Thus, it is essential to reduce the ambient temperature surrounding the produce soon after harvesting. Generally, fi e main methods are used to reduce such temperatures; these are vacuum cooling, water-spray vacuum cooling, hydrocooling using chilled water, forced air cooling, and use of crushed ice in the package.

In vacuum cooling, the pressure surrounding the commodity is reduced and this causes a lowering of the boiling temperature of water on the surface of the crop. This boiling takes place at the temperature of the vegetable. During this process, heat is given up by the product as the water changes to vapors, and cools the product in the process. Commodities that are cooled in this manner include mushrooms, vegetables such as lettuce and caulifl wer. This process is usually done in a vacuum chamber but is better facilitated if the commodities are packaged in

Table 20.1 Optimum refrigeration temperature, relative humidity, and shelf life for various vegetable products

	Optimum storage conditions		
Vegetable	Temperature (°C)	Relative humidity (%)	Expected shelf life
Onions	1–2	70–75	4–5 months
Garlic	0	70–75	6–8 months
Beets	0	90–95	1–3 months
Carrots	0	90–95	4–5 months
Cabbage	0	98	3–6 months
Lettuce	0	90–95	2–3 months
Broccoli	0	90–95	7–10 weeks
Caulifl wer	0	85–90	2–3 weeks
Celery	0	90–95	3–2 months
Sweet corn	0	85–90	4–8 days
Tomato	12.5–13	85–90	2 weeks
Green pepper	10	95	2 weeks
Chili pepper	10	95	2 weeks
Egg plant	10–12	95	3 weeks
Cucumber	10–13	95	10–14 days

Source: Flores-Gutiérrez (2000).

slotted containers. This allows adequate airfl w around the products. Thus, it can be seen that this process is optimized by the use of packaging.

Water cooling is a variation of the vacuum cooling process in which water is sprayed on the commodities and then the vacuum is applied as described above. Examples of commodities that are exposed to this process include celery, lettuce, and green onions.

Hydrocooling is a process of using chilled water to cool a variety of freshly harvested vegetables such as celery, radishes, and sweet corn. As is the case with vacuum cooling, these commodities are usually packaged in boxes or pallet bins in order to facilitate the cooling process.

During forced air cooling, refrigerated air is forced through stacks of vented containers by creating a pressure difference across the containers (Barbosa-Cánovas et al. 2003). This process removes heat from the packaged commodities and reduces the temperature. Packaged commodities that can be cooled by this method include caulifl wer, melons vine-ripened tomatoes, and peppers.

Package icing is another method of cooling. In this cooling method, crushed ice is used to reduce the product temperature and maintain the reduced product temperature. This method is commonly used for specifi fresh produce items such as broccoli.

Respiration Control

This is perhaps the most important role that packaging plays in the shelf-life extension of fresh produce. After the harvest, fruits and vegetables are still alive and are actively respiring. During this process, they uptake oxygen and produce carbon dioxide, certain volatile substances, and heat. Classificatio of selected vegetables on the basis of their respiration rates is shown in Table 20.2. The respiration rate of harvested produce is known to increase with increasing temperatures thus severely affecting the shelf life of the commodity. Thus, the higher the respiration rate of the item, the shorter would be its shelf life. This is so because the products of respiration are compounds that influenc many metabolic processes in vegetables, which directly impact the quality parameters such as firmness sugar content, aroma, and fl vor. Studies on the respiration rates of vegetables were one of the earliest physiological phenomenon researched; Platenius, as early as 1942, studied the respiration rates of 10 vegetables at 24°C and found a wide variation in the rates ranging from 11.8 mg CO_2 kg^{-1} h^{-1} in potatoes to 692.8 mg CO_2 kg^{-1} h^{-1} in asparagus.

Table 20.2 Respiration rates of selected perishable commodities at 5°C

Respiration class	Respiration rate (mg CO_2 kg^{-1} h^{-1})	Plant commodities
Very low	<5	Chestnuts, nuts
Low	5–10	Onion, potato, garlic
Moderate	10–20	Cabbage, carrot, lettuce, tomato
High	20–40	Caulifl wer, avocado
Very high	40–60	Artichoke, green, or snap beans
Extremely high	>60	Asparagus, mushroom, pea, spinach

Source: Gross et al. (2004).

Factors affecting respiration rates have been studied by many researchers (Kader 1987; Lee et al. 1991; Smyth et al. 1998; Piergiovanni et al. 1999; Fonseca et al. 2002). The most important environmental factors that impact respiration rate are temperature, atmospheric (gases) composition, and physical stress.

Since respiration is an internal physiological process of all living entities, it cannot be completely stopped. However, if the respiration rate is not slowed enough, it will result in an accelerated end of a particular commodity's shelf life. Still, the option of decreasing the respiration rate and, thus, increasing the shelf life could be done by manipulating

the external environment in which the harvested commodity is stored. Two main packaging processes that have shown the ability to reduce respiration rates are modifie atmosphere packaging (MAP) and active packaging.

Packaging and Gas Permeability

Gas permeability of the packaging materials is one of the most important factors that needs to be considered while designing packaging systems for fresh or fresh-cut produce. Several commercial instruments are available for assessing the gas permeation parameters of packaging films The oxygen transmission rate (OTR) for a fil can be determined according to ASTM F 1927 (ASTM International standard method for oxygen transmission rate test of barrier materials under controllable humidity by coulometric detector). This ASTM International method recommends the use of an instrument fitte with a coulometric detector that is sensitive to the presence of oxygen molecules and produces an electrical signal proportional to its quantity (ASTM, 2004). The OTR for a given fil could be determined by using the following equation:

$$\mathrm{OTR} = \left(\frac{E_e - E_0}{A_L}\right) \tag{20.1}$$

where E_e = steady-state voltage level with oxygen gradient applied to test fil (mV), E_0 = zero voltage level (mV), A = specimen area (m^2).

In addition to the permeability of the packaging material, the movement of the modifie atmosphere gases in or out of the package (mass transfer) is also influence by the concentration gradient or driving force of each gas. If the example of the MAP of cabbage is considered, the driving force (also called the partial pressure) of the O_2 concentration would be 21% − 8%. Here, 21% represents the atmospheric concentration of oxygen outside the package and 8% is the oxygen concentration within. The influenc of this on the mass transfer of O_2 would be:

$$F_{O_2} = \frac{P_{O_2} A(p_{o,O_2} - p_{i,O_2})}{l} \tag{20.2}$$

where F_{O_2} = flu (mol s^{-1}) for O_2, P_{O_2} = fil permeability for O_2 (mol m m^{-2} Pa^{-1} s^{-1}), A = specimen area (m^2), P_{i,O_2} = partial pressure of O_2 inside the package, P_{o,O_2} = partial pressure of O_2 outside the package, l = fil thickness (m).

This formula could also be substituted for mass transfer of CO_2 into or out from the modifie atmosphere package. Beaudry et al. (1992) reported that if the steady-state mass transfer of O_2 or CO_2 is reached and the respiration of the commodity does not change, the rate of respiration for O_2 could be obtained if the flu is divided by the weight of the produce in the package. This steady state occurs at the point when the O_2 transmission rate through the fil is equal to the O_2 uptake by the produce, assuming that all other conditions remain constant.

In a sealed tray packaging system, where the dimensions of the package in not uniform, the true permeability could only be determined by the use of finit element analysis calculations. However, the permeability of the package for O_2, for example, could be estimated by the determination of the permeance (Perm O_2) according to the following equation:

$$\mathrm{Perm}\,O_2 = \frac{\mathrm{OTR}}{P_{i,O_2}} \tag{20.3}$$

where Perm O_2 = the permeance of the package for O_2 or CO_2, P_{i,O_2} = the driving force or partial pressure of O_2 or CO_2 in the test gas side of the diffusion cell of the permeation testing equipment (this assumes that the carrier gas side of the cell has zero O_2 or CO_2).

To determine the water vapor transmission rate (WVTR) of a material, the driving force (Δp) of the water vapor (the difference in relative humidity inside compared with that outside the package) has to be calculated from

the saturation vapor pressure of water at the storage temperature of the produce. This driving force could be expressed in mmHg units. Thus the permeability (P) of a material to water vapor could be calculated from the following:

$$\text{WVTR} = \left(\frac{C \times A \times \Delta p}{t}\right) \tag{20.4}$$

where C = the permeability constant of the fil for water vapor (g mil m^{-2} day^{-1} $mmHg^{-1}$), A = specimen area (m^2), $|\Delta p| = p_i - p_o$ (the driving force of water vapor in the package), p_i = vapor pressure of water inside the package (mmHg), p_o = vapor pressure of water outside the package (mmHg), t = fil thickness (m).

The permeance (Perm H_2O), as it relates to the movement of moisture in or out of the packages, could be determined from the following equation:

$$\text{Perm } H_2O = \frac{WVTR}{\Delta P} \tag{20.5}$$

Fick's Law governs the issue of driving force for all gases and heat across a film This law is based on the fact that whenever a difference in concentration of a given gas exists between two environments that are separated by a film the movement of the gas would be from a higher to a lower concentration by diffusion across the film This movement could be described as the amount of the gas transferred per unit area of the fil perpendicular to the direction of movement per unit time; this movement will be proportional to the change in concentration over the distance traveled. This can be expressed as Fick's firs law. Assuming that this steady-state diffusion is in one direction, a gradient of concentration is present, and diffusion only occurs along the x-axis. The rate of transfer of the gas (J) across any section of the fil is given by:

$$J = -D\frac{dC}{dx} = D\frac{c_1 - c_2}{t} \tag{20.6}$$

where C = the penetrant concentration in the film x = the direction of the diffusion normal to the film D = the molecular diffusion coefficient c_1 = high concentration side of the film c_2 = low concentration side of the film t = fil thickness.

Once the mass balance of an element is taken into account, Equation (20.6) can be used to derive the fundamental differential equation of diffusion (Crank 1980):

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right) \tag{20.7}$$

where x, y, and z are the three dimensions of space. In polymeric and nonhomogeneous systems, the diffusion coefficien largely depends on the concentration. The diffusion coefficien in polymeric and nonhomogeneous systems varies from point to point and Equation (20.7) is more accurately expressed as (Crank 1980):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial}{\partial z}\right) \tag{20.8}$$

where D is a function of x, y, z, and C. In most applications, diffusion is restricted to one direction. For example, many times a gradient of concentration is present and diffusion only occurs along the x-axis. In these cases, Equations (20.7) and (20.8) can be reduced to (Crank 1980):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{20.9}$$

Equation (20.9) is commonly referred to as Fick's second law of diffusion for unsteady-state systems.

One factor that significantl influence the permeability of polymeric film is temperature. Polymers are composed of hydrocarbon chains that may or may not cross link with adjacent chains within the matrix of the material. The morphology of a polymer refers to the arrangement of these chains and the

resultant influenc they have on the crystalline and amorphous nature of the polymer. The higher the degree of the amorphous regions in a given polymer, the larger will be the number of void spaces thus resulting in higher permeability to diffusing gases, vapors, and chemical moieties. As the temperature of a polymer increases, the increased mobility of the molecules causes an increase in randomness of the chains and this causes its permeability to gases to increase. The Arrhenius Equation could be used to show the relationship between the increase in temperature and an increase in the O_2 or CO_2 permeability of a given polymeric film In Equation (20.3), the O_2 could be substituted for CO_2.

$$P_{O_2} = P_{o,O_2}\, e^{\left(\frac{-E_a^{P_{O_2}}}{RT}\right)} \qquad (20.10)$$

where P_{O_2} = the fil permeability for O_2 (mol m m^{-2} Pa^{-1} sec^{-1}), P_{o,O_2} = Arrhenius constant (mol m m^{-2} Pa^{-1} sec^{-1}) for O_2, $E_a^{P_{O_2}}$ = activation energy (J mol^{-1}) for the permeation of O_2, R = gas constant (8.3144 J mol^{-1} K^{-1}), T = temperature in Kelvin (K).

Polymeric film are the material of choice for fresh produce packaging. This is so because of their low cost, fl xibility, light weight, transparency, glossiness, tear strength, sealability, property of being nonreacting with the produce, ease of printing and labeling, water resistance, nontoxicity, and relatively high gas permeability. For must commodities, polyethylene (PE) or PP are the polymeric film of choice. Other film that are also used, but to a much lower extent, include polylactic acid (PLA), PVC, acetate, and oriented polystyrene.

Microperforation and Gas Permeation

Another method that is widely used in vegetable packaging is that of microperforation of the packaging material (Zanderighi 2001; Anon 2007). Microperforation is the placement of holes or apertures in the packaging material (usually polymeric films) This is done by the use of needles, pins, laser, flame high pressured air, etc. The objective of microperforation is to allow the packaging fil and its contents "to breathe." As mentioned earlier, a delicate balance between the permeability of the packaging material and the respiration needs of the packaged produce is required for optimum shelf life. The objective of microperforation is to control the permeation rate so that the optimum rate of oxygen/carbon dioxide gaseous exchange is maintained on the inside of the package. To obtain this rate, the size and shape of the perforations are precisely controlled (Lee and Renault 1998).

Packaging of Fresh Vegetables

Moisture Control

The water status of a commodity is a factor that influence its maturity. This can especially be seen with leafy vegetables. In the case of cut vegetables, water loss has a more severe effect on its shelf life. This is so because cutting of all plant products causes them to lose the protective ability provided by the skin or cuticle. Excessive moisture loss hastens wilting or withering and this leads to early senescence. However, the loss of moisture, especially from cut leafy vegetables, can be reduced by the use of appropriate packaging materials. In such cases, the material must be carefully selected to reduce moisture loss, but it must not be too high a barrier to moisture that it causes condensation to develop on its underside. If this moisture condensation occurs, it could encourage the growth and survival of harmful microorganisms. One of the most efficien techniques to solve this problem is by the use of an antifog coating applied to the inside of the packaging material. Moisture-absorbent sachets, though

economical to use, have not found wider acceptance among consumers.

Microbial Control

The conditions that favor microbial growth on vegetables are high temperatures, mechanical damage, overripeness, and high levels of CO_2 (Singh 1999). Temperature is one of the main factors that regulate the growth of microorganisms. In addition to lowering the respiration rate of harvested vegetables, a high concentration of CO_2 is known to inhibit the growth of microorganisms, especially at low temperatures. This is so because the solubility of CO_2 increases as temperature decreases. Thus, at low temperature, CO_2 is capable of dissolving on the surface of moist plant products and can inhibit the growth of microorganisms. Thus, a combination of low storage temperature combined with that of the equilibrium-modifie atmosphere for a given produce, at the optimal storage conditions for good sensory as well as the microbial quality, can be achieved. These ideal conditions will also serve to limit enzymatic browning and lipid oxidation of cut produce and help to maintain its nutritive value, color, and crispness (Apichartvorasilp 2001; Martinez-Ferrer et al. 2002; Chonhenchob et al. 2007.

Natural Color Maintenance

Maintenance of the natural color of fresh leafy vegetables is a desirable marketing attribute. In the case of green leafy vegetables, chlorophyll is the dominant pigment. Any factor that influence the metabolism of chlorophyll also diminishes its presence in the vegetable; such factors include light, humidity, temperature, certain plant hormones, enzymes, and damage to the vegetable. Enzymes are organic catalysts present in fresh produce even after harvesting. These enzymes tend to "spill" from damaged or bruised products and can lead to rapid decolorization of the vegetable. Fresh-cut vegetables can physiologically be considered as bruised commodity and would experience the same enzymatic effects as damaged produce. However, this loss of color could be minimized by an appropriate MAP regime at refrigerated temperature when compared with the same commodity stored in air. An ideal MAP storage condition can also help the maintenance of the original nutrient content of a vegetable. Vitamin C, for example, could be rapidly lost from fruits and vegetables if the storage temperature is too high or if moisture lost is excessive.

Modified Atmosphere Packaging

The main goal of MAP is to reduce respiration, dehydration, enzymatic activity, and microbial spoilage of fresh and cut vegetables. This is a technique in which the gaseous composition surrounding a packaged product is deliberately adjusted to produce one that is different from the normal gaseous atmosphere (Kader et al. 1989). The intent of this adjustment is to increase the shelf life of the packaged product. In the MAP of fresh vegetables, the main purpose of this storage technique is to decrease the respiration rate of packaged product and thus increase its shelf life. In creating MAP, both the O_2 and CO_2 concentrations within the sealed package are simultaneously adjusted to a level that is lower for O_2 and higher for CO_2 than the normal atmosphere. In this process, the concentration of the gases at any time during storage is a function of temperature, the gaseous (O_2 and CO_2) consumption, and production of the commodity and the permeability of the packaging material.

During respiration, the nutrients stored within the cells of the plant are metabolized for the growth and survival of the plant materials, like vegetables. By lowering the respiration rate of the plant tissue, a reduction in the loss of these nutrients is concurrently achieved thus resulting in a longer shelf life.

However, if the CO_2 concentration within the package is too high, excessive browning, off fl vors, and an increase aging rate of the product could occur. On the other hand, if the O_2 concentration is too low, an anaerobic condition could develop within the package and this could lead to rapid deterioration of the vegetable. Because the respiration rates of different crops are not the same, the modifie atmosphere must be selected carefully. Since the intent is to keep this optimum atmosphere as long as is reasonably possible, the choice of the packaging material is extremely important. This ideal atmosphere for maximum self life of the vegetable may be very different from that of normal air on the outside of the package and by the process of diffusion, the air on the outside and the gases on the inside would seek to equilibrate each other. If this gaseous equilibration movement is not controlled, the benefit of the MAP will be quickly lost. When designing a MAP system, it is essential to ensure that two extremes are not allowed to develop, i.e., with respect to O_2 and CO_2 concentrations. These are the anaerobic conditions within the package or the development of O_2 concentration that is too high. If an anaerobic condition develops, the commodity will go into anaerobic respiration and its quality will depreciate rapidly. This situation could develop if the gas permeability of the packaging material is too low. In an ideal situation, the packaging material must be sufficientl permeable to allow excess CO_2 to diffuse out of the package. At the same time, this material should not allow too much O_2 to enter the package because that will cause the respiration rate of the vegetable to increase to an undesirable level. Thus, a delicate balance between the permeability of the packaging material and the respiration rate of the vegetable must be established. Once this is achieved, an optimum equilibrium-modifie atmosphere would be established inside the package for the given vegetable. Typically, a MAP with 5–8% CO_2 and 1–3% O_2 levels have been shown to improve the storage shelf life of cabbage (Brown 1992).

Controlled Atmosphere Packaging

CA packaging is another storage technique that is similar to MAP. However, with CA packaging, O_2 and CO_2 concentrations within the package are controlled independently from each other. In some cases, the use of CA packaging could be implemented by using gases other than O_2 or CO_2. Examples of these can be seen in reports published by Bhowmik (1984), who studied CA packaging of fresh peaches by wrapping them in a proprietary polymeric fil followed by treatment with a fungicide. Bhowmik and Wilson (1986) also reported similar studies involving the shrink-wrapped cantaloupes that were stored under identical environmental conditions—at 7°C temperature and 85% relative humidity.

Active Packaging

This refers to an interactive or "smart" package intended to sense an internal or external environmental change, and respond by changing its own properties or the internal environment of the package. Types of active packaging systems that are used to package fresh and processed vegetables include oxygen scavengers, moisture controllers, gas-permeability control mechanisms, and systems for ethylene control and antimicrobial packaging. Examples of active packaging applications include, but are not limited to, reduction of lipid oxidation in packaged processed foods, reduction in microbial growth in selected foods, increase shelf life of fruits and vegetables by reducing regular or anaerobic respiration, and a reduction in ripening and maturation of produce. Active packaging systems are usually incorporated within the matrix of the material or could be applied as a coating on the surface. In some cases, they could be within a separate package and placed within the primary packaging. An

example of this is a sachet fille with an oxygen scavenger or a desiccant and placed within a sealed package.

Active packaging systems designed to control the oxygen environment within a package act as interceptors, scavengers, antioxidants, and oxygen absorbers. Interceptors act to prevent oxygen from reaching the product by allowing themselves to be oxidized by oxygen diffusing into the package. Scavengers chemically combine with and remove diffusing oxygen or oxygen from the headspace of the product. Oxygen absorbers act by trapping oxygen within the polymeric micropores when they are incorporated within the matrix of a plastic material (Brody 2002). Antioxidants are used mainly in processed products to prevent the oxidation of lipids ingredients, which could lead to the formation of rancid fl vors, color loss, and objectionable odors in the food.

Active packaging systems, used to influ ence permeability changes in polymeric packaging, do so in response to changing storage temperatures. An example of this is the use of a wax-based coating on a fil that melts with increasing temperature, which in turn changes the permeability of the material. Another example of permeation control is by the use of side-chain crystallizable polymeric materials. These are acrylic polymers with variable side chains and melting points, which are temperature sensitive. Landec® is a commercially available plastic that uses this technology. These are useful for fresh produce, fruits, and vegetable packaging to control optimum O_2:CO_2 ratios.

Ethylene controllers, used as active packaging, act by reducing ethylene thus delaying the overripening, e.g., in tomatoes. The commonly used ethylene controllers are silica gel, porous alumina, or vermiculite impregnated with potassium permanganate ($KMnO_4$). In this situation, the permanganate acts by oxidizing the ethylene to ethylene glycol. Since the production and/or the presence of ethylene within the environment of plant-based products increases the rate of deterioration, reducing the concentration of ethylene in the vicinity of the product increases its shelf life. Other examples of ethylene controllers are activated charcoal impregnated with bromine or palladium and Tetrazine—a compound with an electron-deficien nitrogen containing trienes (Brody 2002).

Edible Coatings

Edible coatings have been used to control gas exchange (oxygen, carbon dioxide, and ethylene) between the food product and the surrounding atmosphere or between components in mixed foods. Edible outer layers can provide supplementary and sometimes essential means of controlling physiological, microbiological, and physicochemical changes in food products (Kittur et al. 1998). Durango et al. (2006) developed an edible fil using yam starch and chitosan and showed that it had antimicrobial properties and good fl xibility. As mentioned earlier, waxing is extensively used as an edible coating to reduce moisture loss in fresh produce and to enhance it appearance. Various syrups can also be used to coat processed products and they could act to reduce rancidity and moisture loss in the commodity. As an example of the use of edible packaging for vegetables, Emmambux and Minnaar (2003) used a cellulose-based edible coating on process carrots and showed that it reduced moisture loss during storage.

Packaging of Processed Vegetable Products

An Overview

Vegetables can be processed by a variety of technologies depending on the intended product. Vegetables can be diced, crushed, squeezed, shredded, blended, peeled, and used to make juices, sauces, chutneys, dips, purees, preserves, and also could be an ingredients in a variety of bakery products,

Table 20.3 The main types of petroleum-based polymers used in fruits and vegetable product packaging

Polymer name	Packaging application
Polyethylene (PE)	*High density PE (HDPE)*: bottles, jugs, bags, drums *Low density PE (LDPE)*: films pouches, bags, heat sealing layers *Linear low density PE (LLDPE)*: films heat sealing layers
Polypropylene (PP)	Films, bottles, caps, hinges for dispensing closures.
Polyvinyl chloride (PVC)	Plasticized PVC: films stretch wrap, clam shells
Polyvinylidene chloride (PVDC)	Provides high oxygen and water vapor barrier in films cups, bowls, etc.
Polystyrene (PS)	*Crystal (glassy) PS*: drinking glasses, cups, eating utensils, film *Foam PS:* cushioning material, cups, plates, bowls, clamshells, and insulation
Nylon-6	Low temperature fl xibility, good fl x strength, films bags, boil-in-bag applications, vacuum packaging, MXD-6 has good oxygen barrier.
Polyethylene terephthalate (PET)	*Amorphous PET (APET)*: Bottle, film *Crystallized PET (CPET)*: Oven-able trays *Glycol PET (PETG)*: Tubing, films sheets, bottles
Ethylene vinyl alcohol (EVOH)	Used for high oxygen barrier in films cups, bowls, etc. Must be protected from moisture.

beverages, etc. Many vegetables are also processed for consumption as side dishes or as a part of the main entrée in meals.

Depending on the processing method used to prepare vegetables products, factors influ encing the choice of packaging include cost, transparency, fl xibility, convenience, size, microwavability, lightweight, ease of opening, compatibility with the product, market appeal, and legal requirements. The major types of packaging used to package vegetable products are cans, bottles, jars, trays, pouches, bags, cups, and fl xible films The materials used to fabricate these packages include tin-free steel, coated steel, aluminum, glass, paperboard, polymers, and composite materials. The choice of these materials is influence by the nature of the processing technology, the anticipated shipping, handling and storage stresses on the package, and the availability of supplies.

Petroleum-based Materials Used for Vegetables Packaging

The main types of petroleum-based polymeric materials used for packaging are shown in Table 20.3. The main types of bio-based and biodegradable polymers used to fabricate packages for processed products are shown in Table 20.4.

Polyolefin belong to a class of polymers that include PE and PP. PE comes in a variety of forms including high, low, and linear low-density PE as the main types used in vegetable packaging. High-density polyethylene (HDPE) has the highest percent crystallinity and is mainly used to make bottles, jugs, cups, etc. Low-density polyethylene (LDPE) is extruded into film and sheets, and is used as adhesive layers in laminates and a heat-sealing layer in fl xible packages. Linear low-density polyethylene (LLDPE) is the biaxially

Table 20.4 The main types of bio-based or biodegradable polymers used in vegetable products packaging

Polymer name	Packaging application
Polylactic Acid (PLA)	Bottles, films labels, compositable thermoformed cups, eating utensils and bowls
Polycaprolactone (PCL)	Adhesives, biodegradable bags, and containers
Polyhydroxyalcanoates (PHAs)	Food containers, pouches, tubs, bottles, film
Chitosan	Coffee cups, food containers and trays, lightweight foam pieces for cushioning
Cellulose	Films, sheets

oriented form and has a higher barrier to gases than HDPE and LDPE at the same gauge. The higher crystallinity of HDPE resulted from a lower degree of branching in its polymeric chains when compared with the higher degree of branching and lower crystallinity of LDPE. Because of its low glass transition temperature, LDPE is the material of choice for frozen products. This is so because it is less inclined to become too brittle and easily fractures when frozen. Nylon 6 is also used for frozen vegetable packaging and storage because of its excellent fl xibility at low temperatures. Polyolefin are good barriers to moisture but poor barriers to oxygen. Its excellent moisture barrier is due to its nonpolar nature. However, since it demonstrates little crosslinking, its oxygen barrier properties are fairly low.

PP is also used for the heat-sealing of fl xible and semirigid packages. However, because of its higher density and melting point as compared to PE, PP is used to seal polymeric packaging that is subjected to retorting conditions. Like PE, PP is also a good moisture barrier but shows relatively high permeability to oxygen. However, it shows better resistance to oils and grease when compared with PE. Because of its crystallinity, both PE and PP show poor transparency when compared with other types of polymers.

PVC requires varying degrees of plasticizing in order to extrude it into sheets. This factor is used as an advantage in using PVC for heat shrink labels. Due to their excellent moisture barrier, PVC film are used for refrigerated storage applications where visibility of the product should not be precluded by condensation on the underside of the film Because of the use of plasticizers in PVC to make films the migration of these chemicals to the packaged product must be a consideration, especially if the contenders have a high lipid concentration. If the migration is excessive, it could affect the taste of the product and this could become a concern to regulatory agencies. PVC is used to make highly transparent blisters that could be used to display various fresh vegetables. Unplasticized PVC is rigid and tough and is difficul to be extruded into films However, it find good uses for the manufacture of crates that could be used for the bulk packaging and/or transportation of recently harvested vegetables

Polyvinylidene chloride (PVDC) is the material of choice for applications where high barrier to moisture and oxygen is required. This material is mainly used for retorted shelf-stable products since it has a relatively high melting point; it is usually laminated with PP in such cases. Ethylene vinyl alcohol (EVOH) is also used for its high oxygen barrier properties, but this breaks down in the presence of moisture. As a result, EVOH is usually laminated with high moisture barrier materials. Studies by Halim et al. (2009) have shown that even though sandwiched between polyolefin in a laminate structure, EVOH is not well protected when exposed to retorting conditions. However, EVOH laminated materials could be suitable for pasteurization processing because pasteurization temperatures, pressure, and processing times are usually lower than that of retorting.

Many carbonated beverages are packaged in polyethylene terephthalate (PET) bottles because PET shows good structural stability at a wide range of temperatures and fairly good barrier to moisture and carbon dioxide. PET bottles are also widely used for noncarbonated beverages such as ice tea, juices, and certain energy drinks. Crystalline PET has a high melting point and as a result is used extensively as dual ovenable trays. As a result, it is used to package frozen entrées that are exposed to microwave or conventional oven temperatures. Nylons are also used for high temperature packaging as is the case in boil-in-bag applications.

Composite packaging is made of fabricated structures, which have more than one type of homogeneous material. The various sublayers that make up the heterogeneous composite material are carefully chosen to

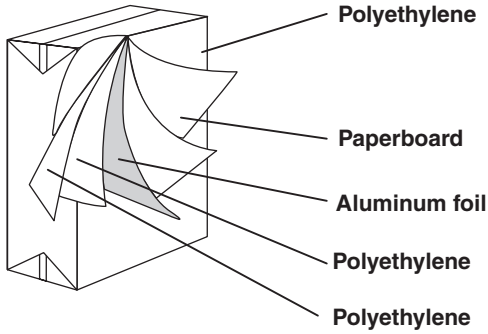


Figure 20.5 The sublayers in a composite material used for making brick-type packages.

impart a specifi property to the structure. Figure 20.5 shows a composite material used to make brick-type packages for nonretortable applications, e.g., vegetable juices. The wall of this is composed of a polyolefin aluminum foil, paperboard, and selected adhesives to bind the individual sublayers. Composites are also used to make various types of cans, by combining metal, paper, and plastic materials. In some cases, these cans may have bodies made of aluminum foil and paperboard while the ends are made of metal. Composite brick-type packages are used to package a variety of fruit juices, purees, and soups that are treated by aseptic processing. If these packages are to be used in retorting conditions, the heat-sealing layer must be PP.

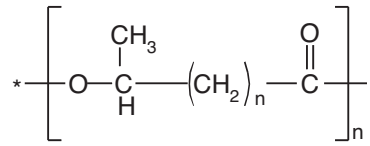
Bio-Based Materials Used for Vegetables Packaging

PLA is aliphatic polyester derived from lactic acid. The lactic acid used in this process comes mainly from corn or sugar beet. In the polymerization process for PLA, the formation of lactide is an intermediate step. Three stereoisomers of lactide exist, i.e., L-lactide, D-lactide, and meso-lactide. The stereochemical composition of the resulting polymer is influence by the stereochemical make up of the lactide monomer stream. This has a resultant effect on the melting point, the rate of crystallization, and the percent crystallization of the polymer. Engineering approaches such as biaxial orientation and microperforation can be used to influenc the crystallinity and permeability of PLA, respectively. Within recent times, PLA-blown fil was commercialized under the trade name, Earthfirs ® PLA.

Although PLA is an excellent oxygen barrier, it is susceptible to plasticization by exposure to moisture. This limits its use in providing good oxygen barrier in moist environments. In addition, PLA tends to be brittle and this influence its thermal stability when exposed to conditions such as heat sealing. If used to make pouches, this problem could be solved by the use of cold sealing techniques such as ultrasound welding. To enhance the rheological properties of PLA for operations where shear sensitivity and/or melt strength are essential, branching in the polymeric chain may be necessary during the polymerization process. Other factors that are essential to be controlled are the molecular weight distribution and the D-isomer content.

PLA is proving to be a viable alternative to petrochemical-based plastics for many applications. It is produced from renewable resources and is biodegradable, decomposing to give H_2O, CO_2, and humus, the black material in soil (Drumright et al. 2000). PLA has found uses as cutlery, trays, cups, films and in applications in selected fabric materials (Lunt 1998). One common disadvantage of PLA and other bio-based materials is the fact that the cost is higher than that of petroleum-based polymers. However, there are ongoing efforts to lower the cost of PLA and to increase its competitiveness (Achmad et al. 2009).

Polycaprolactone is a biodegradable polymer that is derived from crude oil (petroleum products). It can be synthesized from a ring opening reaction of ε-caprolactone combined with heat and a catalyst such as stannous octanoate. It is used mainly in polyurethanes as a surface coating for many resins, adhesives, and synthetic leather and fabric. It is also used to make biodegradable compostable



n=1	R =	hydrogen	poly (-3-hydroxypropionate)
		methyl	poly (-3-hydroxybutyrate)
		ethyl	poly (3-horoxyvalerate)
		propyl	poly (-3-hydroxyhexanoate)
		pentyl	poly (-3-hydroxyoctanoate)
		nonyl	poly (-3-hydroxydodecanoate)
n=2	R =	hydrogen	poly (-4-hydroxybutyrate)
n=3	R =	hydrogen	poly (-5-hydroxyvalerate)

Figure 20.6 The general structure of polyhydroxyalkanoates (Ojumu et al. 2004).

bags, which can be used for fresh produce. Polycaprolactone can be degraded by the hydrolysis of its ester linkage into simpler compounds.

Polyhydroxyalkanoates (PHAs) are biodegradable thermoplastics produced by many bacterial species as they participate in the fermentation of certain sugars. For example, poly (-3-hydroxybutyrate (PHB) is a PHA that is produced by microorganisms such as *Alcaligenes eutrophus* or *Bacillus megaterium* (Dawes 1988). The type of bacteria that produce PHAs do so when carbon is available but there is limited availability of certain nutrients that are essential for their growth. When produced, the bacteria store this polymer as a carbon and energy reserve, much like starch or glycogen in plants and animals, respectively. PHAs are named depending on the number of carbons in its polymeric chain. These can be used to make plastics with properties differing according to the number of carbons in the monomeric structure. These are described in Figure 20.6.

Polyhydroxybutyrate (PHB) can also be synthesized from plant origin. Somleva et al. (2008) reported that this was successfully engineered from a biomass crop called Switchgrass (*Panicum virgatum* L.). However, PHB has some problems with applications to the food system because it is brittle and stiff. Because PHB has a poor site for chemical modification the blends of PHB with other fl xible polymers can overcome these undesirable properties (Kim et al. 2003).

Chitosan is a naturally occurring polysaccharide that is similar to cellulose and is found in the exoskeleton of crustaceans such as crabs. Figure 20.7 shows the monomeric repeating unit of chitosan. Dutta et al. (2003) reported that chitosan has a great potential for a wide range of applications because of its biodegradability, biocompatibility, antimicrobial activity, nontoxicity, and versatile chemical and physical properties. Thus, chitosan-based film have proven to be very effective in food preservation, including their use for the packaging of vegetable products.

Polymers Based on Plant Fibers

Interest in natural fiber combined with traditional polymers has seen an increased interest in the industrialized countries (Zampaloni

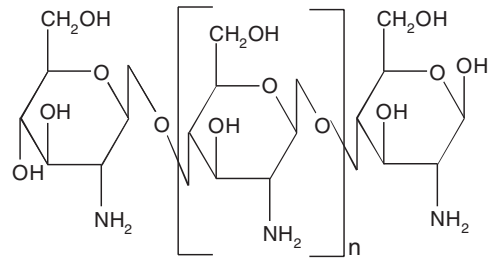


Figure 20.7 The structure of chitosan.

et al. 2007). This is so because of their low cost and the ease at which they degrade. In addition, natural fiber are generally lighter in weight than man-made fibers If used to reinforce polymers, they provide mechanical strength to the plastic that is comparable to that of glass fibe (Aguilar-Palazuelos et al. 2007). Plant fibers which are made of cellulose, hemicellulose, lignin, ash, and small traces of minerals, are known to degrade when exposed to the environment. When exposed to environment, certain microorganisms with specifi enzymes are capable of attacking the cellulose and hemicellulose (tertiary carbohydrates) within the cell walls of the fiber by hydrolyzing them into smaller, more easily digestible subunits. These subunits then become vulnerable to further breakdown through oxidation, hydrolysis, and dehydration. If exposed to direct sunlight, lignin is known to undergo photo oxidation degradation. Since lignin acts as an adhesive that holds the cell walls together, the chemical breakdown of lignin exposed the cellulose and hemicellulose to attack by soil microorganisms.

Plant-based materials have been used for centuries to package vegetables. They have been used to manufacture baskets, bags, crates, etc. In some applications, the leaves of certain plants are used to package processed vegetable products as shown in Figure 20.8.

Figure 20.8 Banana leaf used to package processed rice cake.

This figur shows banana leaves being used to package rice cake.

Summary

Packaging is one of the main driving forces in marketing and convenience in developed countries. Packaging plays an important role in the preservation and the extension of shelf life of vegetables from the time of harvest up to their consumption by consumers. Immediately after harvesting, packaging helps to reduce bruising, damage, and subsequent rapid shelf-life loss to the commodity. Since the cooling of the harvested vegetable significantly reduces respiration rate, this is best facilitated with the help of packaging. Packaging also helps to reduce the incidence of infestation, disease progression, and microbial attack of harvested vegetables. Modifie atmosphere and active packaging systems have been used to significantl increase the shelf life of cut vegetables in particular. This is so because of the increased potential for these commodities to lose moisture and texture, have a higher respiration rate, be susceptible to microbial attack, and lose of color and nutrients.

Packaged processed-vegetable products are also susceptible to spoilage but the factors that influenc shelf-life loss are sometimes different from those of the fresh vegetables. The main technologies used to process vegetables include retorting, pasteurization, irradiation, dehydration, and freezing. To maintain the shelf life of these products, the selected packaging must be compatible with the processing method used. For retorted products, cans, glass jars, and semirigid polymeric trays and cups are used. Many types of composite brick-type packages have also been developed for retorting operations. Irradiated products must be packaged in materials that are approved for that process because of the risk of the development of radiolytic compounds, especially in plastic materials. Most frozen vegetable products are packaged in PE,

nylons, or crystalline PET materials because of their fl xibility and lower tendency to become too brittle in subzero conditions. The value that various packaging systems add to the fresh or processed vegetables is quite signifi an and continues to grow.

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Chapter 21

Waste Management and Utilization in Vegetable Processing

Dalbir S. Sogi and Muhammad Siddiq

Introduction

Vegetables processing operations can generate a substantial amount of wastes while transforming raw vegetables into finishe products. For example, canning of vegetables is a major waste-generating operation. The vegetable peeling, coring, trimming, sizing, sorting, seeds, leaves, etc., produce substantial solid wastes. These biodegradable wastes if not handled and disposed off properly can pollute the environment and affect our quality of life. The governmental regulatory agencies in different countries, e.g., the Environmental Protection Agency (EPA) in the United States have guidelines for waste classification management, and disposal. The chemical oxygen demand (COD) and biological oxygen demand (BOD) of the treated industrial waste is monitored by the state level departments of environmental quality (DEQ) in the United States. The objective is science-based waste management and utilization for the protection of environment. This chapter reviews the three areas of waste management in vegetable processing operations: (1) waste generation; (2) waste management and treatment; and (3) waste utilization.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Waste Generation

The generation of food processing waste is only one part of the bigger environmental concern across the overall supply chain model depicted in Figure 21.1. Within the food industry, vegetable processing produces a variety of waste from various unit operations. Table 21.1 summarizes the process of waste generation during a typical vegetable canning operation. The canning of vegetables tends to produce the highest amount of waste, especially wastewater, as compared to freezing or dehydration. For an effective waste management, cooperation between food industry, municipality, and state/federal regulatory agencies is required.

The actual amount of waste from one processing plant to another can differ signifi cantly. In most processing plants in the developed countries, water used during processing is recycled continuously using filter and neutralizers to minimize large volumes of wastewater, which is treated before disposal to eliminate or minimize impact on the environment. However, in developing countries, which lack capital-intensive wastewater recycling and predisposal treatment facilities, the environmental hazards have not received the similar due importance.

The economic progress in countries like China and India has brought focus to the development of the food-processing sector. In 2008, China produced about 50%

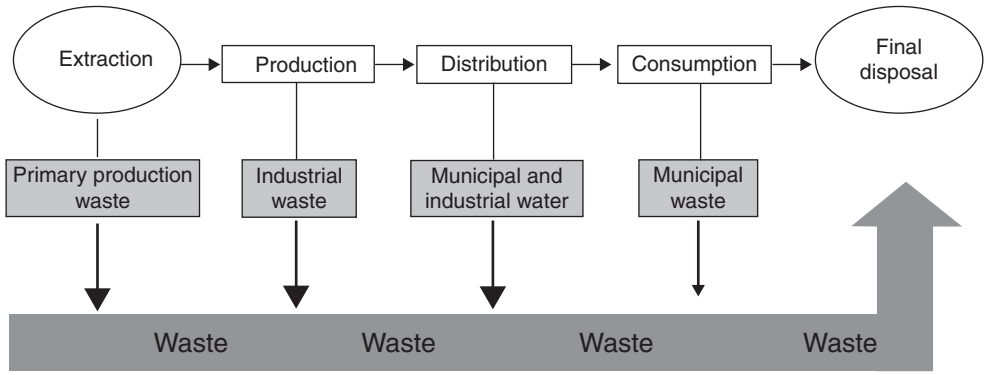

Figure 21.1 Life cycle of waste generation (OECD, 2005).

(457.7 million tons) of the world production of vegetables (including melons) of 916.1 million tons (FAO 2010). A significan amount of these vegetables is processed for domestic use and export; thus, the amount of waste generated has increased significantl .

Table 21.2, gives waste generated as a result of different methods used for peeling potatoes. In addition, the characteristics of the raw product can influenc the overall volume of waste generated. For example, in potato peeling, its size, shape, defects, etc., can affect the amount of waste generated even if the peeling method was the same. The potato tuber's composition and cell size can also result in varying losses of soluble solids (mostly starch) leaching out of the peeled tuber, with additional losses occurring during cutting operations used in chips and fries processing. Peeling is the most important step in potato

Table 21.1 Waste generation during typical vegetable canning operations

Unit operations	Waste type (solid, liquid, mixed)	Waste class (chemical, biological, hazardous, mixed)
Dry (air) cleaning	Mostly solid	Mixed
	Field debris	
Washing	Wastewater	Chemical
	Suspended solids	Mixed
	Debris	
Peeling	Solid	Chemical
	Wastewater	Biological
	Mixed	Hazardous (from lye)
Cutting (slices, dices)	Solid	Biological
	Mixed	
Postcut washing	Wastewater	Chemical
		Biological
Blanching	Wastewater *(water-blanch)*	Chemical
	Steam condensate *(steam-blanch)*	Biological
Filling and brining	Some wastewater	Chemical
Exhaustion	Wastewater	Minimally chemical
	Steam condensate	
Lid closure/seaming	Solid *(from spills)*	Mixed
	Liquid *(from spills)*	
Thermal process	Wastewater	Mixed
	Steam *(retort vent)* steam condensate	
Cooling	Wastewater	Mild chemical

Table 21.2 Waste generation from potato peeling operations—comparison of different peeling methods

Peeling method	Peel loss (%)	Waste volume (lbs/ton)
Abrasion (mechanical)	20–30	400–600
Conventional caustic (lye–rinse)	15–20	300–400
Infrared caustic (lye–dry heat–rinse)	10–13	200–260
"Dry" caustic (lye–hold–mechanical–rinse)	6–12	120–240
Manual (optimum peel rate)	8–12	160–240

Source: Uebersax (2009).

processing and its optimization helps in reducing the volume of solid waste (Marakassi 2002).

Generally, any losses resulting from preparing vegetables for canning, freezing, or any other type of processed product translate directly into some form of waste generation, either solid or liquid.

The estimate of the amount of waste produced from the vegetable processing in selected countries is given in Table 21.3. Generally, there is insufficien data available exclusively focusing on the waste from vegetable operations and it is not unusual to see such data being reported in a combined form for fruit and vegetable processing, food service operations, or the figure being given for a single vegetables processing operations, e.g., potato or tomato processing.

The estimate of the global sale of the processed food is over US $3 trillion (Ragmi and Gehlhar 2005), which can be an indirect indicator of the volume of food processed and the waste produced. The specifi waste index gives a general guideline to assess the quantity of the waste generated. It is define as the ratio of waste produced per unit quantity of finishe product. The specifi waste index for potato has been reported to be 0.5 (Russ and Pittroff 2004).

Waste Management and Treatment

Waste management is a worldwide problem due to the following environmental and nonenvironmental issues:

1. *Water pollution*—Solid or liquid waste pollutes the water due to its biodegradable matter that consumes dissolved oxygen during the course of decomposition and affects the aquatic life in rivers, lakes, and sea. The polluted water cannot be used for human, animal, and plants;
2. *Soil pollution*—The disposal of solid waste can cause undesirable changes in soil composition, making it difficul for agriculture or other usages;
3. *Air pollution*—Decomposing solid waste releases malodorous compounds in the air and affects the quality of life for population residing in the area;
4. *Unhygienic conditions*—Pathogenic microbes, flies mosquitoes, and rodents

Table 21.3 Quantity of the waste produced from vegetable processing

Country	Waste (MT*/yr)	Waste type	Reference
India	675,000	Vegetable processing	MFPI (2004), FAO (2010)
Portugal	14,000	Tomato pomace	Carvalheiro et al. (1994)
Germany	380,000	Potato, vegetable, and fruit processing	Henn (1998)
Belgium	105,000	Vegetable, garden, and fruit processing	Lucas (1997)

*Metric tons.

breed on solid waste and create an unhealthy environment, which may result in an epidemic;
5. *Aesthetics*—Solid waste spoils the aesthetic value of an area, which leads to lower real estate value;
6. *Social concern*—Environmental activists and electronic media have sensitized public about the ill effects of pollution;
7. *Legal requirement*—The national and international regulations are becoming more stringent to address the environmental issues; and
8. *International trade*—The processing techniques that cause minimum damage to the environment are being encouraged. Importing countries make their choices on the basis of such concerns that the product must have been produced/processed using environment-friendly technologies.

Waste Minimization

Waste minimization is the firs step of waste management. In a workshop by the Organization for Economic Cooperation and Development (OECD) the definitio (Reimer and Kristoffersen 1999) of waste minimization was agreed to included three elements: (1) preventing and/or reducing the generation of waste at source; (2) improving the quality of the waste generated, such as reducing the hazard; and (3) encouraging reuse, recycling, and recovery. Although this definitio is broad, it gives priority to preventive measures like cleaner production and also includes reduction of unavoidable waste. Figure 21.2 shows elements of waste management versus waste minimization strategy.

The ultimate goal of waste minimization is to keep as much waste as possible away from the fina disposal. It does not include: (1) external recycling; (2) improvement of waste quality by sorting of waste; (3) reuse of product or part of products for purposes other than the original; and (4) energy recovery.

Waste Management

Solid and liquid wastes originate during vegetable processing from various unit operations such as washing, sorting, trimming, peeling, coring, cutting, slicing, dicing, juice extraction, etc. For processed products, good quality vegetables should be selected containing negligible quantity of undesirable matter and unit operations should be optimized in order to minimize the waste generation

As indicated earlier, the canning process tends to produce higher quantities of waste than, for example, drying or freezing. The vegetable juice extraction process normally results in higher solid waste contents. According to Lopez (1981), the high organic strength of the usual cannery wastes is the principal reason for the difficult encountered in their disposal, as the raw untreated cannery wastes consist of small particles, and sometimes discarded whole pieces, of raw product, skins, and seeds suspended in water, which carries in solution the juices of the product being canned. In comparison to domestic sewage, cannery wastes are typically high in sugars and starches and the pollution strength, determined as biochemical oxygen demand (BOD), can be up to 10 times greater. The objective of any waste management plan and strategy should be twofold: (1) processes and strategies to minimize waste; and (2) selection of appropriate waste treatment and/or disposal strategies.

Quantity of waste generated from each unit operations should be studied and appropriate steps should be taken to minimize or manage it. For effective waste management programs, before plans and specification for installation of waste disposal equipment are prepared, the following basic considerations should be investigated in the interests of simplicity of design and economy of operation (Lopez 1981):

Waste character: Determine if the waste contains materials that are hazardous or potentially hazardous to public health. It

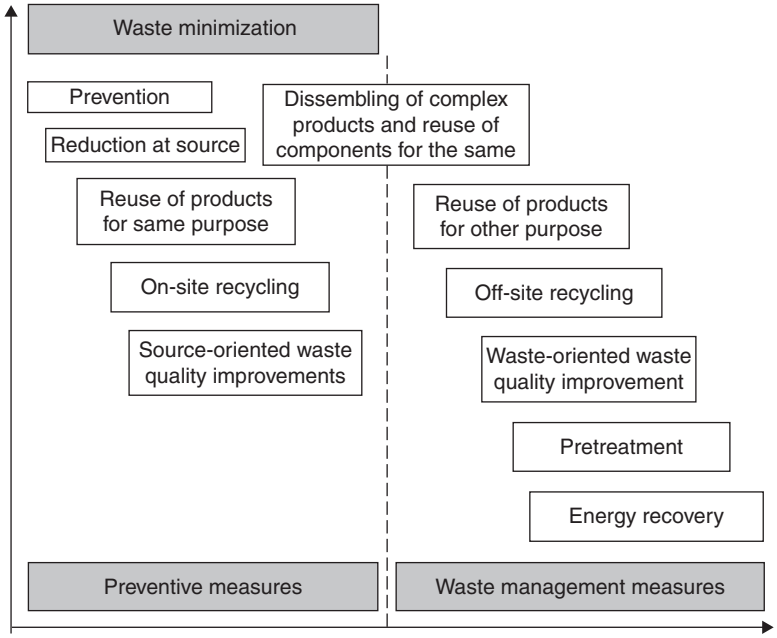

Figure 21.2 Key elements of waste management versus waste minimization (from Reimer and Kristoffersen 1999).

is also critical to assess the concentration of organic solids in the waste and the relative concentration of suspended and soluble solids. An initial estimate should be made of the suspended solids amounts that could be removed by screening or any other filtratio techniques.

Flow measurements of waste: Determine the volume of wastewater that will require treatment. Ideally, the fl w should be measured using fl w meters or other devices; from this data, daily and yearly volumes of wastes should be calculated.

Segregation of highly contaminated wastewaters: For effective planning, consider the possibility of separating individual waste fl ws at the point of origin into contaminated waters requiring treatment, and waters with little or no contamination, which could be discharged without treatment. The latter group would include can-cooling waters, condenser waters, etc. This initial determination is important because the volume of wastewaters requiring treatment determines the size of the treatment plant.

Possibility of water reuse/recycling: The water reuse in certain operations can substantially reduce the total amount of water used, and thus reduce the volume of wastewater requiring disposal. While such reduction in wastewater volume may not be accompanied by a reduction in the total organic strength, nonetheless, it would make the treatment of the waste more economical. However, when planning for water reuse, due considerations should be given to the fact that improper reuse of water can potentially lead to microbiological or food safety problems. In many cases the water to be reused may need to be pasteurized before considered safe for use.

Study of means to reduce amount of gross solids added: The disposal of solid waste

into drains/gutters should not be allowed, as this can cause an unnecessary burden on the screens, disintegration of larger solids into particles passing the screen, and leaching of soluble solids from gross solids; all of these can result in an increased organic strength of liquid wastes, which must be treated before disposal.

Considerations of regulations governing industrial wastes: Plans for treatment of wastes should take into account if it will be acceptable to pollution control agencies, especially, in cases where the efflu ent is to be discharged into a public water course, or if it will be suitable for acceptance into a municipal treatment system. The effluen should be suitable for rapid oxidation and stabilization without causing any odors if land disposal method is to be used.

Selection of treatment and disposal procedures: Finally, the selection of the method of treatment/disposal should consider the space availability for a treatment plant, the effect of climate on the method of disposal, and whether a continuous or batch type treatment is desirable. It is also helpful to consider any future expansion of the processing operations that may result in additional waste amounts requiring treatment and disposal.

Pollution Loads

BOD is a measure of the amount of oxygen that bacteria will consume while decomposing organic matter under aerobic conditions. COD, which does not differentiate between biologically available and inert organic matter, is a measure of the total quantity of oxygen required to oxidize all organic material into carbon dioxide and water. COD values are always greater than BOD values (EPD 2009).

The establishment of target pollution loads is an important step in the effective management of wastes. Table 21.4 shows data on selected target loads from processing of individual vegetables, whereas, Table 21.5 shows these numbers on the industry-wide basis. These numbers are the waste loads arising from the production processes *before* the addition of pollution control measures. These levels are derived from the average loads recorded in a major study of the industry and should be used as maximum levels of unit pollution in the design of new waste treatment plants (Anon 1998). The target loads per unit of production shown can be achieved by implementing cleaner production processes and pollution prevention measures, which in turn can provide both economic and environmental benefits

Waste Management Operations

The wastes from vegetable processing can be managed by adopting the following strategies: (1) *reduce*—minimization of solid waste production; (2) *recover*—waste utilization to produce by-products/coproducts (e.g., nonfermented and fermented products); (3) *recycle*—the solid waste from vegetable processing contains nutrients that can be used to nourish the domestic animals. It can be a renewable source of energy in the form of biofuels. The waste can be converted into compost to be used as soil conditioner. These techniques would recycle the elements in the biosystem without any serious environmental implication. Examples include animal feed, bioenergy, and compost; (4) *dispose*—there will always be some waste that would have no further use and thus will need to be disposed of away from the factory premises. It can be done without damaging the environment by following methods: incineration, land fillin etc.

The US-EPA has compiled a "checklist" or activity list for running an efficien waste

Table 21.4 Model for liquid waste inventories in vegetables processing industry

Vegetable product	Waste volume (m^3/metric ton)	BOD* (kg/metric ton)	TSS† (kg/metric ton)	Solid waste (kg/ metric ton production)
Asparagus	69.0	2.1	3.4	130
Beets	5.0	20.0	3.9	–‡
Broccoli	11.0	9.8	5.6	200
Brussel sprouts	36.0	3.4	11.0	–
Carrots	12.0	20.0	12.0	200
Caulifl wer	89.0	5.2	2.7	–
Corn, canned	4.5	14.0	6.7	40
Corn, frozen	13.0	20.0	5.6	–
Dry beans	18.0	15.0	4.4	–
Lima Beans	27.0	14.0	10.0	–
Mushrooms	22.0	8.7	4.0	–
Peas, canned	20.0	22.0	5.4	40
Peas, frozen	15.0	18.0	4.9	–
Potato, frozen projects	11.0	23.0	19.0	40
Potato, dehydrated project	8.8	11.0	8.6	–
Snap/green beans, canned	15.0	3.1	2.0	–
Snap/green beans, frozen	20.0	6.0	3.0	–
Spinach, canned	38.0	8.2	6.5	–
Spinach, frozen	29.0	4.8	2.0	–
Sweet potatoes	4.1	30.0	12.0	

Source: Economopoulos (1993).
*Biochemical oxygen demand.
†Total suspended solids.
‡Data not available.

management system (see Box 21.1). Readers are referred to a number of texts available on detailed treatment strategies for the handling, treating, and disposing solid and liquid wastes from food processing operation.

Besides solid waste, wastewater is typically a major portion of waste in a vegetable processing and packaging plant. Figure 21.3 shows a wastewater treatment and disposal plan for water from both washing and processing operations. Reductions in wastewater volumes of up to 95% have been reported through implementation of good practices; for example, recirculation of process water from onion preparation reduces the organic load by 75% and water consumption by 95%. Similarly, the liquid waste load (in terms of BOD) from apple juice and carrot processing can be reduced by 80% (Anon 1998); where possible, measures listed below should be adopted:

- Procure clean raw vegetables, thus reducing the concentration of dirt and organics (including pesticides) in the effluent
- Use dry methods such as vibration or air jets to wash/clean raw vegetables. Dry peeling methods, where possible to use, reduce the effluen volume (by up to 35%) and pollutant concentration (organic load reduced by up to 25%).

Table 21.5 Effluents from fruit and vegetable industry

Parameter	Maximum value (mg/L, except pH)
pH	6–9
BOD*	50
COD†	250
TSS‡	50
Oil and grease	10
Total nitrogen	10
Total phosphorus	5

Source: Anon (1998).
*Biochemical oxygen demand.
†Chemical oxygen demand.
‡Total suspended solids.

Box 21.1 Operating the waste management system—activity list.

- Develop a waste management system identifying the standard procedures necessary for a unit to operate according to its design throughout the intended working life.
- Provide proper maintenance and operation of ground water, surface water, and air controls.
- Develop daily procedures to place waste, operate environmental controls, and inspect and maintain the unit.
- Review at a regular interval, such as annually, whether the waste management system needs to be updated.
- Develop a waste analysis procedure to ensure an understanding of the physical and chemical composition of the waste to be managed.
- Develop regular schedules for waste screening and for unit inspections.
- If daily cover is recommended, select an appropriate daily cover and establish processes for placing and covering waste.
- Implement security measures to prevent unauthorized entry.
- Provide personnel with proper training.
- Establish emergency response procedures and familiarize employees with emergency equipment.
- Develop procedures for maintaining records.
- Establish nuisance controls to minimize dust, noise, odor, and disease vectors.

Source: US-EPA (2008).

- Separate and recirculate process wastewaters.
- Use countercurrent systems where washing is necessary.
- Use steam instead of hot water to reduce the quantity of wastewater going for treatment (taking into consideration the tradeoff with increased energy use).
- Minimize the use of water for cleaning floor and machines.
- Remove solid wastes without the use of water.
- Reuse concentrated wastewaters and solid wastes for production of by-products.

Waste Treatment

Waste generated from vegetables processing industry contains organic and inorganic materials with high COD and BOD contents. The water should be properly treated before disposal to municipal water. The different treatments steps are presented in Table 21.6.

The most important steps in industrial waste treatment are secondary or biological treatment where biodegradable waste is decomposed to amino acids, monosaccharides and fatty acids. Finally, methane is formed. Biological treatment is carried out in three stages: aerobic, anaerobic, and facultative. In aerobic treatment (e.g., activated sludge process), microbes grow by consuming nutrients present in the waste material in the presence of oxygen and reduce BOD levels significantl (Figure 21.4). Anaerobic waste treatment is a

Table 21.6 Levels of industrial waste treatment

Level	Treatment
Preliminary	Removal of grits, sticks, leaves, grease, oil, and floatin materials
Primary (screening, sedimentation, fl w equalization)	Removal of portion of suspended solids and organic matter
Secondary (biological treatment)	Removal of portion of biodegradable materials and suspended solids
Tertiary (postbiological)	Removal of residual suspended solids
Advanced	Removal of dissolved solids and suspended solids after secondary treatment

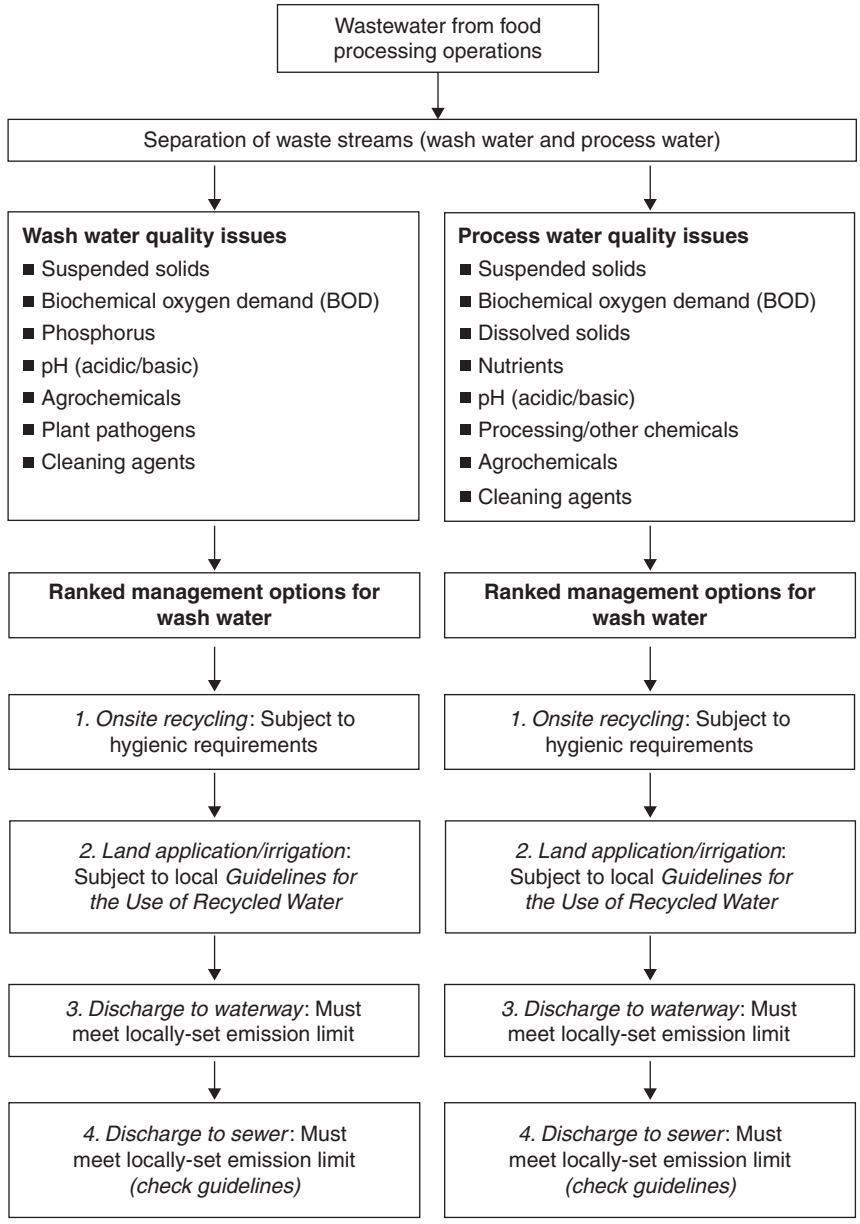

Figure 21.3 Options for the disposal of treated wastewater (Adapted from DPIEW, 2002).

major technology for the treatment of wastewater from the vegetable processing industry where organically high-polluted wastewater is generated (Diamantis et al. 2007). Different bioreactors are used for the treatment. The common bioreactors used for the treatment are continuous stirred tank reactor (CSTR), up fl w anaerobic sludge bed reactor (UASB). An anaerobic reactor used for vegetable waste treatment is shown in Figure 21.5. Various microorganisms degrade biopolymer to propionic, acetic acid, and further into methane

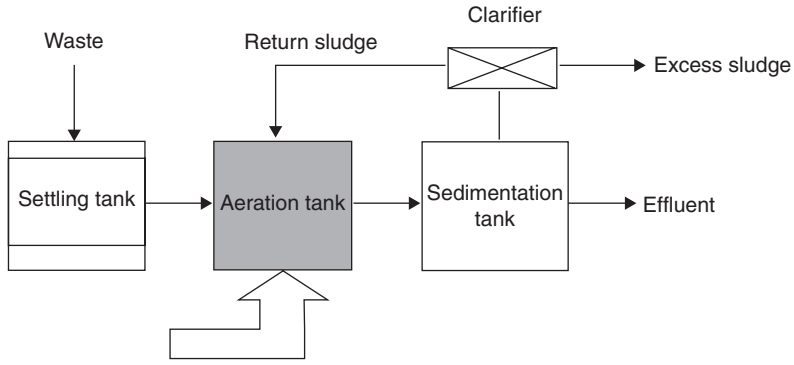

Figure 21.4 Waste treatment using aerobic system.

and carbon dioxide (Figure 21.6) (Diamantis et al. 2007). Details on this are available in a number of industrial waste treatment books.

It might be difficul to utilize the entire waste coming out of vegetable processing by preceding techniques due to a variety of reasons. For solid wastes, if no other value-added uses (discussed later under *Waste Utilization*) exist, such waste should be disposed of either as incineration or land fill

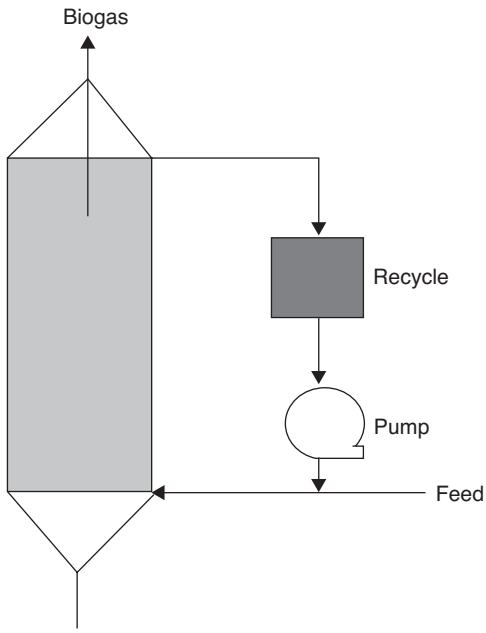

Figure 21.5 Anaerobic sludge bed treatment.

ing: (1) *incineration*—this technique has been followed ever since food processing industry came into being. It is the controlled burning of waste at high temperatures in a facility designed for efficien and complete combustion (Rhyner et al. 1995). This process generates carbon dioxide, water, sulfur dioxide, ash, gases, and heat energy. It requires less space than landfill Vegetable waste contains high moisture and needs to be dried to become combustible. The heat energy so generated is used for drying the fresh waste. Smoke originating from incinerators causes air pollution. It should be equipped with electrostatic precipitators, scrubbers, or other equipment to reduce emissions to levels acceptable to regulatory agencies (Rhyner et al. 1995). The solid end-product is ash, which needs to be disposed off in landfills (2) *land filling* landfil is the most economic, though not always environmentally safe, way of disposal where the waste is buried into the earth. Traditional landfill were not managed in a scientifi way thus resulting in the emission of landfil gases (methane and carbon dioxide) and leachate. Landfil gases pollute the air and cause green house effect whereas leachate contaminates the ground water. Modern landfill take care of these two problems by preventing the leachate to contaminate the ground water and also collecting the landfil gas as energy source (Maximova and Koumanova 2006). This gas is used for

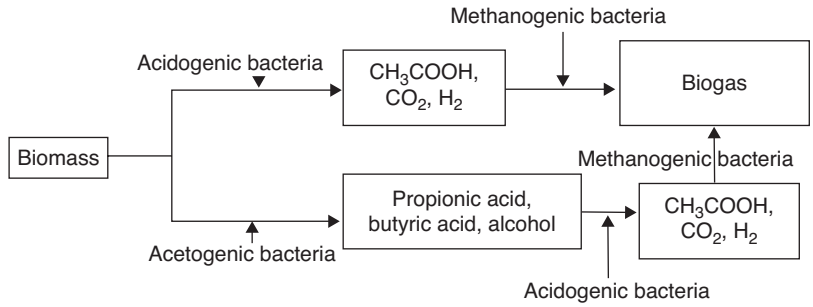

Figure 21.6 Anaerobic conversion of biogas.

the production of electricity, hot water, and steam. Vegetable processing waste can also be dumped into the landfil and the gas can be used as an energy source for the processing unit.

Operating Plan

According to US-EPA (2008), an operating plan, "should serve as the primary resource document for operating a waste management unit. It should include the technical details necessary for a unit to operate as designed throughout its intended working life. At a landfill for example, the operating plan should illustrate the chronological sequence for fillin the unit, and it should be detailed enough to allow the facility manager to know what to do at any point in the active life of the unit." The key elements of an operating plan, as recommended by US-EPA, should include:

- A daily procedures component
- Lists of current equipment holdings and of future equipment needs
- Procedures to inspect for inappropriate wastes and to respond when their presence is suspected
- Procedures for addressing extreme weather conditions
- Personnel needs and equipment utilization
- Procedures to address emergencies, such as medical crises, fires and spills
- Quality control standards
- Means of compliance with local, state, and federal regulations

Record Keeping

Record keeping should be an integral and vital part of cost-effective and efficien waste management operations (US-EPA 2008). Records should be maintained for an appropriate period of time, but it is a good idea to keep a set of core records indefinitel . The EPA guidelines further recommend checking with state or local authorities to determine what, if any, record keeping is required by law and to determine how long records should be kept. Records can serve as a valuable almanac of activities, as well as a source of cost information to help fine-tun future expenditures and operating budgets. Data on waste volume, for example, can allow a prediction of remaining site life, any special equipment that might be needed, and personnel requirements (US-EPA 2008). Box 21.2 lists some of the recommendations on the types of record that should be kept at a processing and waste management site.

Waste Utilization

Waste from vegetable processing is organic in nature and can be processed to obtain a number of value-added products. These products can be nonfermented or fermented ones.

Box 21.2 Types of operational and health and safety records that should be kept and maintained

Operational records, appropriate and as applicable:

- Waste analysis results
- Liner compatibility testing (where a liner system is considered appropriate)
- Waste volume
- Location of waste placement, including a map
- Depth of waste below the fina cover surface
- Frequency of waste application
- Equipment operation and maintenance statistics
- Environmental monitoring data and results
- Inspection reports, including photographs
- Design documents, including drawings and certification
- Cost estimates and other financia data
- Plans for unit closure and postclosure care
- Information on financia assurance mechanisms
- Daily log of activities
- Calendar of events

Health and safety records:

- Personal information and work history for each employee, including health information such as illness reports
- Accident records
- Work environmental records
- Occupational safety records, including safety training and safety surveys

Source: US-EPA (2008).

Nonfermented Products

In these products, microbes are not involved to bring about desirable change or synthesize compounds. The waste is utilized to produce following by-products.

Food Products

The solid waste may be used in the preparation of food products wherever possible. Tomato trimmings from canning, drying, and freezing can be used for preparation of tomato juice, puree, or ketchup. Asparagus stalks cut in short segments can be canned for soup stock (Cruess 2004).

Pectin

Vegetable wastes are fair source of pectin, which have major role in gel formation in jam and several other uses in food, pharmaceutical, and cosmetic industries. Carrot pomace contains 22–25% pectin on dry basis (Torre et al. 1995) and can be utilized for the extraction of the pectin.

Oil

Tomato seeds are major component of pomace and contain 20.53–29.6% crude fat (Tsatsaronis and Boskou 1975; Brodowski and Geisman 1980; Carlson et al. 1981; Bhullar and Sogi 2000). The oil can be extracted by mechanical or solvent extraction. This oil can be used in native form or after refinin as cooking oil or in fat rich products like margarine and mayonnaise (Sogi and Kaur 2003).

Proteins

Tomato seeds contain 22.2–33.9% proteins (Brodowski and Geisman 1980; Carlson et al. 1981; Lateif and Knorr 1983; Sogi and Bawa 1998). The cake left after oil extraction can act as nonconventional proteins source. It can be further used to produce protein concentrate and hydrolysates (Kramer and Kwee 1977; Sogi et al. 2005). Siddiq et al. (2009a, b) characterized the physicochemical and functional

properties of defatted maize germ (DMG) flou , a protein-rich by-product from maize or corn oil industry; their results showed that acceptable quality bread could be made with added DMG flou up to 15% level.

Pigments

Tomato skin contains red pigment lycopene. The skin can be separated and solvent extracted to obtain oleoresins rich in lycopene (Hackett et al. 2004; Kaur et al. 2008). It can be used as coloring for fat-rich food products and also as anticancer drug (Rao and Agarwal 1998, 1999). Carrot pomace is rich in beta-carotene that can be extracted and used as vitamin supplement and coloring (Nawirska and Kwaniewska 2005).

Super critical extraction, also called green technology, can extract pigments from waste (O'Day and Rosenau, 1982). The efficien y of lycopene extraction can be improved by adding modifier having lipophilic character like edible oil (Baysal et al. 2000; Vasapollo et al. 2004; Kassama et al. 2008).

Starch

Potato and corn processing generate starch waste. Starch is removed from potato slices during washing operation (Mishra et al. 2004). It can be used for food, feed, or other purposes especially in textile industry. The cyclodextrin produced from starch is used for the removal of cholesterol from milk, butter, and egg (Valle 2004).

Dietary Fibers

Dietary fiber contain both soluble and insoluble fractions and can be used for designing "functional foods" (Rodrıguez et al. 2006). Vegetables processing waste such as carrot, tomato, and spinach pomace can be used for the production of dietary fibers Asparagus spears contain fiber up to 40–50% on fresh weight basis (Rodrıguez et al. 1999). The dietary fibe content of the cabbage pomace was 34.76% on dry weight basis while cellulose and hemicellulose content was 15.20 and 14.13%, respectively (Nawirska and Uklanska 2008). Soluble dietary fibe fractions in carrot pomace were more than 70% of the total fiber (Rodrıguez et al. 2006). Dietary fibe from cabbage has been isolated and characterized by Jongaroontaprangsee et al. (2007).

Miscellaneous

Tomato peel can be utilized for the preparation of varnishes and resins (Cruess 2004). Pretreatments of the cellulolytic vegetable processing waste with acids (Tuse et al. 1981), alkali (Sitlon et al. 1980.), or enzymes (Fan et al. 1981) are effective to release a variety of fermentable sugars. Lycopene, an antioxidant, was extracted from tomato peel and its degradation kinetics at temperature range of 51–100°C studied by Kaur et al. (2006); their results showed a strong correlation between lycopene content and Hunter color values.

Fermented By-Products

The waste from vegetable processing is a good medium for fermentation and a number of products are produced through microbial action.

Single-Cell Protein

Potato peels supplemented with ammonium chloride have been used for the production of protein by using a nontoxic fungi *Pleurotus ostreatus*. *Alcaligene faecalis* grew on deliginifie corncobs and produced protein (Srinivasan and Callihan 1971). *Aspergillus* spp. Strain VKPMF-559 utilized corncobs to produce a biomass containing varied quantity of proteins (Nazarenko et al. 1994). Solid state fermentation of carrot waste by *Aspergillus niger* also produced protein rich mass (Sethi 1978; Davy et al. 1981; Garg et al. 2000). Vegetable waste from the aubergene, tomato,

cabbage, carrot can act as substrate for lysine production by *Brevibacterium* spp (Trifonova et al. 1993).

Antibiotics

The butts of asparagus were steamed and pressed to get juice, which was then concentrated (Cruess 2004). It was an excellent medium for growing microorganisms for production of antibiotics (gramicidin).

Mushroom Culture Media

Lignocellulosic and other food and agricultural wastes have been utilized for the production of mushrooms (Chang et al. 1983).

Fermentable Sugars

The tapioca fibrou waste residue can be utilized for the production of glucose syrup, high fructose syrup, and confectioner's syrup (Kunhi et al. 1981). Cellulosic cassava waste saccharifie with a culture filtrat from *Trichoderma viride* and a soil *Basidiomycetes*, together with commercial amylases, enabled an enhanced sugar formation. A large-scale enzymatic depolymerization of xylan extracted from corncob meals yielded various sugars, like xylobiose, xylotriose, and arabinose oxylooligosaccharides (Pellerin et al. 1991). Enzymes from *Aureobasidium* spp. strain NRRL Y-2311–1 have been used to saccharify corn fiber (Leathers and Gupta 1996).

Animal Feed

The vegetable waste is rich in crude fibe , crude protein, and mineral (Esteban et al. 2007). It can be used as animal feed which would not only solve waste disposal problem but also reduce the cost of animal products (Samuels et al. 1991; Westendorf et al. 1998; Myer et al. 1999; Westendorf, 2000). The waste can be heated at 65°C to kill pathogenic microbes and to reduce the moisture content. Animal feed of acceptable quality was formulated containing 20% of vegetable waste by Esteban et al. 2007).

Tomato skins and seeds can be pressed in a continuous press, dried in a rotary drum drier, ground in a hammer mill, and used as stock food (Rabak 1917). Waste of potato, cabbage, caulifl wer, turnip, sweet potato, carrot, beans, etc., can be used for making cattle feed. Potato waste has been successfully employed in the formulation of animal feed after fermentation.

The vegetable waste can also be converted into silage. This process involves cutting of green fodder in 2–3 inches length, placing into a silo pit, pressing to remove air, covering with a polythene sheet, covering and sealing with mud, and fermentation for 40–45 days by lactic acid bacteria (Jerath 2009). The silage can be fed to animals, especially during the fodder scarcity period. The potato and sweet corn processing wastes can be used along with fodder for the preparation of silage.

Bioenergy

The energy from vegetable waste is renewable and environment-friendly. The waste that pollute environment can be used for energy generation. Ethanol can be produced from the vegetable processing waste to partially replace the petrol in vehicles. Enzymatic and nonenzymatic (acid, alkaline) hydrolysis of carrot and tomato wastes was done to obtain reducing sugars and the hydrolysates were fermented with a mixed culture of *Zymomonas mobilis* and *Candida tropicalis* to produce ethanol (Patle and Lal 2007). Ethanol yields of 2.8 and 1.4% have been reported for carrot and tomato, respectively.

Biogas or methane is produced by anaerobic bacteria in anaerobic digester by hydrolyzing cellulose, hemicellulose, lignin, and protein. The process has three stages: (1) hydrolysis; (2) acidogenesis; and (3) methanogenesis (Bryant 1979). Hydrolysis is the limiting step in solid waste digestion (Vavihn and Rytov, 1997). Carbohydrates

are digested quickly because of easy hydrolysis followed by proteins, lipids, lignins, and cellulose. The waste needs to be inoculated with hydrolytic, acetogenic, and methanogenic bacteria to enhance the biogas generation. Sometime, alkali or lime may also be added to vegetable processing waste for neutralization. Vegetable processing waste can produce methane that can be used in boilers to produce steam that substantially reduce the fuel consumption.

Composting

Conversion of plant material into compost is very old process involving natural microflor or earthworms. In traditional method, it takes long time to transform the large organic compounds into small ones, which can be assimilated by plants. However, it is a very promising technology to manage the waste in shortest possible time with the application of biotechnology.

Microbial Composting

In this process, a wide variety of microorganisms act on complex organic matter and decompose it into simple compounds (Neklyudov et al. 2006); static piles, aerated piles, or continuous reactors can be employed. Good compost is a humus-like substance without any off-odor and nourishes the plant as organic fertilizer. The pathogenic microbes are inactivated by heat generated during composting and also suppressed competitively by nonpathogens.

Vermicomposting

The vermiculture uses earthworms as natural bioreactors for efficien biodegradation of solid wastes from vegetable processing in $1^1/_2$ month only whereas in traditional method, it takes 6–12 months (Pramanik et al. 2007). Earthworm's gizzard acts as a mill and grinds the waste ingested by the worms. The gut of the worms provides optimum temperature, pH, oxygen, and other favorable conditions for the microbes to flouris and carry out degradation. The species of earthworms that are being used for compost production are *Eisenia foetida*, *Eudrilus eugeniae*, *Perionyx excavatus*, *Lumbricus rubellus*, and *Pheretima elongata.*

Conclusions

Vegetable processing generates a substantial quantity of solid waste and its disposal affects the environment. Vegetable processors need to follow multifaceted strategies to handle the waste to transform it from liability to asset. The waste generation needs to be reduced by using efficien technologies. There is an opportunity to recover the by-products specially those having nutraceutical and functional properties. The waste can also be transformed to feed for cattle, fish pig, and poultry. The bioenergy, in the form of biogas and ethanol, is promising area to meet the requirement of the vegetable processing unit itself and also for general use. Fast composting with suitable microbes and worms has great potential to meet the growing needs of organic agricultural produce. A part of the solid waste left unutilized can be disposed off by suitable means like incineration and land filling

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Part IV

Product and Food Plant Safety and HACCP

Chapter 22

Controlling Food Safety Hazards in the Vegetable Industry—The HACCP Approach

Luke F. LaBorde

Introduction

All too often the public is subjected to alarming news reports about the latest foodborne illness outbreak or product recall. Although only a tiny fraction of food products are involved in these events, consumer confidenc in the safety of our food supply is at an all time low. The problem of food safety is by no means insignificant The Centers for Disease Control and Prevention (CDC) estimates that each year approximately 76 million individuals or approximately 1 out of every 4 people in the United States acquire a food-related illness (Mead et al. 1999). Most cases involve only minor digestive symptoms but severe cases result in approximately 325,000 hospitalizations and 5,000 annual deaths. The proportion of total foodborne illnesses traced to vegetables and fruits, in particular those that are eaten raw, has increased steadily in the last few decades. In the 1990s, produce-related cases increased 12-fold (Sivapalasingam et al. 2004). Between 1997 and 2005, the frequency with which produce has been identifie as causing illness outbreaks has more than doubled (Doyle and Erickson 2007).

Epidemiologists cite a number of reasons for this disturbing trend (Lynch et al. 2009).

Within the last few decades, there has been a dramatic shift in consumer preference away from thermally processed vegetables (canned or blanched/frozen) toward ready-to-eat, fresh, or fresh-cut products. Consumers are at a higher risk for illness from these products since heat treatments that could once be relied upon to kill human pathogens are no longer part of the process.

Fresh-cut ready-to-eat products require more handling and preparation steps. There are now more opportunities for contamination during handling, preparation, and distribution.

The desire for fresh produce throughout the year has made it necessary for northern regions to bring products in from distant parts of the globe. The complexity of the supply chain makes it more difficul to assure that adequate sanitation practices for growing, packing, and processing foods are followed.

Advances in medical technology and public health control have extended the life span of older people and those with chronic illnesses. A side effect of some treatments is impairment of the immune system, which results in fewer defenses against human pathogens in food.

Beyond the suffering of those afflicte with a foodborne illness, there are severe economic consequences to society. Total costs in terms of medical costs, productivity losses,

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

and costs of premature deaths are estimated to be several billion dollars each year (Roberts 2007). Food companies also pay a tremendous price when costs for expensive laboratory tests, discarded products, increased insurance premiums, lawsuit settlements, and lost business are factored in.

The HACCP Concept

Hazard Analysis Critical Control Point or HACCP (pronounced "hassip") has emerged as the gold standard for protecting consumers from foodborne illness.

HACCP is a food safety system in which potential food safety hazards are considered at each step of a manufacturing process and control measures are specifie to prevent or reduce food safety hazards to acceptable levels. A HACCP plan is a written document based on established HACCP principles that describe how control measures will be implemented and what procedures are necessary to make sure that the control measures are consistently working as designed (Scott and Stevenson 2006). Definition of some of the terms used in HACCP are presented in Table 22.1.

HACCP originated during the space race of the 1960s. The Pillsbury Company working together with the US Army Natick Laboratories and the National Aeronautics and Space Administration (NASA) tried to develop a system that would assure 100% safety of food products supplied to astronauts while confine in a small space capsule. Pillsbury quickly realized that their existing quality control system, which was based on periodic end product testing, was not adequate to meet this goal. They concluded that the only way to prevent foodborne illness during long space flight was to develop a system that proactively identifie potential food safety hazards at each step of the production process. Pillsbury thereafter applied the HACCP system to the rest of their products.

Soon after a 1985 National Academy of Sciences report recommended that HACCP be incorporated into food regulations, the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) recommended uniform procedures, known as the seven HACCP principles, for developing HACCP plans (NACMCF 1998). In 1997, the World Health Organization's (WHO) Codex Alimentarius Committee on Food Hygiene endorsed HACCP and developed guidelines for international trade (WHO/FAO 1997). Since then government agencies worldwide have recognized HACCP as the most effective system available for controlling food safety hazards. HACCP is mandated in the United States by the Food and Drug Administration (FDA) for seafood (Federal Register 1995) and juice (Federal Register 2001) products and by the United States Department of Agriculture (USDA) for meat and poultry establishments (Federal Register 1996).

The reasons for the worldwide endorsement of HACCP are evident when considering the advantages it has over the traditional inspection-based system.

HACCP is proactive instead of reactive. In the traditional system, finishe product testing is relied upon to demonstrate absence of contamination. If contamination is detected after testing, the usual recourse for a food company is to destroy or recall the product. In HACCP, food safety is built into the process well before production begins and is managed at each process step on a continuous basis. An unsafe practice or condition is, therefore, prevented or corrected before the finishe product is shipped. This proactive approach can save considerable amounts of time and money in the long run.

In HACCP the manufacturer is primarily responsible for food safety. HACCP shifts food safety responsibilities away from government inspectors and toward

Table 22.1 Definition of terms used in HACCP

Term	Definitio
Control	The state in which correct procedures are being followed and criteria for safety are met.
Control measure	Any action or activity that can be used to prevent, eliminate, or reduce a hazard.
Control point (CP)	A step at which a hazard must be controlled. A CP must be controlled through prerequisite programs or as a critical control point (CCP).
Corrective action	Procedures followed when a deviation from a critical limit occurs.
Critical control point (CCP)	A process step where a significan hazard must be controlled.
Critical limit	A maximum and/or minimum value to which a biological, chemical, or physical parameter must be controlled at a CCP to control a significan hazard.
Hazard	Any biological, chemical or physical substance, object, or property which may cause a food to become unsafe for human consumption in the absence of its control.
Hazard Analysis	The process of collecting and evaluating information on hazards associated with each step of the process.
Monitoring	The act of conducting a planned sequence of observations or measurements to assess whether the criteria for each of the critical limits are met and the CCP is successfully under control.
Risk	The possibility, based on probability of occurrence and severity of outcome, of suffering harm from a food safety hazard.
Prerequisite programs	Company policies and procedures that provide the basic environmental and operating conditions necessary for the production of safe foods.
Significan hazard	A potential food safety hazard that, because it is sufficientl likely to occur and is capable of causing severe illness or injury, warrants control in the HACCP plan.
Validation	Collection and evaluation of scientifi and technical information to determine whether the HACCP plan is capable of effectively controlling hazards.
Verificatio	Activities other than monitoring that determine the validity of the HACCP plan and that the system is operating according to the plan.

the manufacturer. HACCP does not completely replace the inspection systems but it makes the inspection process more efficien since the focus can be on reviewing records that document a company's continuing commitment to food safety control measures rather than relying entirely on random visual inspections and periodic end point product testing.

HACCP takes a systematic approach to food safety. This means that potential hazards are evaluated at each process step in the fl w of food and the most significan hazards are regularly monitored. The food manufacturer can then prioritize and designate resources to control hazards at critical control points (CCP) in the process where control is essential to keep food safe.

HACCP doesn't end once the plan is written. Regular monitoring and verifica tion activities are required to make sure the plan is functioning well. Updates to the plan are made any time the process, product, or processing environment changes or when new scientifi information emerges on how best to control food safety hazards.

As the number of foodborne illness outbreaks continues to climb, we can expect to see a shift away from the traditional government inspection system and toward government mandated HACCP. Wherever regulations are absent, the private sector will no doubt increase their scrutiny over their suppliers by requiring HACCP plans as a condition of purchase.

Prerequisite Programs

HACCP is not a stand-alone system. It should instead be viewed as one part of an overall food safety control system Figure 22.1. HACCP is the highest level of food safety control where potential hazards that are likely to occur and can severely affect the health of consumers are identifie and controlled. Underlying the HACCP plan, there must be a strong foundation of prerequisite programs and company-wide commitment from both management and workers to produce safe food products.

Prerequisite programs describe company policies and procedures that provide the basic environmental and operating conditions necessary for the production of safe and wholesome foods (Sperber et al. 1998). They are usually managed as facility-wide or company-wide programs and therefore may apply across all product lines. Effective prerequisite programs include clear instructions, written as standard operating procedures (SOP), for what procedures need to be performed, at what frequency, who has responsibility for carrying them out, and what actions are required if they are not performed according to plan. Compliance with standards should be regularly reviewed through checklists and self-inspections and policies revised when necessary for completeness and effectiveness.

An occasional deviation from requirements specifie in a prerequisite program is generally not expected to have an immediate, or critical, effect on the safety of the product. However, the importance of strong prerequisite programs cannot be understated. They provide a solid foundation for the HACCP plan by controlling the majority of low-risk potential hazards that occur in a food plant. Well-designed prerequisite programs make the food safety plan more manageable since they minimize the number of CCP necessary in the HACCP plan. The process for choosing between a prerequisite program and a CCP to control a potential food safety hazard is discussed later in this chapter.

The day-to-day activities, policies, and procedures designed to prevent food contamination in packing houses, processing facilities, and warehouses can be categorized under prerequisite program titles listed in Table 22.2. The following are brief descriptions of some typical prerequisite programs.

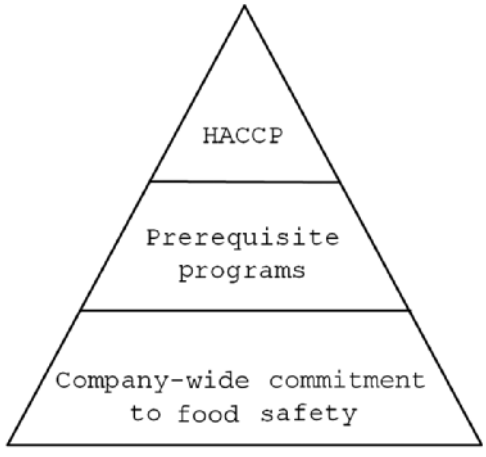

Figure 22.1 HACCP within a total food safety plan.

Table 22.2 Common prerequisite programs

HACCP prerequisite programs
Buildings and grounds maintenance
Raw materials specification
Good agricultural practices
Receiving and storage
Transportation
Water and ice safety
Employee hygiene
Equipment preventive maintenance
Heating/ventilation/air conditioning (HVAC)
Maintenance of hand-washing and toilet facilities
Cleaning and sanitizing
Laboratory testing
Chemical control
Glass control
Foreign material control
Allergen control
Pest control
Waste disposal
Labeling
Product traceability and recall
Consumer complaints
Food defense/security
Employee training

Grounds and Buildings

The goal of a grounds and buildings prerequisite program is to prevent potential contaminants from entering a food establishment and coming into contact with food. Areas of concern include the design and layout of the grounds, the condition and maintenance of buildings where food is handled, processed, or stored, and the potential for neighboring properties to contribute to contamination. Regularly scheduled self-inspections are necessary to uncover conditions that could lead to contamination or encourage microbial growth. For instance, excessive litter and trash or tall grass and weeds attract and provide hiding areas for pests that can spread harmful microorganisms. The structural integrity of roofs, windows, and entrances are areas of concern since these are the firs line of defense for keeping out dust, water, and pests. Policies for employee and equipment traffi patterns need to be established to prevent cross-contamination between raw material areas and finishe products. This program should also include a master cleaning schedule that specifie which areas need cleaning, how and when they are to be cleaned, and who is responsible for each task.

Equipment Design and Maintenance

An equipment prerequisite program should provide clear specification and policies for the design, use, and maintenance of equipment that comes into contact with food. Standards for the type of materials suitable for food contact surfaces include using materials that do not absorb water, are resistant to corrosion, and do not chemically react with foods or cleaning chemicals to produce harmful substances. Equipment should be designed so that it is durable under normal conditions of use, constructed to ensure effective and effi cient cleaning, and so that it does not become a source of microbial, physical, or chemical contaminants such as dripping condensate, metal fragments, lubricants, or fuel. Written schedules should be developed for cleaning, sanitizing, maintaining, and calibrating all equipment that has an impact on the safety of food products. Glass, in food-handling areas, should be avoided if at all possible. For instance, glass thermometers should be replaced with shatterproof plastic or stainless steel versions and glass lights should be replaced with shatterproof bulbs. When glass materials must be used, as is the case when products are packed in jars or bottles, a separate glass control prerequisite program is necessary. The program should specify handling and inspection procedures in addition to clean up procedures, should breakage occur.

Employee Hygiene and Personal Practices

Plant personnel are often the most important source of biological, chemical, and physical hazards in food plants. Policies and procedures must be in place to ensure that everyone entering food areas follows hygienic practices that prevent food contamination. This includes line workers, supervisors, top management, maintenance workers, and visitors. Workers must be regularly monitored to make sure that jewelry, coins, paper clips, and other personal items are not brought into areas where food is exposed. An employee hygiene program sets standards for general personal cleanliness such as wearing proper work attire and using hair restraints. Hygienic standards should include keeping workers away from food-handling areas who show symptoms of diseases that can be transmitted through food (e.g., fever, vomiting, jaundice) or who have infected wounds or sores on the hands, arms, and face.

Frequent hand washing is the best defense against food contamination and it should be mandatory that every worker who handles food be trained to understand how and when to properly wash their hands. When gloves are required, a written policy should clearly

describe when and how they should be used and how often they should be changed.

Water and Ice Safety

Water or ice that contacts food, food contact surfaces, or is used by employees for drinking or hand washing should be tested regularly to assure that it is free from harmful microorganisms and chemicals. Although water may be potable (safe to drink) when it enters the facility, diligence is required to prevent opportunities for cross-contamination to occur within the building plumbing system. A water safety prerequisite program should describe procedures necessary to prevent backfl w of contaminated water (e.g., sewage, chemicals, recycled water) into the potable water supply and vacuum breakers and check valves need to be checked periodically to make sure that they are operating correctly and air gaps on faucets, holding tanks, and cleaning equipment should be in place at all times.

Receiving and Storage of Raw Materials

Raw materials and ingredients entering the food plant have the potential to bring in contaminants that can compromise the safety of food products. Inspection criteria may include incoming trailer and pulp temperatures, packaging integrity, signs of pest activity, evidence of physical hazards such as stones or metal fragments, and general signs of spoilage. It is common practice to require vendors to include letters of guarantee or certificate of analysis with each shipment that attest to the safety of their product.

Since most vegetables are highly perishable, continuous temperature control is essential to minimize microbial growth during storage. Policies and procedures for cold storage should include daily monitoring of cooler temperatures, maintenance and cleaning of refrigeration units, and firs in firs out (FIFO) inventory management.

Chemical Control

Cleaners, sanitizers, pesticides, fuels, and lubricants are potential chemical hazards if they are not used properly. A chemical control policy prevents food contamination by establishing procedures for their safe use. Toxic chemicals should be restricted to authorized individuals who have been trained on the proper use of toxic chemicals and these should be stored in secured locations which are physically separated from food areas. Original and working containers should be properly labeled so that the risks associated with their use are clear to the user. A material safety data sheet (MSDS) that is readily accessible to all employees should be kept on fil for each purchased chemical.

Pest Control

Insects, rodents, and birds entering food-handling areas can carry microorganisms that cause human disease. The general housekeeping procedures described in a grounds and building prerequisite program serve to control pests by denying them food sources and harborage sites. A pest control program, whether conducted in-house or contracted to a pest control service, should include specifi procedures for placement and monitoring of bait stations, traps, and insect electrocution devices. Access to chemicals should be restricted to authorized individuals who have been trained on their use and who understand the risk that pesticides present to exposed food products.

Traceability and Recall

Every food company should be prepared to trace the origin of raw materials and ingredients back to their source. Although a traceability program does not directly prevent product contamination, it can protect a food company by limiting the extent of a recall and therefore the expenses that may be incurred

as a result. The US FDA has issued regulations under the Bioterrorism Preparedness and Response Act of 2002 that require food processors, packers, and shippers to be able to document each supplier of raw materials and ingredients as well as each buyer of the finishe product.

Developing a HACCP Plan

Because a high level of thoroughness is necessary to evaluate and control all food safety hazards, the stepwise approach recommended by NACMCF as shown in Figure 22.2 should be used. In the sections that follow, the fi e preliminary steps and the seven HACCP principles are described.

The Five Preliminary Steps

HACCP preliminary steps are used to determine who will be responsible for developing the plan and what product and process information will be needed to evaluate food safety risks.

Assemble the HACCP Team

The firs preliminary step is to assemble a team of individuals that will write the plan. A clear understanding of the people responsible for the plan will help to ensure continuous oversight and accountability. The best HACCP teams draw from a diverse array of in-house talents and expertise. Ideally, the team should consist of representatives with experience and knowledge in quality assurance, engineering, sanitation, food microbiology, and plant operations. At least one representative from the upper management is recommended, since repairs or investment in new facilities and equipment may be necessary. In very small plants, it is possible that only one or two individuals are available to write the plan. In this case, outside resources such as consultants, trade or professional associations, or university extension specialists may be brought in to join the team.

Describe the Food and its Distribution

The physical, chemical, and microbiological characteristics of the ingredients and the fin ished food product need to be well understood since this information will be used later to evaluate food safety risks at each process step. The name of the product and a list of all ingredients used to prepare it should be included in the description. These might include processing aids, water sources, packaging

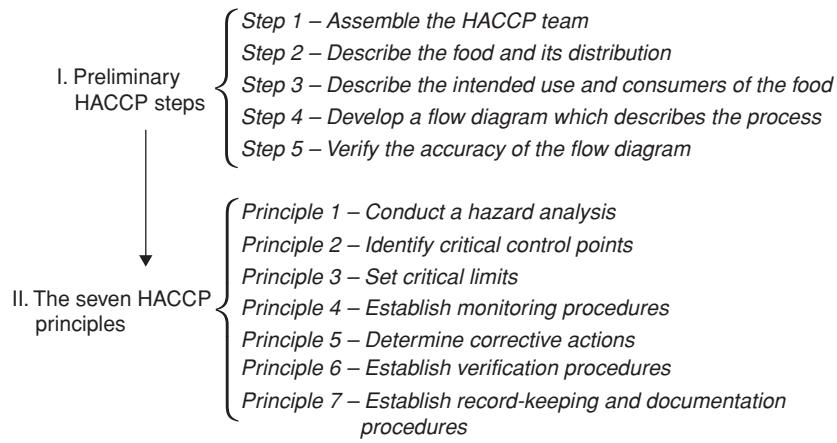

Figure 22.2 Steps required for writing a HACCP plan.

materials, and any toxic chemicals used in or around food ingredients and finishe products. For example, any preservative, fl vor, color, and texture control agents included in the formulation should be listed as well as cleaners, sanitizers, and pesticides used in the processing environment.

A variety of questions come up when packaging and distribution requirements are considered. Will it be packaged into hermetically sealed cans or jars or fille into boxes, plastic bags, or trays. Will it be vacuum packaged? How will the product be shipped and to whom? Will it be shipped directly to a retail outlet, a food service operation, to schools, daycares, nursing homes, or to another operation for further processing? Are there any special distribution requirements such as minimum and maximum allowable temperatures or minimum delivery times?

Describe the Intended Use and Consumers of the Food

Indicate how the product is intended to be used by the consumer and what information they need to know to keep it safe. For instance, is the product intended to be sold as a ready-to-eat food that can be eaten with no further preparation? Or is the consumer likely to sort, wash, and cook it before eating? What is the predicted shelf life? Are there any special labeling requirements that consumers need to know such as instructions for use, use-buy dates, or home storage requirements? Some groups of people, known as susceptible populations, are especially susceptible to foodborne disease. These include the very young, the elderly, pregnant women, and individuals whose immune system is weakened by chronic diseases such as AIDS or cancer or medical procedures such as organ transplants. If the product is targeted to these groups, it may be necessary to include extra food safety control measures in the HACCP plan.

Develop a Flow Diagram which Describes the Process

The fl w diagram graphically describes all steps in the process that are under direct control of the establishment. It is very important to account for all ingredients and process steps since this information will be used later to systematically identify potential hazards. A complete diagram includes all unit operations as well as receipt of raw materials, ingredients, packaging materials, and process chemicals. Storage and transportation steps must be included since these may also affect the safety of the product.

Verify the Flow Diagram

A process fl w diagram written in a meeting room may not be as accurate or up-to-date as desired. The HACCP team should check the accuracy and comprehensiveness of the diagram by going into the plant and confirmin that it follows the actual fl w of food as ingredients are transformed into finishe product. On-site verificatio of each process step will help the team understand time and location relationships between steps that will be useful later on in the hazard identificatio process. After the review is completed, any deficien cies should be corrected before proceeding to the seven HACCP principles.

The Seven HACCP Principles

Once the preliminary steps are completed, the HACCP team can begin working on the seven HACCP principles. These principles are a series of steps that are used to systematically identify hazards that need to be controlled in the HACCP plan, how those hazards will be controlled, what actions need to taken should a control method fail, and how verificatio and record-keeping procedures make sure the plan functions as intended and is well documented.

Conduct a Hazard Analysis

A food safety hazard is any biological, chemical, or physical substance, object, or property which may cause a food to become unsafe for human consumption in the absence of its control. Potential food safety hazards in vegetable production, packing, and processing environments are summarized in Table 22.3.

Biological hazards are harmful microorganisms capable of causing human disease. They include bacterial pathogens (e.g., *Escherichia coli* O157:H7, *Salmonella* spp., *Listeria monocytogenes*), viruses (e.g., Hepatitis A, Norwalk-like viruses), and microbial parasites (e.g., *Crytosporidium parvum*, *Cyclospora cayetanensis*, *Giardia lamblia*). Bacterial pathogens that originate in the intestinal tract of humans and animals are of greatest concern because they often fin their way into agricultural environments; many are capable of surviving and growing in foods, and some can persist for long periods of time in growing, packing, and processing environments. A more detailed discussion of microbial hazards associated with vegetable production and process is presented elsewhere in this book.

Chemical hazards are compounds that, if used improperly, can contaminate food and cause illness. These include pesticides, fuels, lubricants, cleaners, and sanitizers that are used to grow, pack, and process vegetables. Also included are foods that are capable of causing life-threatening allergic reactions in a small number of individuals. But more often, chemical hazards are associated with chronic illnesses that result after long-term exposure to toxic agents. For instance, some molds that grow on foods can release harmful toxins, known as mycotoxins, which are toxic or even carcinogenic.

Physical hazards are foreign objects in food that, although usually not life-threatening, can cause serious injury (cuts, punctures, broken teeth) to consumers. The list of physical hazards in harvesting, packing, and processing environments include wood splinters, stones, stems, jewelry, and personal items worn by food handlers, and metal fragments that can break off from machinery.

Potential hazards associated with each step of a process and method to control those hazards are collected and evaluated in the hazard analysis. Because the decisions made in the remaining HACCP steps are based on the results of the hazard analysis, it is essential that the team conduct a thorough and honest assessment of all possible hazards. The HACCP team must rely on their knowledge of the process, product, and processing environment to determine biological, chemical, and physical hazards that could occur at each process step in the fl w diagram. Since this is essentially a brainstorming step, the list could be quite large. Therefore, an important goal of this step is to prioritize hazards on the basis of two factors: how likely they are to occur and how severe the consequences would be to consumers in terms of illness or injury.

Figure 22.3 graphically illustrates the conceptual relationship that probability of occurrence and severity of outcome have on the level of risk. If a potential hazard has a low probability of occurrence and would result in only a mild outcome in terms of disease or injury, the hazard is considered a "lower risk" and it can be controlled at a process step known as a control point (CP). Control measures for CPs can be described in one or more applicable prerequisite programs. In contrast, a hazard that is more likely to occur and can cause severe illness or injury is considered a "higher risk." In HACCP, higher risk hazards are termed "significan hazards" and must be controlled in the HACCP plan at a CCP.

The dividing line between the two types of risks is seldom as clear as shown in Figure 22.3. The HACCP team must use the information gathered about the process and product during the preliminary steps as well as their own good judgment to decide how each hazard will be controlled. External factors may also play a role such as whether or not the

Table 22.3 Potential biological, chemical, and physical hazards occurring in vegetable fields, packing houses, and processing facilities

	Hazard		
Location	Type	Source	Prevention
Field	Biological	*Escherichia coli* O157:H7, *Salmonella,* hepatitis A virus in animal feces or on fingertip of harvesters	• No raw manure on field • Keep animals out of field • Adequate fiel sanitation units • Worker hygiene training
	Chemical	Pesticides, fuel, oil spills from fiel equipment	• Pesticide training • Maintain and repair fiel equipment
	Physical	Stones, insects, thorns in fields Wood splinters from fiel packing containers	• Sort/inspect produce before fiel packing • Use plastic harvest containers
Packing house	Biological	*E. coli* O157:H7, *Salmonella,* hepatitis A virus on fingertip of food handlers. *Listeria monocytogenes* cross contamination from standing water, dripping condensate, inadequately cleaned food contact surfaces. *Salmonella* in rodent feces.	• Adequate toilet/ handwashing facilities • Worker hygiene training • Keep floor dry, insulate overhead pipes • Keep work areas clean and dry • Clean/sanitize food contact surfaces • Implement a pest control program
	Chemical	Postharvest mold growth and mycotoxin formation. Unsecured containers of lubricants, solvents, paint	• Chill produce rapidly • Discard moldy produce • Store toxic chemicals in a locked cabinet
	Physical	Splinters from wood pallets, metal fragments from equipment; unprotected glass windows and light fixtures food handlers wearing jewelry, watches, and other personal items.	• Use plastic pallets and containers to hold food • Use shatter proof glass or protect windows and lights from breakage • Do not allow workers to bring personal items in food areas
Processing facilities	Biological	*E. coli* O157:H7, *Salmonella,* hepatitis A virus on fingertip of food handlers. *L. monocytogenes* cross contamination from standing water, dripping condensate, inadequately cleaned food contact surfaces. *Salmonella* in rodent feces.	• Adequate toilet/ handwashing facilities • Worker hygiene training • Clean/sanitize food contact surfaces and process environment • Implement a pest control program • Heat process or disinfect to kill pathogens
	Chemical	Pesticides, cleaners, fuels, lubricants. Sanitizers not approved for food contact surfaces. Human allergens from ingredients or process cross contamination	• Purchase only chemicals approved for use in foods or on food contact surfaces and follow label directions • Label foods for presence of food allergens
	Physical	Metal fasteners, glass windows and light fixtures jewelry, watches, and other personal items	• Use shatter proof glass or protect windows and lights from breakage • Prohibit personal items in food areas

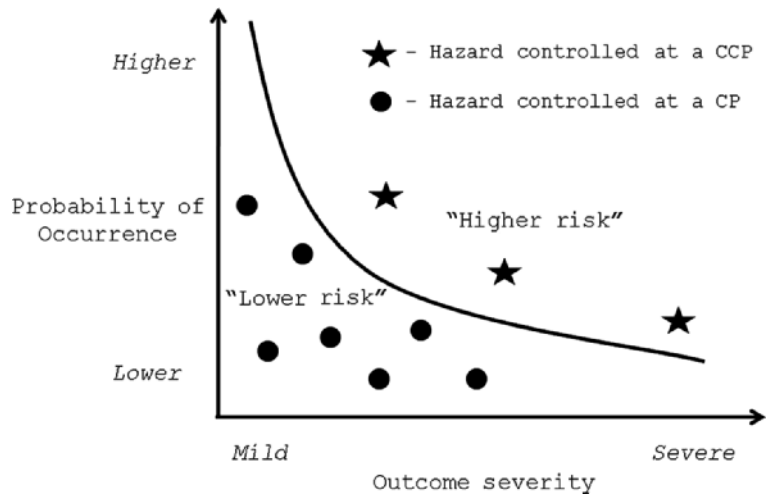

Figure 22.3 Relationship between hazard probability of occurrence and severity of outcome on food safety risk level.

product or process is associated with a history of outbreaks or recalls. It may also be the case that the level of risk and appropriate control measures are mandated by government regulations or buyer requirements.

The hazard analysis provides an excellent opportunity to systematically evaluate the effectiveness of existing prerequisite programs for controlling "lower risk" hazards. It should become clear during the discussion of the remaining HACCP steps that failure to control significan hazards at CCPs has many more consequences than that for prerequisite programs. Diligent efforts to strengthen prerequisite programs have long-term benefit because fewer significan hazards will be identifie in the hazard analysis and thus the number of CCPs will be reduced.

Identify Critical Control Points

A CCP is a process step where a significan hazard can be prevented, eliminated, or reduced to an acceptable level. Each significan hazard identifie in the hazard analysis must be controlled at a CCP. The HACCP team must therefore decide which process step is the most appropriate CCP.

The ideal CCP should be easy to monitor on a continuous basis so that a hazardous situation can be quickly detected and an immediate correction can be made to the process. It should also be the last step at which a control measure exists that will eliminate the hazard or reduce the likelihood of its occurrence to an acceptable level. For example, a CCP to control metal contamination is ideally located at a process step once the product has been packaged and after which further metal contamination is extremely unlikely. Some examples of process steps that have been used as CCPs in HACCP plans are blanching, pasteurization, acidification and metal detection.

Decision trees have been developed to assist HACCP teams in determining CCPs (NACMCF 1998). An adaptation of the decision tree is shown in Figure 22.4.

It is important to realize that if a control measure for the hazard does not exist at some point in the process, then the step, process, or product must be modified The HACCP team will then have to use their own knowledge of the process and product or seek outside help to come up with process modification that will adequately control the hazard. This sets HACCP apart from other food safety control

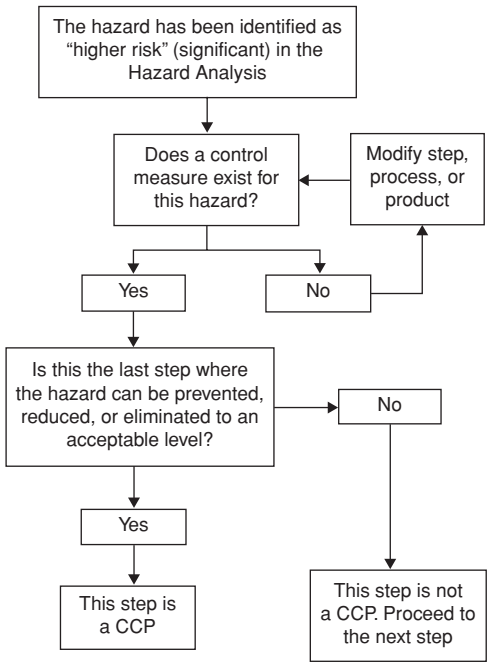

Figure 22.4 Example of a decision tree used to locate a critical control point for a significant hazard.

systems. If the process cannot be made safe, then the product should not be made!

Set Critical Limits

A critical limit is a maximum and/or minimum value to which a biological, chemical, or physical parameter must be controlled at a CCP to prevent, eliminate, or reduce to an acceptable level the occurrence of a significan food safety hazard. While a CCP identifie the step where a hazard is controlled, the critical limit provides the range of values that will successfully carry out the CCP.

By definitio each CCP has one or more control measures that will assure that a hazard is prevented, eliminated, or reduced to an acceptable level. For each control measure, the HACCP team must specify one or more critical limits. Critical limits are ideally the minimum or maximum numerical values for time, temperature, pH, fl w rate, sanitizer concentration, or other variables that affect the safety of food. When a critical limit is successfully achieved, the CCP is said to be "in control." If a deviation from the critical limit occurs, the CCP is "out of control" and action must be taken to correct the situation as soon as possible.

Determining a critical limit requires knowledge of the hazard and technologies available for achieving control. For instance, a thermal process treatment such as blanching or retort sterilization would require knowledge of temperature and time conditions necessary to achieve an acceptable reduction in harmful microorganisms. A disinfectant wash treatment for a fresh-cut vegetable would similarly require knowledge of adequate concentrations and exposure times necessary to achieve desirable microbial reductions. This data may be obtained from the scientifi literature, regulatory guidelines, or from experts in the field If data are not available, original research may be necessary to establish parameter for achieving desirable treatment results.

Establish Monitoring Procedures

Monitoring is the act of conducting a planned sequence of observations or measurements to assess whether the criteria for each of the critical limits are met and the CCP is successfully under control. Monitoring tracks the operation of the process and determines if a process adjustment is needed. It also provides written documentation of the process control system. The ideal monitoring procedure provides instant results so that immediate action can be taken if the critical limit is not achieved. Monitoring procedures should include who will do the monitoring, what is actually monitored, and how often it has to be done.

Monitoring can be either continuous or discontinuous. Continuous monitoring can be accomplished automatically by using equipment or sensors. For example, a continuous fl w blanching system in a vegetable freezing operation or a steam retort for sterilization

of canned vegetables provides continuous and automatic updates of temperatures and fl w through rates. Discontinuous monitoring uses visual observations or relies on predetermined sampling procedures. Periodic measurement of the concentration and pH of a vegetable disinfectant wash solution are examples of discontinuous monitoring. During the ingredient receiving step, the presence of a certificat of analysis or letter of guarantee indicating that incoming vegetables are free of pathogens could also serve as a monitoring step. Pathogen testing of ingredients upon receipt is seldom desirable as a monitoring procedure since results might not be available until long after the product has been shipped and corrective action is possible.

Determine Corrective Actions

If monitoring activities indicate that a critical limit is not being met and that a CCP is out of control, actions must be taken to immediately correct the process. The HACCP team must, therefore, determine corrective actions well in advance of a problem so that immediate action can be taken that will limit the amount of product exposed to the uncontrolled hazard. Corrective action procedures should describe what should be done with product that fails to meet the critical limit and what actions should be taken to prevent further problems with the process.

For corrective actions to be effective, employees must be given a sufficien level of authority to stop the process, retain product that is not in compliance, and adjust the process while holding the product. If corrective actions become too frequent or if they are not practical, then the HACCP team may need to reevaluate the control measures associated with the CCP to more effectively prevent repeated occurrences of the hazard.

If, for example, monitoring of blanch water temperature indicates that the temperature has fallen below the critical limit of say 75°C, an immediate corrective action would be necessary. One option would be to isolate all products that passed through the blancher since the last acceptable temperature reading, adjust the blanch temperature to the correct value, and then pass the affected products through the blancher again. The CCP would then be under control and the safety of the products assured. The value of achieving a high level of process control is apparent in this case since this corrective action would likely have an adverse affect on product quality.

Establish Verification Procedures

As mentioned earlier, HACCP is a dynamic system of food safety controls that is subject to regular change. The purpose of the verifica tion step is to develop procedures for periodically reviewing CCP, critical limits, monitoring activities, and other parts of the HACCP plan to make sure it is operating as intended and is effectively reducing food safety risks. Regular reviews of monitoring records are important to verify that they have been properly completed. Calibration of monitoring devices and periodic microbial testing of raw materials, ingredients, finishe products, and food contact surfaces are other examples of verifi cation activities.

An important part of verificatio is validation. Validation means obtaining evidence that all elements of the HACCP plan are actually effective in reducing food safety risks. An example of HACCP plan validation is to regularly review the latest scientifi information on minimum heat or chemical disinfection parameters to determine if the procedures used in the plant are actually effective in reducing pathogen levels to acceptable levels. When research is lacking, a company might consider conducting their own laboratory experiments or supporting outside researchers to test the validity of their control measures. For industries currently covered under federal or state HACCP regulations, specifi procedures may be required to validate the HACCP plan.

Establish Record-Keeping and Documentation Procedures

Record keeping is perhaps the most difficul part of HACCP and it is no wonder that some have insisted that HACCP really stands for "Horribly Agonizing and Completely Complicated Paperwork!" But record-keeping and documentation procedures are increasingly relied upon by government inspectors and customers as proof that all foodborne hazards have been considered and are adequately controlled. Good record keeping is also valuable to observe trends that might lead to a hazardous situation so that corrective actions can be taken before a serious problem occurs. A paper trail that accounts for the source of raw ingredients and the destination of shipped product is also a way to protect a company from unwarranted blame for an outbreak or recall.

Records to include in a HACCP plan include information acquired in the preliminary steps, the hazard analysis, and procedures and results for monitoring, corrective actions, and verificatio activities. It is also important to keep records of instrument calibrations, microbial testing results, and reviews of the entire HACCP plan. Specifi requirements for what kind of HACCP records need to be kept and for how long they should be kept may be part of government regulations or customer requirements.

Use of HACCP in the Vegetable Industry

HACCP in its original form was designed for the food manufacturing industry where process steps such as blanching, retorting, and pasteurizing are capable of consistently achieving large reductions in human pathogens. The high level of process control in the vegetable canning and freezing industries lends itself well to the stringent HACCP requirements for continuous monitoring, corrective actions, verification and record keeping.

Opportunities for fresh produce to become contaminated on the farm, in the packing house, and during fresh-cut processing are numerous (Beuchat and Ryu 1997; Suslow et al. 2003; Beuchat 2006; FDA 2008) and some pathogens associated with fresh produce are capable of causing severe illness or even death. It is, therefore, likely that a number of biological hazards would emerge as "significant during the course of hazard analysis conducted at a farm or a packing house. Surface sanitization treatments are capable of reducing microbial loads on whole and fresh-cut vegetables (Gorny 2001). However, none are completely effective in eliminating human pathogens (Parish et al. 2003). Therefore, other control measures before this step, such as prohibition of raw manure on fields proper harvester hygiene practices, and use of uncontaminated irrigation water, would be necessary to prevent the presence of pathogens on the finishe product. The absence of validated control measures to prevent, eliminate, or reduce significan hazards to acceptable levels at single process steps has led many to question the appropriateness of applying HACCP principles on the farm (Sperber 2005).

This situation has inspired "HACCP-based" approaches that rely on the cumulative effect of multiple, but only partially effective, control measures at more than one process step. Rushing et al. (1996) proposed a generic HACCP plan for fresh market tomatoes that included cleaning and inspection of packing bins, quality maintenance of dump tank water, and hand-sorting steps. Leifert et al. (2008) recognized that complete control of food safety hazards is unlikely at any single step in a farm operation and recommended replacing the term CCP with "risk reduction point" (RRP). RRPs were proposed for storage and application of animal manure, composting, and use of irrigation water.

There is no doubt that on-farm food safety practices and packing house sanitation and

hygiene procedures contribute to the safety of the product. But it seems unlikely that these activities could be justifie as HACCP control measures, since continuous monitoring procedures, minimum and/or maximum values for critical limits, and verificatio procedures would be difficul if not impossible to implement according to the original NACMCF guidelines. Moreover, these activities are not a part of the process fl w but instead are part of the basic environmental and operating conditions necessary for the production of safe and wholesome food. As such they are more appropriately conducted within prerequisite programs.

In order to avoid diluting the meaning of the word HACCP, it has been suggested that this term should be reserved for food safety programs that incorporate all of the seven HACCP principles. Anything less than this may lead to misunderstandings of the level of food safety assurance that is achievable (Untermann 1999).

A more widely utilized approach for controlling pre- and postharvest food safety hazards has been to implement a set of agricultural food safety control measures known as good agricultural practices (GAP). GAP programs specify farm food safety practices and documentation procedures for minimizing contamination from domestic and wild animal feces, adjacent properties, irrigation water, and food handlers. GAP are discussed in more detail elsewhere in this book.

Voluntary GAP guidelines for farm and packing house operations were firs issued by FDA in 1998 (FDA 1998). Since then, commodity-specifi food safety guidelines have been developed for several crops including tomatoes (Gombas 2008a), melons (Gorny 2005), leafy greens (Gombas 2008b), and mushrooms (AMI 2009). Wholesale buyers of fresh produce are acutely aware of their own liability in the event of a food safety incident and are increasingly demanding that their grower suppliers submit to regular third-party farm inspections to verify compliance with established standards.

GAP programs have adopted many of the positive attributes of HACCP such as accountability, monitoring, corrective actions, verification and documentation. But they are not HACCP control measures as define by NACMCF and instead should be viewed as prerequisite programs. Consumers must realize that complete elimination of food safety risks associated with fresh and fresh-cut produce is not possible until process technologies advance to the point at which HACCP is fully applicable to pre- and postharvest sectors of the vegetable industry.

Summary

The underlying concept behind HACCP is that experience and scientifi data must be used to determine process-specifi food safety hazards and appropriate, verifiabl control measures. HACCP has been proven to be the international gold standard for protecting consumers from foodborne illness and injury. It also protects the food industry from the economic consequences of a recall or outbreak. Government agencies worldwide have endorsed the HACCP approach for keeping foods safe.

Getting ready for HACCP should be a top priority for every food company. It is highly probable that recalls and outbreaks associated with vegetables and other food products will continue to occur and that HACCP requirements for food processors will continue to become a necessary part of doing business. There is much debate about the appropriateness of HACCP for the pre- and postharvest vegetable industry. Monitored and verifiabl control measures for farm hazards are difficul to achieve using a strict HACCP approach and may be more suitably controlled in a GAP program. Nevertheless, the HACCP principles of proactive identificatio of hazards and verificatio of appropriate control

measures will continue to influenc all food safety systems in the future.

Readers are encouraged to seek out HACCP courses offered by university extension, commodity groups, or consulting businesses. A high-quality course will generally take 2–3 days to provide more detailed coverage of the concepts presented in this chapter. Breakout activities are especially valuable since hands-on experience is the best way to acquire the skills needed to write a HACCP plan. After taking a HACCP course, participants should be well prepared to assemble a HACCP team and begin writing a HACCP plan that is specifi to their company's process and product.

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Chapter 23

Good Agricultural Practices and Good Manufacturing Practices for Vegetable Production

Elizabeth A. Bihn and Stephen Reiners

Introduction

Food safety is very important to both producers and consumers of foods. Some foods are processed according to validated and verifie protocols to ensure safety. Other foods, such as fruits and vegetables, are consumed fresh. Fresh produce (fruits and vegetables) consumption has been increasingly linked to foodborne illness outbreaks due to unintentional contamination with enteric human pathogens (USFDA 2001; Sivapalasingam et al. 2004; Vierk 2008). Unintentional contamination by *Escherichia coli* O157:H7, *Salmonella*, *Cyclospora*, and hepatitis A accounted for 96% of the outbreaks and 95% of the illnesses in reported produce-related outbreaks from 1996 to 2007 (Vierk 2008). Contamination of fresh and fresh-cut fruits and vegetables with pathogens can occur anywhere in the supply chain and once it occurs, it is difficult if not impossible, to remove (Beuchat and Ryu 1997; Gagliardi et al. 2003; Doyle and Erickson 2008). There are technologies, such as irradiation, that may offer protection in the future, but at this stage, preventing contamination by microbial pathogens is the most effective approach.

The production of fresh fruits and vegetables involves areas where human pathogens could be present and transferred to fresh produce resulting in contamination. Among these areas, the most likely potential mechanisms of *E. coli* O157:H7 and *Salmonella* contamination include soil amendments (i.e., manure, compost, etc.), water (irrigation or flood ing/runoff from adjacent land), direct contact with wildlife, airborne deposition from off-farm activities such as cattle/dairy and manure/composting operations, and postharvest handling (Beuchat and Ryu 1997; Beuchat 2002; Aruscavage et al. 2006; Brandl 2006; Brooks and Brashears 2008).

Produce outbreak investigations by local, state, and federal regulatory authorities have consistently linked pathogen contamination to the fiel or postharvest handling environment but have rarely provided definit ve evidence identifying exactly what factor or factors lead to the unintentional contamination (CDC 1997; Hilborn et al. 1999; Herwaldt 2000). More commonly, investigators compile lists of suspected risk factors that most likely contributed to the contamination event. Even when researchers deliberately expend time and effort looking for specifi human pathogens in the field they often cannot locate them (Riordan et al. 2001). The produce contamination may occur by a multitude of means and no means can account for contamination even among specifi produce pathogen pairings such as *E. coli* O157:H7

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

contamination of leafy greens or *Salmonella* spp. contamination of tomatoes. Growing and fiel conditions are infinitel variable and can vary dramatically between growing regions, resulting in variable rates of contamination (Miller et al. 2007). Furthermore, cultural practices used to grow, harvest, and pack even one crop may have a multitude of variations even within any given growing region resulting in different microbial risks (Miller et al. 2007). These situations are compounded by hundreds of commodities being grown with different physiological traits that make them more or less likely to be contaminated (Stine et al. 2005). Continued high profil foodborne illness outbreaks associated with produce consumption have increased the pressure on fresh produce growers to implement food safety practices and document their program for external entities such as buyers or third-party auditors. Recent peer-reviewed produce food safety research from academic and government institutions around the world has found numerous new potential sources, vectors, and means of unintentional contamination of produce (Miller et al. 2007; Doyle and Erickson 2008; Izumi et al. 2008; Orozco et al. 2008). This new scientifi data coupled with a lack of definit ve information as to the causes of recent produce-associated foodborne illness outbreaks create a problem for produce growers and postharvest operators. The pressure to develop, implement, and document produce safety practices is high but it is not always evident what practices will most effectively reduce the risks that exist. It is particularly frustrating when current scientifi research cannot provide a clear and decisive road map for produce safety.

This chapter focuses on vegetable production as it relates to food safety, although many of the same issues face fruit growers. Our goal is to increase understanding of produce safety issues and guide the practical implementation of food safety practices on farms and in packinghouses based on current scientifi data and an understanding of vegetable production. Protecting vegetables from contamination is as complex as the food system that is required to grow, harvest, store, transport, and market the commodities. In addition, there are risks introduced by consumers. Since growers cannot control fresh produce through the entire food system, they must focus on identifying and controlling risks that exist on the farm and in the packinghouse. This chapter limits the discussion to the following areas: record keeping, worker health, hygiene, and training, soil amendments and manure, production water, wildlife, postharvest water, cleaning and sanitation, pest control, traceability and recall, and crisis management. These are areas that have been identifie as significantl important through Delphi studies conducted for good agricultural practices (GAPs) related educational programs.

Clarifying the Language of Produce Safety

If produce safety were viewed as a continuum from farm to table, GAPs would be the firs step. The concept of GAPs was introduced in the 1998 publication by the Food and Drug Administration, Center for Food Safety and Applied Nutrition entitled *Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables*. The guide focuses on risk reduction, not risk elimination because "current technologies cannot eliminate all potential food safety hazards associated with fresh produce that will be eaten raw" (USFDA 1998). Since microbial contamination is difficul to remove once attached, the focus of GAPs is prevention. Fresh produce growers and packers directly impact safety through their actions and through the implementation of produce safety practices such as GAPs. The foundation of any produce safety program is a company-wide commitment that extends from the farm owner to the newest farm employee. Everyone in the produce operation impacts safety so everyone needs to

understand his or her role in the implementation of the produce safety plan.

Good Agricultural Practices

Food safety begins on the farm. GAPs are any agricultural management practice or operational procedure that reduces microbial risks or prevents contamination of fruits and vegetables on the farm or in the packinghouse. GAPs are not one set of define practices, but provide latitude for every vegetable grower to implement their own practices to prevent and minimize risks because each operation is unique and its practices may differ depending on many variables including cultural practices, location, and commodities grown. GAPs practices focus on fiel production including such areas as soil amendments, irrigation water sources, and worker training. As production and handling of fresh vegetables moves into areas where the level of control is higher than a fiel environment, good manufacturing practices (GMPs) should be applied.

Good Manufacturing Practices

GMPs in manufacturing, packing, or holding human food are codifie in the Code of Federal Regulation, Chapter 21, Part 110. Currently, fresh vegetables are exempted from this legal code as stated under Exclusions "(1) The following operations are not subject to this part: Establishments engaged solely in the harvesting, storage, or distribution of one or more "raw agricultural commodities" as define in section 201(r) of the act, which are ordinarily cleaned, prepared, treated, or otherwise processed before being marketed to the consuming public. (2) FDA, however, will issue special regulations if it is necessary to cover these excluded operations" (21 CFR, part 110). Though exempt from the regulation, GMPs outline important practices that should be followed to reduce chemical, physical, and microbial hazards that may be present in packinghouses, greenhouses, or other buildings with doors, windows, and screens that offer a level of control that is absent in fiel environments. There has also been discussion of removing this exemption, so it is important to understand GMPs and how they are applied to food production facilities.

Subpart headings present in the GMP Code include:

- Subpart A: General Provisions
  - 110.3 Definition
  - 110.5 Current good manufacturing practices
  - 110.10 Personnel
  - 110.19 Exclusions
- Subpart B: Building and Facilities
  - 110.20 Plant and grounds
  - 110.35 Sanitary operations
  - 110.37 Sanitary facilities and controls
- Subpart C: Equipment
  - 110.40 Equipment and utensils
- Subpart E: Production and Process Controls
  - 110.80 Processes and controls
  - 110.93 Warehousing and distribution
- Subpart G: Defect Action Levels
  - 110.110 Natural or unavoidable defects in food for human use that present no health hazard
- Subparts D and F are left marked as reserved.

Throughout this chapter, GMPs relevant to the production and packing of fresh vegetables are discussed. There is some level of overlap between GAPs and GMPs and since fresh produce operations are currently exempt from implementing GMPs, there was not a significan effort made to specificall categorize actions as one or the other. Effort was placed on explaining risks that may be present and providing examples of implementation during fresh vegetable production and packing to reduce these risks.

HACCP

As produce moves into more complex systems such as fresh-cut operations or

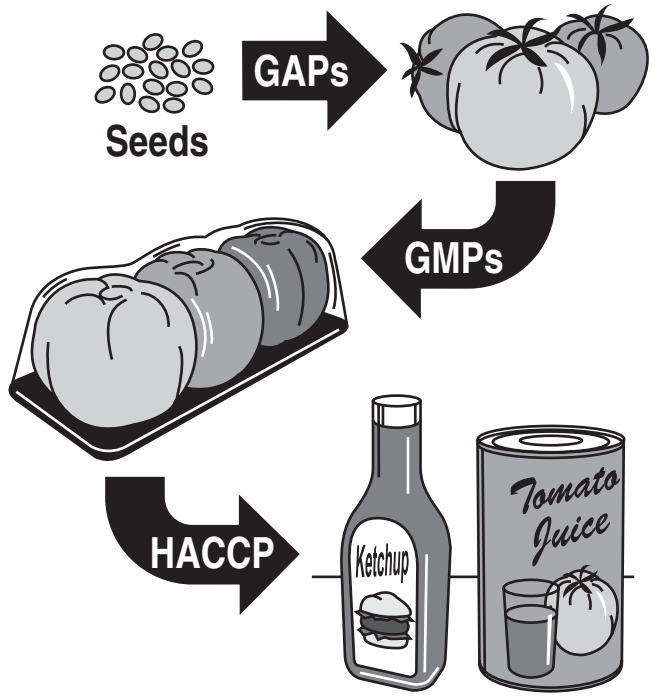

Figure 23.1 The progression of food safety programs from the field to the processing plant: good agricultural practices (GAPs) in the field, good manufacturing practices (GMPs) in the packinghouse, and Hazard Analysis Critical Control Point (HACCP) in the processing plant.

processing plants, the application of HACCP is appropriate (Figure 23.1). HACCP stands for Hazard Analysis Critical Control Point. This multifaceted system includes conducting a hazard analysis to identify the dangers that exist in processing, packaging, and selling foods (NACMCF 1998). Once the dangers are identified critical control points (CCPs) are established to control the risks. These CCPs defin procedures where control can be applied and food safety hazards can be prevented, eliminated, or reduced to acceptable levels. Rushing et al. (1996) reported on a HACCP program established in a fresh-market tomato packinghouse where a level of control over the operation was established and three CCPs were identified This same level of control is not attainable at the fiel level, which is why applying HACCP at the fiel level is difficult if not impossible.

This last statement is hotly debated as some feel the application of HACCP at the fiel level is completely appropriate even if no CCPs are identifie or can be established. HACCP is covered in detail in another chapter of this book, but the importance of including this discussion in this chapter is to make the argument that what really matters is implementing practices that improve food safety and definin expectations that are clearly communicated in a manner that is understandable throughout the food system.

Traditionally, processors are more familiar with food safety practices, including HACCP, than primary producers. As foodborne illness outbreaks and the desire to develop system-wide traceability have increased, buyers have started to request their suppliers to follow food safety practices so as to ensure that the product they are acquiring is safe. This results

in contracts and discussions where food safety language is included and buying requirements established. When contracts require farms to have a HACCP plan, it can create confusion because it is not clear what CCPs should be established. As an example, review the risk that wild deer presents. Fields are open to wildlife 24 hours a day, 7 days a week, and 365 days a year. Deer are known vectors of *E. coli* O157:H7 and they have access to production fields so they clearly represent some risk (Sargeant et al. 1999). Some level of control can be achieved, but to date there is no deer-proof fence or 24-hour-armed-guard system established on farms. What would be the critical limit for number of deer in a field What would be the corrective action if you exceeded the set limit? How would you know you exceeded the set limit?

The goal of all food safety programs is to improve safety by reducing or eliminating risks through the implementation of effective practices. Eliminating risks on the farm is not realistic at this point but reducing risks is certainly achievable (USFDA 1998). To achieve risk reduction at the farm level, it is important to provide guidance that is realistic and that resonates with those who must implement it, namely the growers. Promoting a system such as HACCP that requires a distinct level of control in a production system that is open and not feasibly monitored 24 hours a day adds confusion and frustration that is not productive and does not lead to the implementation of food safety practices that reduce relevant risks.

Record Keeping

Record keeping is a key to the implementation of GAPs and GMPs. The record keeping mantra is "If it is not written down, it did not happen." Record keeping is important for growers and packers because it allows them to follow their progress in implementing and updating produce safety practices. It is required if the farm or packinghouse needs to have a third-party audit to verify produce safety practices. In the event of a foodborne illness outbreak, record keeping will allow growers to provide detailed information to inspectors and show due diligence in the implementation of produce safety practices.

Development of a detailed farm food safety plan is the firs step to good record keeping. This plan should include standard operating procedures (SOPs) for critical actions to ensure they are done properly and result in effective risk reduction. All actions should be documented including worker training, water testing, manure applications, cleaning and sanitation practices, and pest control activities, to name a few. Template record-keeping sheets are available for free download from the National GAPs Program at http://www.gaps.cornell.edu/rks.html. The sheets can be readily modifie to meet individual farm needs and to include company logos if so desired.

A system for maintaining and retaining records should be developed so that they remain up-to-date and accessible. The National GAPs Program suggests maintaining records for a minimum of 2 years, although keeping records longer may be required by law or may be desirable for programs such as organic certification The record-keeping system should also include a standard operating procedure that explains when and how to properly dispose of old records. This will keep relevant records more organized and reduce the need for additional storage space.

Worker Health, Hygiene, and Training

Workers' health and hygiene practices cannot be emphasized enough when it comes to produce food safety. Often fruits and vegetables that are consumed raw are harvested by hand. In addition to being harvested, most packing facilities include at least one hand culling step and result in hand packing of the commodities into boxes that have been

assembled by hand. Anything that is on the hands of those who are involved in harvesting, culling, packing, or making boxes can be transferred to the fresh produce. These include viruses, bacteria, and parasites. Workers can shed pathogenic microorganisms through their urine, feces, saliva, and nasal mucus (Todd et al. 2008).

Every farm and packinghouse operation should have a written illness reporting protocol. Any worker who is ill should report the illness, it should be documented, and the worker should be sent home or placed in a job where there is no chance of contaminating the fresh produce, equipment, packaging materials, or other workers. Since many agricultural workers do not receive sick leave, they may be hesitant to report illnesses if it results in being sent home. Training needs to clearly outline the company illness reporting policy and explain the risks to fresh vegetables as well as to the workers if they continue to work while they are ill. In addition, supervisors should be trained to recognize signs of illness such as frequent trips to the toilet so they can assist employees that may be ill. It is important to keep ill workers away from fresh produce, but it is also important to understand that some workers may be asymptomatic carriers of pathogens, meaning they do not appear sick or exhibit symptoms of sickness.

A comprehensive worker hygiene training program is critical to food safety so that all employees understand the importance of proper hygiene. Proper hygiene includes wearing clean clothes, arriving at work clean by bathing daily, practicing proper hand washing after using the toilet, before and after work, after taking breaks, before and after eating, and any time employees come into contact with dirty surfaces or substances. When produce associated outbreaks are caused by hepatitis A or *Shigella*, the source of the pathogens is almost always produce handlers since humans and other primates are the main reservoirs for these pathogens (Fiore 2004; Wheeler et al. 2005; USFDA 2009). The pathogens are transferred through the fecal–oral route highlighting the need for all fresh produce handlers to practice proper hand washing.

In order to practice proper hygienic practices, commodities such as hand washing sinks, water, soap, and paper towels must be provided for all employees. All toilets and hand washing facilities must be monitored to ensure they are well stocked and cleaned when they are dirty. Providing clean, well-stocked facilities shows company commitment to the produce safety program.

It is particularly important to mention that hygiene practices such as hand washing must be practiced by all employees, including farm owners, managers, and crew leaders. If company policy states that all employees are required to practice proper hand washing, but farm owners and managers do not adhere to these practices, the policies and trainings become worthless. When those who make the policy do not follow the policy, it demonstrates to other employees that the policy is not important. Although most people report washing their hands, in one study 60% of food service personnel were observed to not wash their hands after using the toilet (Emery 1990). Knowing that foodborne illness causing organisms can be transmitted to fresh vegetables during handling should make worker training programs critically important in all fresh vegetable operations and a company-wide priority.

Worker training programs must be very specifi about expectations and describe desired practices in detail. It is most effective to allow workers to practice the behaviors while a trainer is present so that they can receive positive reinforcement when practices are done correctly and further training when done incorrectly. Some practices, such as disposing of used toilet paper in the toilet, are not things that are easily practiced in the company of others but those practices can be monitored by checking toilet facilities throughout the day to ensure toilet paper is not being

disposed of in the garbage can or on the floo . Improper disposal of toilet paper is a problem on many different levels. First, it disrupts the use of toilet facilities by creating unpleasant smells and unsanitary conditions if it is deposited on the floo or in cardboard boxes. In addition, used toilet paper thrown on the floo can contaminate the floo and be moved from the toilet area on shoes resulting in direct fecal contamination of food production areas including field and packinghouses. This particular issue is also grounds for an automatic failure of some third party food safety audits, including the USDA GAP/GHP audit. Most facilities in the United States have either indoor plumbing or portable toilet facilities that are sufficien to handle toilet paper waste, but workers need to be explicitly told that this is the appropriate practice.

Company policies regarding illness reporting and worker hygiene practices should be outlined in the farm produce safety plan. All employee training should be documented noting training content, name of trainer, date of training, and a list of all employees who attended the training. Every employee should be trained prior to starting work. This can be a challenge for operations that bring on additional harvest and packing crews in the middle of the season since it is the busiest time of the year. Having a well-outlined policy and training program will allow for the proper implementation of worker training programs to reduce microbial risks that exist from direct hand contact of fresh vegetables. Conducting training programs, providing proper hygiene facilities such as sinks, water, soap, and paper towels, and enforcing implementation of company policies is relatively inexpensive and significantl reduces food safety risks during the production and packing of fresh vegetables.

Soil Amendments and Manure

Soil amendments are used to add organic and inorganic nutrients to the soil as well as improve soil tilth and fertility. Synthetic fertilizers such as urea, diammonium phosphate, and potash do not pose a microbial risk because they contain no animal products. Other soil amendments like limestone, gypsum, and rock powders are also safe. These soil amendments still require proper management to avoid negative impacts on the crop and the environment. All soil amendments must be stored, handled, and applied as specifie on the label or based upon production recommendations to protect the crop, environment, and people handling the materials.

Soil amendments containing raw animal manure can come from a variety of sources including cows, pigs, horses, chickens, and their bedding. It can be liquid, solid, or combined into slurry. All manure can carry pathogens and needs to be managed to prevent the microbial contamination of fresh vegetables.

Recommended timing for a raw manure application prior to harvest varies from 90 days to 5 years. The National Organic Program (NOP) requires that manure be incorporated into the soil for not less than 90 days prior to the harvest of a product whose edible portion does not have direct contact with the soil surface or soil particles, or 120 days prior to the harvest of a product whose edible portion has direct contact with the soil surface or soil particles (NOP rule 7 CFR Part 205.203).

The Commodity Specifi Food Safety Guidelines for the Production and Harvest of Lettuce and Leafy Greens (LGMA 2008) states the best practice as "DO NOT USE raw manure or soil amendment that contain un-composted, incompletely composted or non-thermally treated animal manure to field which will be used for lettuce and leafy green production" (LGMA 2008). Florida T-GAPs developed for tomatoes, allows only properly composted manures to be used in tomato field and greenhouses, and stipulates that records of dates of composting, methods utilized, and application dates must be documented (FDACS 2007). Some leafy greens buyers have required growers to sign contracts

that state that field used to grow leafy greens have not had manure applied in the last fi e years.

Pathogen survival and multiplication in soil is affected by soil type, tillage practices, commodity grown, and nitrogen availability (Gagliardi and Karns 2000; Islam et al. 2005). A 5-year preharvest period for raw manure application may be extreme, but studies have found that microbial pathogens such as shiga-toxin producing *E. coli* strains can persist in soils for up to 18 weeks, which exceeds both the 90- and 120-day-application recommendations (Fukushima et al. 1999). *E. coli* O157:H7 survived for up to 196 days in amended fiel soil, and was detected on the surface of carrots 168 days after application of spiked compost (Islam et al. 2005). Side-dressing crops with raw manure or with straw bedding from animal operations should be viewed as a raw manure application and should be managed accordingly. Understanding that pathogens can survive and multiply in soil and that animal manures can contain pathogens explains why composting or other manure treatment options such as thermal processing prior to application to vegetable ground reduces microbial risks.

If manure will be composted on the farm, proper composting protocols should be followed. Cornell Waste Management Institute (CWMI) provides many resources to assist with the establishment and management of compost piles. Composting is an active process that requires establishing an initial Carbon to Nitrogen ratio between 25:1 and 40:1 and maintaining the temperature between 131°F (55°C) and 170°F (76.7°C) for 15 days in a windrow composting system with a minimum of 5 turnings (NOP 2000). United States Department of Agriculture Task Force set forth composting recommendations that are more fl xible than those listed above and require that compost reach a minimum of 131°F (55°C) for 3 days with sufficien management to ensure all parts of the pile reach this minimum temperature (CWMI 2004). The Compost Fact Sheet Series (#1–8) provides a good foundation of information and is supported by many other CWMI resources at http://cwmi.css.cornell.edu/resources.htm#composting. Some organic certifiers produce buyers, and commodity groups may have other requirements, so it is important to verify practices before compost is applied to field containing fresh produce crops.

There are other parameters to consider when establishing compost piles. Domestic and wild animals should be actively excluded from the composting area to prevent recontamination of the compost. Locate compost piles downhill or at a sufficien distance from vegetable field to assure that rain does not lead to run-off contamination of vegetable fields Distance is important because wind can also present a contamination risk.

Regardless of the soil amendments utilized, each farm should have a soil amendment management plan as a part of its produce safety plan. This management plan should be supported by record-keeping which documents:

- type of soil amendment
- source of soil amendment
- relevant treatment or handling such as compost procedures, temperatures, and analysis
- application dates, rates, and field where it was applied

Production Water

Water quality is important because contaminated water can carry pathogens such as *E. coli* O157:H7, *Salmonella*, and *Cyclospora* and transmit them to fresh vegetables. Currently there are no federal standards for irrigation water quality. In the absence of a federal standard, some industry organizations have adopted US EPA recreation water quality standards or other water quality benchmarks (USEPA 2003; FDACS 2007; LGMA 2008). Establishing water quality standards is a

difficul task particularly when surface water is being used for food production since some level of contamination is expected. Well water is not an unlimited natural resource and it is critically important that decisions about limiting the use of surface water for the production of food crops take into consideration the risks of human illnesses and the limited supply of water alternatives (Bihn and Gravani 2006).

When developing a production water management plan, there are three specifi areas that should be thoroughly reviewed: water sources, methods of application, and timing of applications. Understanding these three principles will reduce the risk of microbial contamination of fresh vegetables.

Water Sources

Water used during production can come from many different sources such as municipalities, wells, and surface water sources including rivers, streams, and irrigation ponds. Normally, municipal water is the safest and provides the lowest risk to produce safety, as it is treated and regularly monitored through testing by municipalities because it is intended as drinking water. Some municipalities have very old water lines that may be disrupted in places throughout the distribution system. Municipal water sources used for production of fresh vegetables should be tested at least once a year to verify the quality at the point of use. Always keep water test results and fil them with your other produce safety records.

Groundwater accessed through wells should also be free from bacteria and should provide a high quality source of water for vegetable production. To maintain the safety of the water, wells should be properly constructed, capped, and maintained. Well-recharge areas should be kept free from livestock or any other things that could contaminate the ground water. Wells should be tested at least once a year to verify the microbial quality of the water.

Surface water is likely to be of lower quality than municipal and well water because it is open to the environment and most vulnerable to external contamination sources including run-off, wildlife, and livestock. Monitoring the quality of surface water used in the production of fresh vegetables is critical to produce safety. Conducting sanitary surveys of all the surface water sources and regularly testing them throughout the production season are two ways to implement a water monitoring program. A sanitary survey should include assessing upstream activities, reviewing land topography, evaluating feral animal activity, and visiting the water source to identify sources of potential contamination.

Test all surface water used during production for generic *E. coli* at least three times during the production season. The laboratory should be asked to use an analysis method that provides a quantitative result instead of an absence-or-presence test. Always keep records of your test results. Surface water testing allows growers to establish a baseline of expected water quality for their water sources and determine if their current water quality meets the standards of buyers or commodity groups. If water test results indicate higher levels of *E. coli* than expected, growers need to take some action to mitigate the risk. These actions could include modifying water application practices, treating water, or using alternative sources of water. All actions should be documented and kept on file

Method of Application

Methods of water application also impact vegetable safety and often vary by crop and region. Production water quality is most important when water is applied directly to the edible portion of the plant such as in overhead irrigation, the application of topical protective sprays, frost protection, and cooling. Research has shown that pathogens present in poor quality water can persist in pesticide mixes, so only drinking water or water

that is the microbial equivalent of drinking water should be used to mix topical sprays (Guan et al. 2001; Sathyanarayanan and Ortega 2004). The importance of good water quality increases as the plants near harvest because there is less opportunity for UV solarization, desiccation, and other environmental factors to reduce microbial pathogens that may be present in the water.

Drip irrigation or other types of irrigation that deliver water directly to the root line represent the lowest risk irrigation method. There are other benefit to drip irrigation such as maximizing water use efficien y, improving yield, and keeping water off of the plant to reduce plant pathogens. Installing drip irrigation in some production systems is not feasible, but it is one option for reducing microbial risks for those with poor quality water.

Timing of Application

Overhead irrigation applied at planting or early in plant development represents less of a risk because it does not contact the edible portion of the plant. If using overhead irrigation that will come in contact with the edible portion of the crop, apply the irrigation water in the morning to promote exposure to the sun and drying of the crop (Steele and Odumeru, 2004).

Preventing Backflow

Regardless of the water source and application method, it is important to inspect irrigation lines, spray equipment, and source water pipes to make sure they are equipped to prevent backfl w. Backfl w is the reversal of fl w in a piping system that is opposite to the normal fl w. Backfl w can lead to unclean water contaminating clean water. All lines should be equipped with backfl w prevention valves and when fillin from a hose or pipe, an air gap should always be maintained to prevent backfl w. Lines from a well that feed into an irrigation pond should not be lower than the overfl w pipes since this could permit pond water to back up into the well.

In summary, water quality is most important when it comes into direct contact with the edible portion of a crop close to or at harvest. To reduce microbial risks associated with production water, vegetable growers should:

- Test all water sources for generic *E. coli*
- Keep all tests results and fil them with other produce safety records
- Conduct a sanitary survey of surface water sources
- Mix topical protective sprays with water that is microbial equivalent to drinking water
- Understand risks associated with different irrigation methods
- Time the application of overhead irrigation to minimize risks

Wildlife

Wild animals such as deer, birds, and feral pigs are quite resourceful at gaining entry into produce field and are commonly found in areas adjacent to fresh vegetable production. Wildlife is a concern because the animals can contaminate field and surface water sources. They are known carriers of pathogenic microorganisms such as *Salmonella* and *E. coli* O157:H7 and wildlife species are very difficul to control due to their strength, agility, and numbers (Sargeant et al. 1999; Smith et al. 2002; Jay et al. 2007). If wildlife is identifie as a problem, growers must actively pursue a solution to the problem. Growers can utilize fencing or nuisance permits issued by state agencies that allow for controlling wildlife that pose a danger to agricultural production.

It is the responsibility of growers to monitor wildlife activity, surface water sources, and vegetable field where they may be present. If animal activity is confirme in vegetable field through the presence of fecal material or commodity destruction due to mass

animal movement paths, these areas should not be harvested because of the risk of contamination.

Farming takes place within the natural environment and, in some locations, conflict between conservation and produce safety are becoming quite severe. Riparian habitat is being destroyed and growers are discontinuing their participation in conservation programs that promote clean water and wildlife habitat because buyers and food safety auditors are requiring them to have bare ground around production field (Beretti and Stuart 2008). Although wildlife may pose produce safety risks, these risks need to be balanced with risks to the environment. Clean water, habitat conservation, and ecological diversity are all very important to a healthy natural environment that is capable of sustaining human life and agricultural production.

Postharvest Water

Any water applied to produce at harvest or during postharvest handling must be the microbial equivalent of drinking water. This includes water used to make top ice or water used to fil flume or dump tanks. Using poor quality water at this point in production can result in contamination with human pathogens or lead to postharvest decay.

There are many uses for postharvest water in the production of fresh vegetables. Water can be used for cooling, moving commodities, washing, and waxing. There are several risks that should be considered when developing a postharvest water management plan, particularly if the water is recirculated or used in flumes dump tanks, or other congregational water settings.

Infiltration

Research related to dump tank and flum water infiltratio of tomatoes began after Bartz (1980) noted that a shipment of fresh market tomatoes was rejected at the receiving point due to decay. Virtually all of the lesions in a representative box of this shipment had begun inside the fruit. Subsequently, Bartz and Showalter (1981) determined that fruit physiology (fresh stem scars) and fruit temperature (warmer than dump tank/flum water) led to a significan infiltratio of fruit with water. Subsequently, hydrostatic forces (increased pressure due to immersion deeper down in the tank) were linked with water absorption by fruit. Studies conducted with *Salmonella montevideo* have verifie that pathogens can enter fresh produce through water used during postharvest activities (Zhuang et al. 1995). Certain vegetables have been identifie as being susceptible to infiltratio including tomatoes, peppers, and melons (personal communication, Michelle Smith).

Postharvest handling of melons, tomatoes, and peppers may include passage through a water flum or immersion in ice-cold water prior to processing for the fresh-cut market. Figure 23.2 depicts the result after a cantaloupe was placed in a sealable polyethylene bag with water soluble methylene blue dye. The bag was then submerged in an ice bath. After the fruit had cooled, the dye was washed off. In Figure 23.2 the extensive penetration of the dye to the interior fles is visible (personal communication, Jerry Bartz). This dye also penetrated directly through the peel and through the netting on the outside of the melon. A similar process was applied to a tomato, with Figure 23.3 documenting the nigrosin dye penetration of the tomato stem scar. Additional infiltratio studies using an aqueous cell suspension of *Erwinia carotovora* resulted in soft rot contamination in the interior of the tomato fruit (personal communication, Jerry Bartz). These images provide visual confirmatio of infiltration but there are other factors that may adversely impact product safety and quality.

Melons, tomatoes, and peppers have unique phenotypic characteristics beyond their susceptibility to infiltration As a group, these three commodities represent an

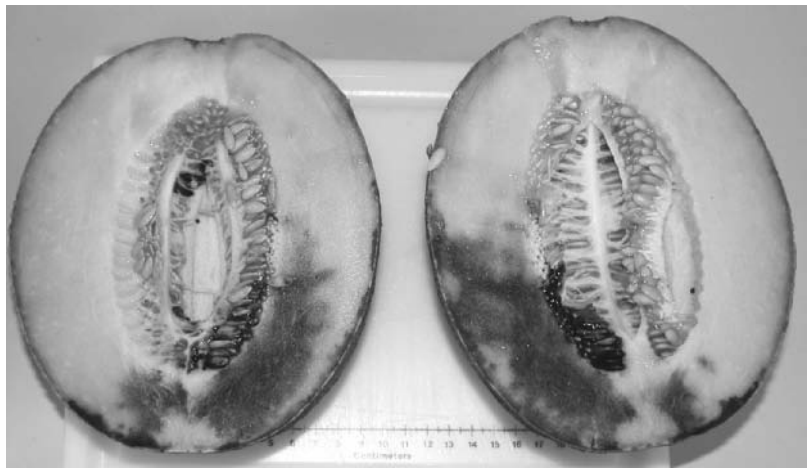

Figure 23.2 Cantaloupe infiltrated with methylene blue dye as a demonstration of postharvest handling risks. (Dr. Jerry Bartz).

opportunity to highlight the importance of understanding commodity-specifi attributes critical to implementing practices that minimize food safety risks. In the category of melons, cantaloupes are of particular concern because the surface netting creates areas where bacteria can attach and be protected from removal by wash tank waters or spray applied sanitizers (Alvarado-Casillas et al. 2007). In particular, *Salmonella* has been the cause of several cantaloupe-associated foodborne illness outbreaks. In studies where cantaloupes were inoculated with a cocktail of foodborne pathogens containing *Salmonella* strains, *E. coli* (O157:H7 and non-O157:H7), and *Listeria monocytogenes*, *Salmonella* exhibited the strongest attachment (Ukuku and Fett 2002; Vierk 2008). This result suggests that bacterial attachment is not simply dictated by the surface of the commodity but is influence by characteristics specifi to the microorganisms or a synergistic effect between the commodity surface and the microorganism.

Figure 23.3 Nigrosin dye penetration of the tomato stem scar. (Dr. Jerry Bartz).

The surface of tomatoes and peppers are smoother, but may still have microstructures and be susceptible to injury or abrasions. Viable *Salmonella* has been recovered from contaminated tomatoes even after submersion in a scale-model flum containing 150 mg/L free chlorine for 2 minutes (Felkey et al. 2006). Stem scars and puncture wounds were identifie as areas most difficul to sanitize in both bell peppers and tomatoes (Felkey et al. 2006; Yuk et al. 2006). Once contamination occurs, it is difficul to remove and identify if it is not associated with rot or some other visual indicator that would result in it being culled.

Water Disinfection

Another important aspect of managing postharvest water quality is disinfecting or

sanitizing water used in flume and dump tanks. Disinfectant levels in the postharvest water should be monitored to ensure that they are at sufficien levels to limit both human and plant pathogens. Many fresh produce operations use sensors to determine the oxidation-reduction potential (ORP) status of their water. Maintaining an ORP between 650 and 700 millivolts (mV) will eliminate pathogenic bacteria as well as spoilage organisms (Suslow 2004). ORP sensors can be combined with automatic injection systems that administer the disinfectant of choice directly to the postharvest water, when the ORP drops below the set limit. There also are hand-held ORP sensors and chemical kits that can be used to monitor disinfectant levels. All water monitoring protocols should be outlined in a SOP and documented as part of the farm or packinghouse produce safety plan. It is important to remember that postharvest water affects both the safety and quality of the fresh produce it contacts.

There are many sanitizers that can be used to achieve this process, but chlorine is the most widely used due to its availability and affordability. When using chlorine, it is important to monitor the levels of free chlorine since hypochlorous acid (HOCL) is the form of chlorine that kills bacteria and other disease-causing organisms. The presence of HOCL is pH dependent, so to achieve 80–95% free chlorine concentration, the pH should be maintained between pH 6.5 and 7.0 (Suslow 1997; Suslow 2001; CCC 2002). However, chlorine may not kill all microbial pathogens.

Parasites such as *Giardia lamblia*, *Cyclospora* spp., and *Cryptosporidium parvum* may be resistant to chlorine, particularly in waters with high organic load such as flume and dump tanks (Jarroll et al. 1981; Leahy et al. 1987; Korich et al. 1990; Fayer 1995; Carpenter et al. 1999). Of significan concern to the fresh produce industry is *Cyclospora* because it has been responsible for many produce-associated foodborne illness outbreaks and very little is known about how this organism contaminates fresh produce (Vierk 2008). Also, it is difficul to culture *Cyclospora* in laboratory settings which makes it difficul to be studied (Quintero-Betancourt et al. 2002). If the risk of contamination by parasites exists for the commodity of interest, then consider treating postharvest water with peroxyacetic acid, ozonation or high-intensity UV light instead of chlorine (Suslow 2004).

Zhuang et al. (1995) recommended that tomato packinghouses maintain dump tank chlorine levels at 200 ppm and the dump tank water at a temperature higher than tomato pulp temperature. Other sanitizers such as acidifie sodium chlorite, peroxyacetic acid, and gaseous chlorine dioxide may be more effective at reducing contamination on produce, so it is critical to review water disinfectant options and choose the one that is most appropriate for the operation (Yuk et al. 2006). Zhuang et al. (1995) also suggested tomatoes be stored at 50°F (10°C) until they are ripened. Maintaining the cold chain is very important because although pathogens such as *Salmonella typhimurium* and *E. coli* O157:H7 do not grow at cold storage temperatures (5°C and 10°C) they can survive on tomatoes, bell peppers, and cantaloupes (Zhuang et al. 1995; Alvarado-Casillas et al. 2007). Bacteria that survive the washing and storing process can then be transferred into the fles during cutting and processing (Selma et al. 2008)

Commodity characteristics, the type of pathogens, postharvest handling practices, water temperature, and water disinfection all impact vegetable safety, so it is important to review farm and packinghouse practices with these factors in mind. Whenever dump tanks, flumes or other water immersion steps are part of postharvest handling, water and pulp temperatures should be monitored to ensure the water is warmer than the fruit to prevent infiltration Water disinfectant levels also should be monitored to ensure pathogenic and

spoilage organisms are controlled in postharvest water.

Cleaning and Sanitation

Maintaining a clean operation covers a multitude of areas ranging from simply keeping field free of debris to detailed SOPs for cleaning and sanitizing specifi pieces of equipment. Starting broadly, consider the general organization and appearance of an operation. All food production facilities should be clean and organized and vegetable farms and packinghouses are no exception. There are certainly challenges that exist as anyone who has been in a functioning packinghouse on a rainy day can attest. Soil, plant debris, rotten vegetables, and used packing containers are all present and need to be managed. This is why every farm and packinghouse should establish basic cleaning and sanitation procedures. All trash should be removed from the field and deposited in dumpsters. Basic cleaning procedures such as sweeping packinghouse floor at the end of each day should be established to keep farms and packinghouses clean and organized.

Beyond these basic behaviors, each farm owner or operator needs to evaluate their operation and determine the need for specifi SOPs. For instance, if harvesting vegetables requires the use of harvest aids such as knives, they should be cleaned and sanitized at the end of each day. The cleaning and sanitizing procedure should be detailed in an SOP to ensure the process is done the same way each time and that it is effective. If harvest containers are reused, these too should be cleaned and sanitized on a scheduled basis.

It is important to review the four steps to cleaning and sanitizing (Table 23.1). Remember that in the discussion of cleaning and sanitizing, the word "soil" refers to unwanted matter including fiel soil, plant material, and other unwanted material that could contaminate fresh produce.

Harvest containers made of wood represent one challenge to cleaning and sanitizing during vegetable production. Wood is very porous and not easily cleaned or sanitized. If wooden packing or storing crates are currently in use, consider replacing them with durable plastic crates that are easily cleaned and sanitized as the wooden crates break and need to be replaced. If a packing facility is being renovated or a new packing facility is being built, it would be extremely valuable and prudent to review all building plans to ensure that the principles of sanitary design are incorporated. Sanitary design principles address the design of space and equipment so that they can be easily and effectively cleaned

Table 23.1 The four steps involved in cleaning and sanitizing food contact surfaces such as harvest aides, harvest containers, and packing lines

1. Prerinse	The firs step in the cleaning and sanitizing process is to prerinse surfaces to remove soil that may have accumulated, paying particular attention to cracks, crevices, and hard-to-reach areas. Prerinsing may require physical actions such as scraping and brushing to remove the soil.
2. Wash	Step 2 requires a thorough washing (cleaning) of the surface to disperse the soil in the detergent solution. All detergent (cleaner) should be mixed according to label directions and applied to the surface to break down the soil and all its components including fats, carbohydrates, and proteins. The chemical action of the detergent and the physical action of scrubbing will help to remove the soil.
3. Rinse	In step 3, the detergent solution containing the soil is rinsed away. This rinse step ensures that the surface is visibly free of soil and detergent solution.
4. Sanitize	In step 4, a sanitizer is applied to the surface as directed on the label. All sanitizers should be mixed according to label directions and tested with a simple test kit specifi to the sanitizer being used to determine that the appropriate concentration (strength) has been achieved. Sanitizers reduce the level of spoilage and pathogenic microorganisms on the surface to safe levels. Step 1–3 must be done properly because if the surface is not clean, then the sanitizer quickly loses its effectiveness.

and sanitized. This results in significan savings in both time and money spent on human resources and chemicals. When updating equipment such as packing lines, consider replacing wood or other porous materials with stainless steel because it is easier to clean and sanitize and it will withstand exposure to cleaning and sanitizing chemicals better.

Pest Control in Packinghouses

Unlike fields packinghouses have walls, doors, and windows that can be used to limit pest entry. Efforts to control pests in packinghouses should focus on four specifi goals: (1) preventing entry; (2) eliminating shelter; (3) eliminating food sources; and (4) eradication (Marriot and Gravani, 2006).

Preventing Entry

All doors should fi properly so that there are no gaps around the doors when they are closed. Rats can enter through a hole the size of a quarter and mice through a hole the width of a pencil. Flies and other pests can pass through even smaller openings. Door seals and screens should be in place and maintained to minimize entry opportunities. Packinghouse doors are often open throughout the day as loads are moved in and out so, efforts should be taken to restrict pest entry as much as possible by closing outside doors when not in use, or installing deterrents such as strip or air curtains.

Eliminating Shelter

Keeping the outside of the packinghouse well mowed and removing debris such as old pallets and boxes will reduce shelters that could be used by pests. In the packinghouse, pallets should be stacked one foot or more away from the wall so that pest control measures such as traps can be used and monitored. Some packinghouses have ceiling crossbars that provide roosting areas for birds. If birds are a problem, netting can be used to cover the ceiling area to deter bird roosting.

Eliminating Food Sources

Employee break areas such as lunchrooms should be kept clean and food items should be properly stored in sealed containers to limit pest access to food. Unused seed should be stored in sealed containers away from the packing areas. Culled vegetables should be removed from the packinghouse daily and not piled near the outside of the packinghouse.

Eradication

Snap traps, glue boards, and other eradication devices should be used to actively eliminate packinghouse pests. Never use poison bait inside the packinghouse, but poison bait stations can be used outside and around the perimeter of the packinghouse. If using insect-control lights, be certain that the lights are not visible from the outside as this will attract insects inside the packinghouse. Place lights on the interior walls facing into the packinghouse to eliminate insects that are in the packinghouse without attracting new insects.

All pest control measures should be outlined in the farm's produce safety plan. Pest monitoring records should be kept, noting the date traps were checked and any pests that were present. All actions taken to control pests should also be noted. If an outside pest control company is being used, request that they provide a detailed list of their service stops so that this information can be kept on fil and farm personnel can verify that they are controlling relevant pests.

Traceability and Recall

In the event of a foodborne illness outbreak, determining the origin of the outbreak is important for stopping the outbreak as well as determining its cause. Being able to track a food product through the food system is

called traceability. Growers cannot necessarily be expected to trace their crops from farm to table because of the complex nature of commodity movement through fields packinghouses, terminal markets, retail stores, and homes, but growers do have a responsibility to have a traceability system in place that tracks the commodities they grow and distribute. Standard traceability programs focus on one step back and one step forward; where did the produce originate (field and where did it go (buyer). If everyone in the food system could trace the produce one step back and one step forward, all produce items could be quickly traced from the consumer to their point of origin during foodborne illness investigations.

This topic of traceability is receiving significan attention in the fresh produce industry as well as in Congress. The Produce Marketing Association, United Fresh, and the Canadian Produce Marketing Association have developed the produce traceability initiative (PTI) with the goal of "achieving supply chain-wide adoption of electronic traceability of every case of produce by the year 2012" (PTI.org). On June 8, 2009 US House of Representatives Bill 2749 entitled the Food Safety Enhancement Act was introduced. This bill contains sweeping food safety reforms that could impact the entire food system in the US including both domestically and foreign produced fresh fruits and vegetables. PTI is just one example of how traceability is impacting the industry, but whether it is industry initiatives or congressional mandates, the need for traceability is clear. The pressure for growers to develop and maintain a traceability system is only going to increase.

At some point in the near future, there may be standards for traceability systems. Until it is a requirement or until one system rises above all others to claim the traceability market place, it is important for growers to develop and implement a traceability system that works for their operation. Initial focus should be placed on identifying lots.

A lot is simply a define and finit portion of a crop. A lot could be define as individual loads that are sold, but a more useful lot definitio would identify a particular harvest from a particular day from a particular field In attempting to determine lot size, it may be beneficia to consider what would happen if a lot was recalled, the larger the lot, the larger the recall, and the larger the potential loss. On the other hand, identifying each pallet as a lot requires more management and detailed traceability.

Product labeling is also part of a traceability system. Each farm should develop a labeling system so that minimally each lot is labeled with the farm name and relevant contact information. Ideally, each piece would be labeled so that it could be traced to the farm of origin. As of March 16, 2009, the Country of Origin Labeling (COOL) law became effective mandating that all fresh fruit and vegetable producers who directly or indirectly supply retailers identify the country of origin of their commodities on the product, on the shipping container, or in the documents that accompany the shipment. To be identifie as a US product, the commodity must be harvested in the US (http://www.ams.usda.gov/AMSv1.0/cool, accessed 6/30/2009).

This represents the firs legal requirement for fresh produce labeling at the farm level and was expressly implemented to provide consumers with more information about the origin of their food. With continued advances in communication and labeling, it is becoming financiall and technologically feasible to identify and trace individual pieces from the farm to the table. Each farm or operation needs to determine how to best defin parameters important for traceability, develop a traceability system, and test the system.

A recall plan is an important document to develop to support the traceability system and its testing through a mock recall. Figure 23.4 provides an outline of information that should be contained in a recall plan. The recall plan will require farm personnel to gather and

A recall plan should include the following:

- Names and contact information of key employees that are members of the recall team
- A specific person who will be the media contact
- Processes for notifying the public and regulatory agencies
- Procedures for implementing the recall
- Strategies for handling recalled produce
- Methods for verifying recall plan effectiveness, including removal of product from the marketplace
- Means of communicating with the customer
- List of critical farm operations that must be maintained during a recall
- List of resources, including testing labs, available to the farm in the event of a recall
- Current phone and fax numbers and email addresses of
  - Key farm management staff
  - Produce buyers and distributors
  - Federal and state regulatory agencies
  - Description of produce and container sizes you market
- Description of how you label and identify lots (units). Lot identification/labels should be able to link each individual lot to the following:
  - Grower(s)
  - Field (location)
  - Date harvested or date received if copacking
  - Individuals involved in harvesting
  - Total number of packages in the lot

Figure 23.4 Guidance for the development of a recall plan. Recall plans will help ensure recalled product is removed from the market efficiently and effectively.

organize important contact information for buyers and other farm resources. The time and energy invested into this activity will prove valuable during any mock recalls the farm conducts as well as in the development of a crisis management plan. In some operations, the recall plan may also serve as the crisis management plan, though the recall plan will be specifi to recovering product that is in the marketplace and that may present an illness risk.

One item on the recall plan outline suggests identifying a specifi person on the farm to be the media contact. Media training is not always an obvious asset to many vegetable producers. It would be valuable to have someone on the farm who has media training since a recall will very often attract media attention. How the recall is portrayed in the media can directly impact the farm either positively or negatively.

Mock Recall

An effective way to test a traceability system and recall plan is to conduct a mock recall. In a mock recall, a farm representative contacts one of its past buyers in an attempt to locate a particular lot and determine how much of the lot has been sold and how much of the lot is still in stock. The farm representative should be able to identify where the lot was grown and when it was harvested, packed, and shipped. The mock recall should be documented and any problems be identifie so that the traceability system can be modifie and improved. The mock recall is also an opportunity to review the recall plan and update contact information.

Crisis Management

Many things can result in crises on farms and in packinghouses such as chemical spills, tractor accidents, foodborne illness outbreaks associated with grown commodities, or the death of a key farm employee. Every farm should have a crisis management plan as part of their farm produce safety plan. The recall plan outlined in Figure 23.4 provides a good summary for the development of a crisis management plan. Much of the information may be the same, particularly in smaller operations. The crisis management plan should identify a crisis management team and list their contact information including cell phones and home phones so they can be reached immediately. In small operations, the team is likely to be very small, making the description of each person's responsibilities very important. The crisis management plan should identify buyers and any individuals who conduct business with the farm so they can be easily contacted if production is interrupted. Any resources that would be of value to the farm during a crisis should also be listed such as insurance company representatives, lawyers, and grower organization contacts. Developing a crisis management plan

and assigning responsibilities is best done before a crisis and those working directly with fresh vegetable growers and packers should encourage the implementation of a crisis management plan.

Third-Party Audits

Third party audit verificatio is an attempt to guarantee that produce safety practices such as GAPs have been implemented. These audits are conducted by a third party that the grower or buyer hires to conduct the audit. They are usually announced and take several hours to several days to complete, depending on the size of the operation. The rest of the time there is no auditor on site monitoring the implementation of the produce safety plan. Some audit companies are introducing unannounced follow-up visits in an attempt to verify practices in a true day-to-day setting, not when operations have had weeks to prepare. This increases the costs of the audits since it requires an additional visit, but it is intended to reflec how actual practices are implemented day-to-day.

An important point regarding audits is that merely passing an audit does not guarantee that the operation has implemented a food safety plan or that it prioritizes food safety. As an example, on March 27, 2008, Peanut Corporation of America (PCA) in Blakely, GA received a "Superior" rating from a third party audit company (PCA 2008). On November 25, 2008, an epidemiologic assessment began of a growing cluster of *Salmonella* serotype *typhimurium* isolates (CDC 2009) that would later be linked to individuals that had eaten peanut products from PCA. On January 28, 2009, PCA announced it was voluntarily recalling all peanuts and peanut products processed in its Blakely, Georgia facility since January 1, 2007, because they have the potential to be contaminated with *Salmonella* (PCA 2009). This highlights the fact that audits are not fool proof and that food safety needs to be built into all operations and practiced daily.

Food Safety Everyday

Ideally, each farm and packinghouse would have a written and implemented produce safety plan that is based on a risk assessment of their operation and of the commodities they produce. Each operation and each commodity they grow have different risks that need to be addressed depending on how they grow, harvest, pack, transport, and market the commodities (Dallaire et al. 2006; Ailes et al. 2008). The need for produce safety in vegetable production cannot be disputed as indicated by all the vegetable-associated produce illness outbreaks (Vierk 2008). In a survey of vegetables available in retail markets over a 2-year period, *Salmonella* was found on peppers, tomatoes, cucumbers, butternut squash, green onions, and carrots (Wells and Butterfiel 1999). The incidence of *Salmonella* was higher if the vegetables had bacterial soft rot evident, but *Salmonella* was found in commodities that appeared healthy with no obvious postharvest rot. This data supports the need for produce safety to be a priority for all vegetable growers even if the commodities they produce have never been involved in a produce-associated foodborne illness outbreak.

It is easy to demand produce safety, but fiel production and postharvest handling provide many challenges. Many small operations are heavy on the workload and light on the human resources. Fresh produce growers are more familiar with quality issues and marketing issues than produce safety issues. For better or worse, produce safety has now become a marketing issue as more and more buyers are demanding produce safety plans and audits to verify produce safety practices. All vegetable growers need to proactively develop a food safety plan to ensure not only the well-being of consumers, but also the sustainability of their farms.

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Chapter 24

Microbial Safety of Fresh and Processed Vegetables

Jaheon Koo

Introduction

About 32.6% of the US population surveyed in 2005 consumed fruits or vegetables two or more times per day, and 27.2% ate vegetables three or more times per day (CDC 2007a). However, outbreaks of human gastroenteritis associated with consumption of fresh produce contaminated with pathogenic bacteria, parasites, and viruses have occurred with increased frequency in recent years (NACMCF 1999). Fresh-cut vegetables, notably lettuce and leafy greens, have been implicated in a significan number of foodborne disease outbreaks since 1995 (Beuchat 2006). Direct evidence of food-associated illness due to contamination of produce, which was primarily related to fresh leafy greens and fruit-vegetables, has implicated poor production practices and animal waste and manure process control practices (NACMCF 1999).

The potential for large-scale outbreaks such as *Salmonella* infection associated with consumption of contaminated tomatoes (CDC 2005) or *Escherichia coli* O157:H7 infections with consumption of fresh spinach (CDC 2006b) are serious food safety concerns. Vegetables such as spinach, lettuce, tomatoes, and sprouts can become contaminated with *Salmonella*, *Shigella*, or *E. coli* O157:H7 (Sivapalasingam et al. 2004). Specifi types of produce that have been identifie as common vehicles in US produce-associated outbreaks include greens-based salads, lettuce, potatoes, and sprouts (DeWaal and Bhuiya 2007). Over the past 25 years, foodborne outbreaks linked to the consumption of leafy green vegetables has substantially increased and that increase cannot be entirely attributed to Americans eating more salads (Herman et al. 2008). In the United States, foodborne diseases in general caused 76 million cases of illness, 323,000 hospitalizations, and 5,000 deaths each year (Mead et al. 1999).

Microbial contamination of vegetables can occur at any point along the farm-to-table continuum including during growing, harvesting, processing, storing, shipping, or fina preparation. Sources of contamination in vegetables are varied as these foods are grown in soil and can become contaminated during growth or through processing and distribution. Contamination may also occur during food preparation in a restaurant or at home. However, the major source of microbial contamination of fresh produce is indirect or direct contact with animal or human feces. Many vegetables are frequently consumed raw without additional process to reliably eliminate pathogens. To reduce potential contamination, Food and Drug Administration (FDA)'s "*Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables*" provides recommendations for growers, packers, and shippers to use good agricultural practices (GAPs) and

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

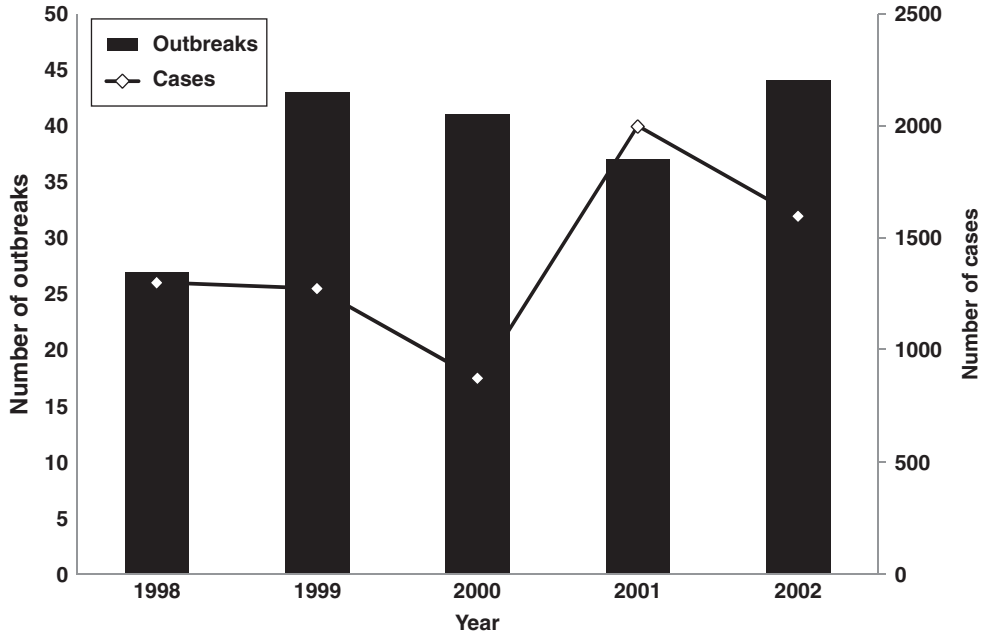

Figure 24.1 Reported foodborne disease outbreaks and cases associated with vegetables in the United States, 1998–2002 (Adapted from CDC 2006a).

good manufacturing practices (GMPs) in preventing or minimizing microbial food safety hazards in fresh produce (FDA 2008a).

Figure 24.1 shows outbreaks and cases associated with vegetables during 1998–2002 and Table 24.1 presents pathogens causing foodborne diseases associated with vegetables during the same period. Methods to detect foodborne disease outbreaks are improving, and several changes to improve the ease and timeliness of reporting foodborne disease outbreaks data have been implemented. The state and local health departments continue to investigate and report foodborne disease outbreaks as part of efforts to better understand and defin the epidemiology of foodborne disease in the United States (CDC 2006a). During this period, notable outbreaks were reported with fresh produce contaminated with *Salmonella*, *E. coli* O157:H7, *Cyclospora cayetanensis*, or *Norovirus*. Among the bacterial pathogens, *Salmonella enteritidis* accounted for the largest number of outbreaks and outbreak-related cases. Changes in dietary habits, methods of vegetable production and processing, sources of produce, and the emergence of pathogens previously not recognized for their association with raw produce have enhanced the potential for outbreaks. This chapter discusses the microbial safety of fresh and processed vegetables.

Microbiology of Fresh Vegetables

Microbial Contamination of Fresh Vegetables

Microorganisms are natural contaminants of fresh produce and minimally processed fresh-cut products, and contamination occurs during harvest, transport, processing, and storage (Beuchat 1996a). The routes of contamination are varied and include application of organic wastes to agricultural land as fertilizer, contamination of waters used for irrigation with fecal material, direct contamination by

Table 24.1 Outbreaks of infections epidemiologically associated with vegetables in the United States (1998–2002)

Microorganisms	Year	Cases
Bacteria		
Bacillus cereus	2001	1
Campylobacter	1998, 2000, 2002	3
Clostridium botulinum	2000	2
Clostridium perfringens	1999, 2001	2
Escherichia coli O157:H7	1998, 1999, 2000, 2001, 2002	12
Listeria monocytogenes	—	0
Salmonella	1998, 1999, 2000, 2001, 2002	25
Shigella	1998, 2001, 2002	4
Staphylococcus aureus	1999	1
Streptococcus	—	0
Vibrio cholerae	—	0
Vibrio parahaemolyticus	—	0
Yersinia enterocolitica	—	0
Other bacteria	—	0
Total bacteria		**50**
Parasitic		
Anisakis	—	0
Cryptosporidium parvum	—	0
Cyclospora cayetanensis	1999, 2001	2
Giardia intestinalis	—	0
Trichinella spiralis	—	0
Total parasitic		**2**
Viral		
Astrovirus	—	0
Hepatitis A	2000, 2001	2
Norovirus	1998, 1999, 2001, 2002	22
Rotavirus	—	0
Total viral		**24**
Unknown etiology	1998, 1999, 2000, 2001, 2002	104
Total number of cases		**180**

Adapted from CDC (2006a)

livestock, wild animals, and birds, and postharvest issues such as worker hygiene (Heaton and Jones 2008). Most spoilage microorganisms are not plant pathogens. These microorganisms can contaminate vegetables in the fiel during harvest. Typically, mechanical damage increases susceptibility to decay and growth of microorganisms. Once the degradation process begins, microorganisms spread rapidly, destroying the tissue and rendering the affected product unacceptable for consumption, resulting in great economic losses (Tournas 2005). Some of the microorganisms causing spoilage of vegetables are also capable of producing toxic metabolites, while others are opportunistic human pathogens, which can be a potential health hazard to individuals handling or consuming the affected products. However, these naturally occurring microorganisms present on fresh-cut lettuce and spinach showed possible antagonistic activity toward *E. coli* O157:H7 due to either acid production or antimicrobial peptides (Johnston et al. 2009).

In recent years, produce items including raspberries, strawberries, cantaloupe, lettuce, alfalfa sprouts, and tomatoes have been implicated as vehicles in multistate outbreaks

associated with *Cyclospora*, *E. coli* O157:H7, *Salmonella*, *Shigella*, and hepatitis A. The occurrence of widely distributed outbreaks associated with contaminated produce items has been recognized as an emerging foodborne disease problem in the United States (Tauxe 2002). A study on microbial quality of produce samples collected from the southern United States showed that neither *Listeria monocytogenes* nor *E. coli* O157:H7 was detected in any of 398 produce samples, but *Salmonella enterica* serotype Montevideo was detected on three cantaloupe samples. For all leafy greens and herbs, total aerobic bacteria ranged from 4.5 to 6.2 log CFU/g. *E. coli* and coliform counts were less than 1.0 log CFU/g and 1.0–2.9 CFU/g, respectively. The total *Enterococcus* counts ranged from 1.3 to 4.3 log CFU/g during production and packaging (Johnston et al. 2005). Ailes et al. (2008) reported that microbial concentrations on fresh produce were higher at the packing shed than at the farm. Identifying primary source of contamination in fresh produce can be tremendously difficult For example, only 2 of 27 outbreak investigations on fresh produce clearly identifie a point of contamination (NACMCF 1999).

Microbial Spoilage of Fresh Vegetables

Spoilage is characterized by any change in a food product that renders it unacceptable to the consumer from a sensory point of view by physical damage, chemical changes (oxidation or color changes), or appearance of offfl vors and/or and off-odors resulting from microbial growth and metabolism in the product (Gram et al. 2002). Since vegetables are harvested from or near the soil, they are susceptible to spoilage by microorganisms of mixed flor of soil, as well as airborne microorganisms. In general, the pH of vegetables is nearly neutral, which is very favorable for the growth of numerous microbial species. Spoilage of fresh vegetables usually occurs during storage and transport by bacteria and fungi and after harvest. Most of the natural microflor on the surface of fresh produce does not exert a deleterious effect on sensory qualities. The high pH in vegetable products will allow a range of gram-negative bacteria to grow, but spoilage is specificall caused by organisms capable of degrading pectin (Liao 1989; Liao et al. 1997). Among these organisms, typically *Erwinia* and *Pseudomonas* species are the specifi spoilage organisms of ready-to-eat vegetable products (Nguyen-The and Prunier 1989; Gram et al. 2002). Most *Erwinia* species grow well at refrigeration temperatures and some strains are capable of growing at 1°C. These organisms can ferment many vegetable sugars and alcohols that are not utilized by other bacterial species.

Lactic acid bacteria (*lactobacilli*, *leuconostocs*, and *lactic streptococci*), *Pseudomonads*, especially members of the *P. fluo escens* and *P. syringae* groups, and *Xanthomonas campestris* also cause substantial decomposition of vegetable (King and Bolin 1989; Barriga et al. 1991; Martinez et al. 2000; Tournas 2005). The production of acylated homoserine lactones (AHL) by spoilage gram-negative bacteria in food is an important parameter when evaluating their spoilage activity (Gram et al. 2002). Among the molds associated with vegetable spoilage, *Botrytis*, *Alternaria*, *Sclerotinia*, *Colletotrichum*, *Rhizopus*, *Phomopsis*, *Ceratocystis*, *Geothrichum*, *Cladosporium*, *Rhizoctonia*, *Phytophthora*, *Perenospora* (mildew), *Bremia*, *Aspergillus*, *Penicillium*, *Fusarium*, and *Mycosphaerella* are the most common (Martinez et al. 2000; Tournas 2005). The use of organic fertilizers, such as animal manures and slurries (Beuchat 1996a; Natvig et al. 2002), abattoir wastes (Avery et al. 2005), and sewage sludge (Al-Ghazali and Al-Azawi 1990) could be the major sources of pathogen introduction directly to the field and run-off could contaminate irrigation water. The microbiological quality of

vegetables depends not only on the numbers of bacteria, but also to a great extent on the types of microorganisms present in various fresh vegetables. In order to slow down vegetable spoilage and minimize the associated adverse health effects, interventions should be taken to follow strict hygiene, GAPs and GMPs during cultivation, harvest, storage, processing, transport, and marketing (Tournas 2005).

Human Pathogens Associated with Fresh Vegetables

Fresh vegetables harbor potential foodborne pathogens that can be a vehicle for the transmission of bacterial, parasitic, and viral pathogens capable of causing human illness (Nguyen-The and Carlin 1994; Beuchat 1996a). Preharvest sources of microorganisms include soil, feces, irrigation water, water used to apply fungicides and insecticides, dust, insects, inadequately composted manure, wild and domestic animals, and human handling (Table 24.2). Figure 24.2 shows possible pathways of how contamination by pathogenic microorganisms occurs. Since vegetables are grown in farms and fields it is impossible to exclude animals from the field Soil fertilized with farm manure or sewage waste may represent a risk of spreading human pathogens, e.g., *E. coli* O157:H7, *Salmonella*, *L. monocytogenes*. Water contaminated with fecal materials, that is used for irrigation and washing of products prior to processing may also be a source of foodborne pathogens (Beuchat 1996a).

Postharvest sources include feces, human handling, harvesting equipment, transport containers, wild and domestic animals, insects, dust, rinse water, ice, transport vehicles, and processing equipment. Although the spoilage bacteria, yeasts, and molds dominate the microflor on raw vegetables, the presence of pathogenic bacteria, parasites, and viruses capable of causing human infections has also been reported (Beuchat 1996a; NACMCF 1999). All types of fresh vegetables can be a vehicle for the transmission of bacterial, parasitic, and viral pathogens capable of causing human illness. *Shigella* spp. (Martin et al. 1986; CDC 1999; Naimi et al. 2003), *Salmonella* (CDC 2005, 2007b), enterotoxigenic and enterohemorrhagic *E. coli* (Ackers et al. 1998; CDC 2006b), *Campylobacter* spp. (Harris et al. 1986; Park and Sanders, 1992), *L. monocytogenes* (Heisick et al. 1989; Beuchat 1996b; Francis et al. 1999; Harris et al. 2003), *Yersinia enterocolitica* (Catteau et al. 1985; Darbas et al. 1985; Lee et al. 2004), viruses, and parasites such as *Giardia lamblia* (Mintz et al. 1993),

Table 24.2 Sources of pathogenic microorganisms on fresh fruits vegetables*

Preharvest
Feces
Soil
Irrigation water
Water used to apply fungicides, insecticides
Green or inadequately composted manure
Air (dust)
Wild and domestic animals (including fowl and reptiles)
Insects
Human handling
Postharvest
Feces
Human handling (workers, consumers)
Harvesting equipment
Transport containers (fiel to packing shed)
Wild and domestic animals (including fowl and reptiles)
Insects
Air (dust)
Wash and rinse water
Sorting, packing, cutting, and further processing equipment
Ice
Transport vehicles
Improper storage (temperature, physical environment)
Improper packaging (including new packaging technologies)
Cross-contamination (order foods in storage, preparation, and display areas)
Improper display temperature
Improper handling after wholesale or retail purchase

*Adapted from Beuchat (1996a) and Beuchat and Ryu (1997)

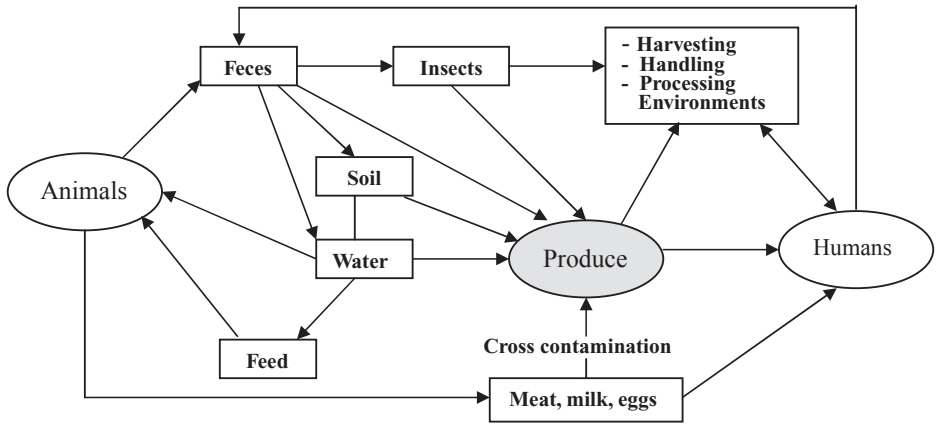

Figure 24.2 Pathogenic microorganisms associated with fresh produce (adapted from Beuchat 1996a).

C. cayetanensis (Döller et al. 2002; Tauxe 2002), and *Cryptosporidium parvum* (CDC 1998) are of greatest public health concern (Solomon et al. 1990; Beuchat 1996a, 1996b; Nguyen-The and Carlin 1994; Pönkä et al. 1999; Sterling and Ortega, 1999).

Among all vegetables, leafy greens (lettuce, spinach, cabbages, chicory, leafy fresh herbs, and watercress) were identifie as the commodity group of highest concern from a microbiological safety perspective. In the United States, during 1973–1997, there were 25 lettuce-associated outbreaks causing 2,078 reported illnesses, 181 hospitalizations, and 6 deaths (Sivapalasingam et al. 2004). In addition, the 11 sprout-associated outbreaks caused 1,071 reported illnesses, 97 hospitalizations, and 1 death. The 3 reported tomato-associated outbreaks caused 234 reported illnesses, 18 hospitalizations, and 1 death. *L. monocytogenes* (Schlech et al. 1983), *Salmonella* (Doyle and Erickson 2008), and *E. coli* O157:H7 (Nguyen-The and Carlin 1994) have been isolated from raw vegetables, which can become contaminated while growing or during harvesting, postharvest handling, or distribution. Harris et al. (2003) reported that *L. monocytogenes* is widely distributed on vegetables, whereas Johnston et al. (2005) reported that *L. monocytogenes* and *E. coli* O157:H7 were not detected from the 398 fresh produce samples including leafy greens, herbs, and cantaloupes in the southern United States.

Escherichia coli O157:H7

E. coli is commonly found in the intestines of warm-blooded animals. Most types of *E. coli* are harmless, but some are pathogenic. The symptoms of *E. coli* O157:H7 infection include severe, sometimes bloody diarrhea and abdominal cramps. Complications of infection may include hemolytic uremic syndrome (HUS), a leading cause of kidney failure in children, and thrombotic thrombocytopenic purpura (TTP), a condition that involves the brain and central nervous system, sometimes resulting in death (Doyle 1991; Buchanan and Doyle 1997). Multistate outbreak of *E. coli* O157:H7 infections from fresh spinach have been reported from 26 states, causing 199 persons infected, with 3 deaths (CDC 2006c). More multistate outbreak of *E. coli* O157:H7 infections have been reported from 5 states, with 71 persons infected at a Taco Bell restaurant where the problem was believed to be contaminated lettuce (CDC 2006d). Between 1995 and 2006, 22 produce outbreaks caused by *E. coli* O157:H7 were documented in the

United States, with nearly half being traced to lettuce or spinach grown in California (Cooley et al. 2007). The *E. coli* O157:H7 can become associated with preharvest leaf lettuce in the fiel via contaminated irrigation water or postharvest cross-contamination from processing wash water (Solomon et al. 2003; Wachtel et al. 2001; Wachtel and Charkowski 2002). The *E. coli* O157:H7 is particularly virulent and possesses greater acid resistance than nonpathogenic *E. coli* (Diez-Gonzalez and Russell 1997), allowing bacteria to survive passage through the stomach and infect the gastrointestinal tract. Further, *E. coli* O157:H7 has been shown to survive relatively well in vegetables and even grow in damaged tissue.

Salmonella spp.

The *Salmonella* infections are most commonly transmitted through various foods, particularly those of animal origin (CDC 2000 and CDC 2006a). Norovirus and *Salmonella* are the two major pathogens in produce (DeWaal and Bhuiya 2007). *Salmonella* spp. are also the most commonly identifie etiological agent associated with fresh-produce-related infection, isolated in 48% of cases between 1973 and 1997 in the United States (Sivapalasingam et al. 2004). Alfalfa sprouts grown from contaminated seeds caused outbreaks of *Salmonella* serotype *Stanley* infections (Mahon et al. 1997) and *Salmonella* serotype *Newport* infections (Van Beneden et al. 1999). Contaminated produce eaten raw is an increasingly recognized vehicle for transmission of *Salmonella*. The firs large multistate outbreak of *Salmonella* infections was linked to contaminated tomatoes in 1990, when *Salmonella javiana* caused 176 illnesses in 4 mid-Western states (Hedberg et al. 1999). More *Salmonella* outbreaks were associated with raw tomatoes: uncooked tomatoes in four States (Illinois, Michigan, Minnesota, and Wisconsin) outbreaks (176 cases of *S. javiana* in 1990) and (100 cases of *S. montevideo* in 1993), Roma tomatoes contaminated with multiserotypes of *Salmonella* (CDC 2005), raw tomatoes in multistate outbreaks (CDC 2007b), multiple raw produce items including jalapeño peppers serrano peppers, and tomatoes (CDC 2008a). Even though *Salmonella* infections were not reported for food commodities, Voetsch et al. (2004) estimated that *Salmonella* infections resulted in 15,000 hospitalizations and 400 deaths annually in the Unites States during 1996–1999, indicating that salmonellosis presents a major ongoing burden to public health in the United States. During 2005–2006, four major tomato-related *Salmonella* outbreaks occurred in the United States (CDC 2007b).

Listeria monocytogenes

L. monocytogenes is widely distributed on plant vegetation, including raw vegetables (Beuchat 1996a). *L. monocytogenes* is a bacterium that is able to grow in refrigerated produce such as lettuce (Carlin and Nguyen-The 1994; Koseki and Isobe 2005). Among 1,000 samples of 10 types of fresh vegetables at the retail level in the United States, *L. monocytogenes* and *Listeria* species were isolated from cabbage, cucumbers, potatoes, and radishes (Heisick et al. 1989). *L. monocytogenes* was found in ready-to-eat frozen vegetables including green beans, tomato products, caulifl wer, peas, and artichoke and a vegetable processing plant (Aguado et al. 2004). However, there were no *L. monocytogenes* outbreaks associated with fresh produce reported in the United States during 1999–2005 (DeWaal and Bhuiya 2007).

Cyclospora cayetanensis

C. cayetanensis is a protozoan parasite that causes a gastrointestinal syndrome known as cyclosporiasis. It is commonly associated with water that has been contaminated by fecal material and has been linked to several foodborne illness outbreaks in the

United States (Herwaldt 2000). Outbreaks of cyclosporiasis were associated with fresh Guatemalan raspberries (CDC 1997a), raw Guatemalan snow peas (CDC 2004), fresh basil (CDC 1997b), and lettuce (Herwaldt 2000). The modes of contamination of implicated vehicles have not been definitively determined for any previous foodborne outbreak of cyclosporiasis (Ortega et al. 1997; Herwaldt, 2000). A better understanding of the biology and epidemiology of the parasite is needed. For imported vehicles of infection, international collaboration is critical to the success of investigations and to the identification of appropriate prevention and control measures (Herwaldt 2000). Washing vegetables does not completely remove *Cyclospora* oocysts (Ortega et al. 1997).

Cryptosporidium parvum

C. parvum is another protozoan parasite to emerge, particularly in relation to the association with water, where water may be used as a primary ingredient (Moore et al. 2007). Unlike *C. cayetanensis*, infection may occur through person-to-person transmission as well as from food or water exposed to direct fecal contamination (Ortega et al. 1997). Until recently, there were no standard methods available for detecting *C. parvum* on lettuce and raspberries (Cook et al. 2006).

Norovirus

Noroviruses are the most common cause of sporadic cases and outbreaks of acute gastroenteritis. Transmission occurs via foodborne and fecal-oral routes as well as through indirect contact with contaminated water (Koopmans and Duizer 2004; CDC 2007c; CDC 2008b). Norovirus was the most common among the confirmed foodborne disease outbreaks in 2006, 54% of outbreaks and 11,879 cases, followed by *Salmonella* responsible for 18% of outbreaks and 3,252 cases (CDC 2009). Vegetables can be considered a transmission vehicle for noroviruses when contaminated by spoiled irrigation water or when prepared by infected food handlers (Gaulin et al. 1999).

Microbial Safety of Fresh and Processed Vegetables

Produce Safety: Organic versus Conventional Produce

According to a 2009 Organic Trade Association (OTA) survey, sales of organic food in the United States have grown by almost 16% in 2008 over 2007, reaching $22.9 billion in 2008 sales (OTA 2009). The organic food sales now account for approximately 3.5% of all US food product sales. Recently, the market for organic foods in general, and organic fresh produce in particular, has expanded at an annual rate of 20% (Dimitri and Greene 2002). Fresh produce remains the top selling organic category, followed by nondairy beverages, breads, and grains, packaged foods (frozen and dried prepared foods, baby food, soups, and desserts), and dairy products (Dimitri and Greene 2002). Whether or not organically produced foods are more nutritious than their conventionally produced counterparts is the subject of an ongoing debate. A recent study indicates that organically produced plant products contained more dry matter and minerals such as iron and magnesium, more antioxidants such as phenols and salicylic acid, 50% less nitrates, and no pesticide residues compared with conventional ones (Lairon 2009).

Regardless of organic or conventional food production system, all foods need to be produced in such a manner that it can be ensured that they are safe to eat. The question of whether the consumption of organically grown food confers any greater microbiological risk to consumers than conventional food has not yet been addressed in a scientific manner. One of the drivers of the organic food industry is the relationship between pesticide

residues in conventional foods and those in organic foods (Winter 2006). It is a reasonable assumption that organically grown food will, in general, contain lower levels of pesticide residues than conventionally grown food. The pesticide residues were 3.2 times more likely to be found in conventional produce than in organic produce, according to the USDA's pesticide data program (Pussemier et al. 2006; Winter and Davis 2006).

In organic farming, animal waste in the form of raw manure or composted manure is routinely applied to the land as a crop fertilizer. The *E. coli* O157:H7 shed from healthy cattle can survive for extended periods of time in the environment (Wang et al. 1996; Kudva et al. 1998; Jiang et al. 2002). After 50 days, *E. coli* O157:H7 was not detected from the lettuce grown at 18°C in organic manure inoculated with *E. coli* O157:H7 at harvest, indicating that transmission of *E. coli* O157:H7 from contaminated soil to lettuce did not occur. The *E. coli* O157:H7 persisted in the soil for at least 8 weeks after fertilizing, but was not detected after 12 weeks (Johannessen et al. 2005). Wang et al. (1996) have reported that *E. coli* O157:H7 can survive in animal manure for up to 49 days at 37°C. In a fiel study by Johannessen et al. (2004), *E. coli* O157:H7 was isolated from fir manure and slurry, and soils fertilized with bovine manure, but *E. coli* O157:H7 were not recovered from the lettuce thus grown using this manure system.

Mukherjee et al. (2004) performed the most comprehensive study comparing microbiological safety of organic and conventional produce. In their study, 476 organic produce samples and 129 conventional produce samples were analyzed for *E. coli*, *Salmonella*, and *E. coli* 0157:H7. The *E. coli* 0157:H7 were not isolated from any produce samples, but *Salmonella* was present in one organic lettuce and one organic green pepper. The percentages of *E. coli*-positive samples in conventional and organic produce were 1.6 and 9.7%, respectively. They found no statistical differences in *E. coli* contamination levels between certifie organic and conventionally grown crops. Lettuce was the produce item containing the highest rates of generic *E. coli* contamination. Solomon et al. (2002) demonstrated transmission of *E. coli* O157:H7 to lettuce plants from contaminated manure incorporated into the soil. While many studies demonstrate qualitative differences between organic and conventional foods with respect to pesticide residues and microbiological safety, it is premature to conclude that either food system is superior to the other.

Preharvest Interventions

Application of GAPs to Fresh Vegetables

Due to increased consumption of fresh produce in the United States, an increasing number of outbreaks caused by foodborne pathogens have been associated with consumption of both domestic and imported fresh produce. The food safety has become a serious issue in the food chain because of pathogens and food contamination. In the United States, a National Food Safety Initiative was announced in 1997, which included several new programs to promote food safety. This initiative included improved inspection systems and preventive measures, new tests to detect pathogens, a national education campaign for safer food handling in homes and at retail outlets, and increased funding for food safety research and risk assessment activities. The initiative focused on providing guidance to both domestic and foreign producers, and was commonly referred to as GAPs (Crutchfiel 1999). The GAPs are the basic environmental, human health, and sanitary operational practices that are necessary for the production of safe, wholesome vegetables. FDA emphasizes that GAPs can only reduce the risk of microbial contamination and cannot eliminate the risk (Calvin 2003). Table 24.3 summarizes the factors considered in minimizing risk of contamination on the basis

Table 24.3 Factors in minimizing potential sources of contamination from production to consumption

Production and harvesting:
Producer awareness of role in food safety
Training and facilities for workers
Avoiding animal manure/sewage/floode land
Irrigating with clean water
Cleaning and sanitizing harvesting equipment
Excluding wild birds and animals from packinghouse
Minimizing bruising and cutting
Avoiding cross-contamination during delivery to processor
Fresh-cut processing:
Program for sanitizing surfaces and machines
Good preliminary decontamination and inspection
Avoiding severe peeling/cutting
Eliminating/minimizing human contact with processed product
Deploying effective washing/anti-microbial dipping
Avoiding postdipping contamination
Packaging/distribution/retail:
Careful selection of packaging material
Monitoring microbial quality of packaged product
Ensuring temperature is $<4^{\circ}C$
Process at low temperature
Suitably designed vehicles
Proper vehicle loading practices
Chill cabinet loading
Modest shelf-life labeling
Education of retailer and consumer
Building these into GAP/GMP/HACCP programs

Adapted from O'Beirne (2007)

of principles of GAPs, GMPs, and temperature control during distribution and education of the end user. It must be noted that this document is guidance, not a regulation, and thus, it is not subject to any type of enforcement. However, it is recommended that every producer of fresh vegetables should consider implementing the risk reduction strategies outlined in the guide. The guidance is based upon certain basic principles and practices associated with minimizing microbial food safety hazards from the fiel through distribution of fresh produce; it identifie eight principles of microbial food safety that can be applied to the growing, harvesting, packing, and transportation of fresh produce (FDA 2008). These principles are:

Principle 1: Prevention of microbial contamination of fresh produce is favored over reliance on corrective actions once contamination has occurred.

Principle 2: To minimize microbial food safety hazards in fresh produce, growers, packers, or shippers should use good agricultural and management practices in those areas over which they have control.

Principle 3: Fresh produce can become microbiologically contaminated at any point along the farm-to-table food chain. The major source of microbial contamination with fresh produce is associated with human or animal feces.

Principle 4: Whenever water comes in contact with produce, its source and quality dictates the potential for contamination. Minimize the potential of microbial contamination from water used with fresh fruits and vegetables.

Principle 5: Practices using animal manure or municipal biosolid wastes should be managed closely to minimize the potential for microbial contamination of fresh produce.

Principle 6: Worker hygiene and sanitation practices during production, harvesting, sorting, packing, and transport play a critical role in minimizing the potential for microbial contamination of fresh produce.

Principle 7: Follow all applicable local, state, and Federal laws and regulations, or corresponding or similar laws, regulations or standards for operators outside the United States for agricultural practices.

Principle 8: Accountability at all levels of the agricultural environment (farm, packing facility, distribution center, and transport operation) is important to a successful food safety program.

There must be qualifie personnel and effective monitoring to ensure that all elements

of the program function correctly and to help track produce back through the distribution channels to the producer, in case if there is any problem.

Postharvest Interventions

Postharvest technologies refer to the stabilization and storage of unprocessed or minimally processed foods from the time of harvest until fina preparation for consumption (Bourne 2004). It is necessary to identify the spoilage vector(s) or major causes of loss of commodity in order to select the preservation technology appropriate for each situation. For vegetables, the main spoilage vectors are bruising, rotting, senescence, and wilting. The wilting is controlled by high humidity and cold storage (Bourne 2004). A brief description of postharvest interventions for ensuring food safety of vegetables is given below.

Decontamination

Even though decontamination of minimally processed vegetables can produce safer and more stable products, the decontamination process may cause sensorial and physiological changes that will influenc the shelf life of minimally processed vegetables (Gómez-López et al. 2009). In the fresh-cut industry, chlorine is commonly used to disinfect produce at a concentration of 50–200 ppm, with a contact time of 1–2 minutes (Beuchat 1998). The chlorinated water alone has been shown to be sufficien to achieve a satisfactory reduction in coliforms, *E. coli*, coliphages, and total plate counts (Legnani and Leoni 2004). Because of its microbicidal activity and low cost, chlorine (as sodium or calcium hypochlorite or Cl_2 gas) is the agent most widely used to sanitize fresh produce (Suslow 2000). Chlorine dioxide (ClO_2) is a strong oxidizing agent that can be applied in solution as well as in the gaseous state. It has bactericidal, fungicidal, and viricidal properties (Vandekinderen et al. 2009a). Treatment with chlorine dioxide and sodium hypochlorite in spinach significantl decreased levels of *E. coli* O157:H7 by 2.6 and 1.1 log CFU/g, respectively (Lee and Baek 2008). Treatment of potato processing water with peroxyacetic or octanoic acid mixtures reduced numbers of yeast and mold (Hilgren and Salverda 2000). The effi ciency of peracetic acid to remove the native flor is highly dependent on the type of fresh-cut produce; the highest microbial reductions were obtained for carrots (0.5–3.5 log CFU/g) and white cabbage (0.5–3.5 log CFU/g), iceberg lettuce (0.4–2.4 log CFU/g), followed by fresh-cut leek (0.4–1.4 log CFU/g) (Vandekinderen et al. 2009b).

Selma et al. (2008) investigated disinfection effica y of ozone (O_3) and UV-C illumination (UV), and their combination (O_3–UV) for reducing microbial flor of fresh-cut onion, escarole, carrot, and spinach wash waters. Disinfection treatment with O_3, UV, and O_3–UV were effective on vegetable wash water, with a maximum microbial reduction of 6.6 log CFU/mL after 60 minutes treatment with O_3–UV. Casteel et al. (2008) showed that free chlorine of 20 parts per million (ppm) for 5–10 minutes inactivated hepatitis A virus on strawberries, cherry tomatoes, and head lettuce by 90–99%. Beuchat et al. (2005) studied the effectiveness of sanitizers in killing vegetative cells and spores of *B. cereus* and found alkaline ClO_2 (pH 10.5–11.0) to be most lethal to vegetative cells and spores as compared to chlorine and Fit™, a commercially available acidic powder sanitizer.

The use of gaseous ozone for eliminating pathogens without compromising food quality is a means of enhancing food safety. Klockowa and Keener (2009) reported that gaseous ozone treated spinach showed reductions in *E. coli* O157:H7 populations with the largest reductions (3–5 $\log_{10}$ CFU/leaf) after 24 hours of storage even though the concentrations of ozone decreased with time and were not detectable after 24 hours.

Electrolyzed oxidizing water (EOW) is a relatively new concept. The EOW is conventionally generated by electrolysis of aqueous sodium chloride to produce an electrolyzed basic aqueous solution containing dilute sodium hydroxide at the cathode and an electrolyzed acidic solution at the anode (Kim et al. 2000). Washing the vegetables for 1 minute in EOW produced from tap water (EOW-T) resulted in 1.9, 1.2, and 1.3 log reductions of psychrotrophs, lactic acid bacteria, and Enterobacteriaceae, respectively, which increased to 3.3, 2.6, and 1.9 log reductions after washing for 5 minutes instead (Ongeng et al. 2006). Acidic electrolyzed water (AEW) and neutral electrolyzed water (NEW) have been studied as alternative sanitizers. Abadias et al. (2008) indicated that treating fresh-cut lettuce, carrot, endive, corn salad, and "Four seasons" salad against *E. coli* O157:H7, *Salmonella*, *Listeria innocua*, and *Erwinia carotovora* with NEW 1:5 (containing about 50 ppm of free chlorine, pH 8.60) was equally effective as applying chlorinated water (120 ppm of free chlorine) with reductions of 1–2 log units.

Modified Atmosphere Packaging

Good manufacturing and handling practices along with the appropriate use of modifie atmosphere packaging (MAP) are relatively effective at inhibiting these spoilage mechanisms to extend shelf life (Day 2002). MAP is effective in prolonging the shelf life of horticultural commodities under low O_2 and relatively high CO_2 concentrations in the package (Makino 2001; Peter et al. 2009). The modifie atmospheres within fresh-cut containers or bags can be beneficia in maintaining quality of the fresh-cut product (Gorny 1997).

Storage of fresh-cut vegetables at relatively high CO_2 concentrations (5–10%), along with low-temperature conditions, results in the inhibition of gram-negative bacteria such as *Pseudomonas* spp. or Enterobacteriaceae, considered the most common spoilage bacteria in fresh-cut leafy vegetables for their higher growth rate at lower temperatures and their pectinolytic enzymes (Jacxsens et al. 2002). Generally 3–5% O_2 and 3–10% CO_2 is assumed as an optimal gas composition to suppress respiration (Jacxsens et al. 2000). Fresh-cut mixed leafy salads packaged at initial conditions of 6% CO_2 and 3% O_2 supported the growth of *L. innocua* (Scifò et al. 2009).

Thermal Treatments

Thermal processing is one of the conventional preservation methods which assure processed foods to be safe and shelf stable. There are various degrees of preservation achieved by heating (Dauhty 1995; Ramaswamy and Chen 2002), such as commercial sterilization and pasteurization.

Because of the varying sensitivities of vegetables to heat treatment, the use of heat in minimally processed vegetables has somewhat limited benefit (Park et al. 1998). These researchers also reported that a mild heat treatment at 60°C for 30 seconds markedly reduced microbial counts in soybean sprouts and watercress, which were highly loaded with microorganisms. Jaquette et al. (1996) reported that treatment of alfalfa seeds in water for 5 or 10 minutes at 54°C caused a significan reduction in the *Salmonella stanley* population, and treatment at $\geq$57°C reduced populations to $\leq$1 CFU/g, while treatment at $\geq$54°C for 10 minutes caused a substantial reduction in viability of the seeds. Treatment at 57°C or 60°C for 5 minutes appears to be effective in killing *S. stanley* on alfalfa seeds without substantially decreasing germination ability of seeds. There was a slight advantage of the heated air treatment at 48°C for 1 hour on fresh-cut celery, compared to the control, as measured by color retention, chlorophyll content, and microbial counts (Viña et al. 2007).

Edible Films and Coatings

One of packaging technology for extending the postharvest storage of minimally processed vegetables is the use of edible coatings or films Edible coatings, thin layers of material that can be eaten, can provide an additional protective coating for fresh products. Rojas-Graü et al. (2009) reviewed the use of edible coatings containing active compounds such as antimicrobial agents, antibrowning agents, texture enhancers, and/or neutraceuticals. Fuchs et al. (2008) demonstrated that coatings were effective at maintaining several quality attributes of green asparagus after 14 days of storage at 4°C. Chitosan could potentially be used to reduce the microbial populations of spears affected with tiprot. This could be especially useful for asparagus stored in MAP, where tiprot-related odors can accumulate in the bags during long storage periods and limit the shelf life of the product. Low-permeability fil bags cannot be recommended as a packaging material for fresh-cut sweet potatoes (Erturk and Picha 2008).

Ponce et al. (2009) reported that edible fil solutions containing 1% of different oleoresins showed limited antimicrobial effects against indicator microorganisms. Olive extract and rosemary showed antimicrobial activity against both squash native microflor and *L. monocytogenes*. Chitosan enriched with rosemary and olive improved the antioxidant protection of the minimally processed squash offering a great advantage in the prevention of browning reactions, which typically results in quality loss in vegetables.

Irradiation

Ionizing radiation is a nonthermal technology that eliminates foodborne pathogens and extends shelf life of fresh vegetables. By irradiation, the use of ionizing radiations, either gamma rays from radionuclides such as Co or Cs, or high-energy electrons and X-rays produced by machine sources, is meant (Farkas 1998). Irradiation was utilized to improve the quality of fresh-cut produce. Irradiation doses up to 1 kilo Grays (kGy) for fresh produce are permitted in the United States (FDA 1995). Gamma irradiation doses between 2.7 and 3.0 kGy would be required to achieve $\geq$90% kill in Hepatitis A virus populations on vegetables (Bidawid et al. 2000). The number of bacteria and fungi in fresh-cut celery decreased by the order of 10^2 and 10^1, respectively, with 1 kGy of irradiation and the number of *E. coli* was decreased to less than 30 (Lu et al. 2005). Polyphenol oxidase and respiration rate of irradiated fresh-cut celery were also inhibited and lower than those of nonirradiated. The vitamin C, soluble solids, total sugars, and the sensory quality of irradiated celery were also better than those of nonirradiated. Hagenmaier and Baker (1997) reported that irradiation at an average dose of 0.19 kGy of commercially prepared fresh-cut lettuce resulted in a product that had microbial population of 290 CFU/g and yeast population of 60 CFU/g, compared with values of 220,000 and 1,400 CFU/g, respectively, for the nonirradiated control after 8 days of irradiation.

It appears beneficia to combine chlorination with irradiation at 0.15–0.5 kGy to produce fresh-cut, chopped lettuce with reduced microbial population. Fan et al. (2003) reported that iceberg lettuce treated with warm water and irradiated at 0.5 or 1 kGy had the best sensory quality without significan loss in texture, vitamin C, or total antioxidants. Fan and Sokorai (2005) assessed the use of electrolyte leakage measurement to evaluate radiation sensitivity of 13 fresh-cut vegetables. Fresh-cut vegetables were gamma irradiated at doses up to 3 kGy at 0.5 kGy intervals. Electrolyte leakage of the samples was measured following irradiation to predict product's ability to tolerate irradiation. Red cabbage, broccoli, and endive had the highest radiation resistance while celery, carrot, and green onion were the most sensitive to radiation.

Table 24.4 Important hurdles for food preservation*

Symbol	Parameter	Application
F	High temperature	Heating
T	Low temperature	Chilling, freezing
a_w	Reduced water activity	Drying, curing, conserving
pH	Increased acidity	Acid addition or formation
Eh	Reduced redox	Removal of oxygen or addition of ascorbate
Pres.	Preservatives	Sorbate, sulfite nitrite,
c.f.	Competitive flor	Microbial fermentations

*Adapted from Leistner and Gorris (1995).

Hurdle Technology

Gamma irradiation was employed to restrain potato sprouting and kill pests in grain. Irradiation proved to be extremely beneficia in terms of prolonging the vegetable shelf life by 3–5 times. In order not to expose vegetables to high irradiation doses, another approach is to use the "hurdle technology," that is to apply more than one technology toward better quality and longer shelf life (Arvanitoyannis et al. 2009). Combination treatments are applied because it is expected that the use of combined preservative factors will have greater effectiveness at inactivating microorganisms than the use of any single factor (Lee 2004). These hurdles may be temperature, water activity (a_w), pH, redox potential, preservatives, and so on, as summarized in Table 24.4.

Fresh-Cut Vegetables

The processing of fresh-cut vegetables by slicing, dicing, and shredding has minimal effect on the vegetable tissue; however, these processes may enhance the possibilities of microbial growth and enzymatic changes. Fresh-cut vegetables are highly perishable due to damaged and exposed tissues and lack of protective skin. Fresh-cut products are vulnerable to discoloration because of damaged cells and tissues, and lack of protective skin (Watada and Qi 1999). Sanitizers commonly used for washing cut vegetables can, to a varying extent, control the enzymatic browning; however, secondary intervention is typically required.

Microorganisms are natural contaminants of fresh produce and minimally processed or fresh-cut products, and contamination results from a number of sources, including postharvest handling and processing (Beuchat 1996a). Due to the nature of the treatments applied to this type of product, a favorable environment and time for proliferation of spoilage organisms and microorganisms of public health significanc is created (Ahvenainen 1996). The processing of fresh-cut vegetables usually involves the induction of wounding stresses in the cut tissues as a result of mechanical injury, leading to an increase in their respiration rate (Watada et al. 1996), which hastens quality deterioration.

Thermally Processed Vegetables

Thermal processing is the most extensively used method of food preservation to destroy microorganisms and to extend its shelf life. Thermal processes are primarily designed to eliminate or reduce the number of microorganisms to an acceptable level and provide conditions that limit the growth of pathogenic and spoilage microorganisms (Ramaswamy and Chen 2002). Thermal treatment is commonly applied in the form of hot water or steam (cooking, blanching, pasteurization, sterilization, evaporation, and extrusion), hot air (drying), and irradiated energy (microwave, infrared radiation, and ionizing

radiation) to fresh vegetables (Ramaswamy and Chen 2002; Fan et al. 2009). There are various degrees of thermal processing (Dauthy 1995):

Blanching: It is mild heat treatment (hot water or steam) usually applied to vegetables mainly to inactivate enzymes prior to further processing.

Sterilization: It is a complete destruction of microorganisms. Because of the resistance of certain bacterial spores to heat, this frequently means a treatment of at least 121°C (250°F) of wet heat for 15 minutes or its equivalent.

Commercially sterile: It refers to the condition that exists in most of canned or bottled products manufactured under GMPs procedures and methods; these products generally have a shelf life of 2 years or more.

Pasteurization: A comparatively mild heat treatment performed on foods to destroy vegetative microorganisms and inactivate the enzymes; this is the objective when vegetable juices and certain other foods are pasteurized.

One of the consequences of inadequate thermal processing is a potential for botulism, a type of food poisoning. Botulism results from the ingestion of the neurotoxic produced by *Clostridium botulinum*, an anaerobic, spore-forming, rod-shaped bacterium, commonly found in soil. The vegetative cells have an optimum temperature growth range of 27–38°C. The spores are moderately heat-resistant and require temperatures above 100°C for inactivation. The toxin production in food occurs only where pH values exceed 4.6; such foods are referred to as "low-acid" foods. Most vegetables fall under low-acid food category. Botulism is, therefore, a threat only when low-acid foods are insuffi ciently processed. The toxin is extremely potent (0.012 μg is the lethal dose for humans) and will produce neurologic paralysis, dizziness, double vision, and nausea. The mortality from botulism averages 65% in the United States.

The Spoilage of canned foods, including canned vegetables, can be usually identifie by swollen containers. According to FDA (1998b), swells can occur in metal containers, plastic pouches, plastic trays, or tubs. Swells result from gas production, which would eliminate the vacuum. Plastic pouches would tend to balloon while plastic tray covers would swell. Cans exhibit various degrees of swelling, known as hard swells, soft swells, springers, and flippers these defects are summarized in Table 24.5. As per FDA (1998b), gas production, and resultant swelling, may be caused by chemical reaction or by bacteria, which may or may not produce toxins. Improper cooling after thermal processing can also buckle cans, creating the appearance of hard swells. It is to be noted that microorganisms in processed containers can result from various causes; e.g., postprocessing entry through fl xing seams (seal), improper

Table 24.5 Metal can defects that can indicate spoilage

Flat (normal)	A can with both ends concave; it remains in this condition even when the can is brought down sharply on its end on a solid, fla surface.
Flipper	A can that normally appears flat when brought down sharply on its end on a fla surface, one end flip out. When pressure is applied to this end, it flip in again and the can appears flat Flippers result from a lack of vacuum.
Springer	A can with one end permanently bulged. When sufficien pressure is applied to this end, it will fli in, but the other end will fli out.
Soft swell	A can bulged at both ends, but not so tightly that the ends cannot be pushed in somewhat with thumb pressure
Hard swell	A can bulged at both ends, and so tightly that no indentation can be made with thumb pressure.

FDA (1998b)

Table 24.6 Spoilage symptoms in acid and low-acid canned foods including vegetables

Type of organism	Appearance of can	Condition of product
Acid products		
B. thermoacidurans (fla sour: tomato juice)	Can flat little change in vacuum	Slight pH change, off-odor and f avor
Butyric anaerobes (tomatoes and tomato juice)	Can swells, may burst	Fermented, butyric odor
Non-sporeformers (mostly lactics)	Can swells, usually bursts	Acid odor
Low-acid products		
Flat sour	Can flat possible loss of vacuum on storage	Appearance not usually altered, pH markedly lowered—sour, may have slightly abnormal odor, sometimes cloudy liquor
Thermophilic anaerobe	Can swells, may burst	Fermented, sour, cheesy, or butyric odor
Sulfid spoilage	Can flat H_2S gas absorbed by product	Usually blackened, "rotten egg" odor
Putrefactive anaerobe	Can swells, may burst	May be partially digested, pH slightly above normal, typical putrid odor
Aerobic sporeformers (oddtypes)	Can flat usually no swelling, except in cured meats when NO_3 and sugar are present	Coagulated evaporated milk, black beets

Source: Jay et al. (2005).

seams or seam defects. Another cause is underprocessed containers that can allow survival of microorganisms, which could result in spoilage. According to FDA (1998b) regulations, since there is no way of determining toxin presence, all swollen cans must be considered a potential health hazard and sampled and, in most cases, any lots with a swell rate in excess of 1% are considered to be unsafe. Table 24.6 shows spoilage manifestation in acid and low-acid canned foods, with common appearance of cans (Jay et al. 2005).

Summary

Outbreaks associated with fresh produce have spurred increasing concern about the safety of fresh vegetables. Pathogenic microorganisms causing outbreaks can be found on or in fresh produce and are found throughout the natural environment. Contamination can occur at any point in our food supply chain from farm to table. Determining the exact source of an outbreak is important when devising strategies and interventions to minimize risks of future outbreaks. Identifying primary inoculum sources for contamination of fresh produce can be difficult Among the greatest concerns with human pathogens on fresh fruits and vegetables are enteric pathogens, viruses, and parasites including *Salmonella*, *E. coli* O157:H7, shigella, hepatitis A, Norwalk-like virus, cyclospora, and cryptosporidium. Unfortunately, current production and processing practices cannot be relied upon to ensure pathogen-free fresh vegetables. Further efforts are needed to better understand the complex interactions between microbes and produce and the mechanisms by which contamination occurs from farm to table. No single strategy will be successful in eliminating contamination of fresh vegetable by human pathogens; effective food safety interventions are needed for implementation throughout the production, processing, and distribution of fresh vegetables.

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Part V

Commodity Processing

Chapter 25

Asparagus, Broccoli, and Cauliflower: Production, Quality, and Processing

Paramita Bhattacharjee and Rekha S. Singhal

Introduction

Brassica family of vegetables (broccoli and caulifl wer) and asparagus are consumed worldwide. Several epidemiological studies have indicated beneficia effects of these vegetables on our health. In this chapter, we review production, processing, quality and nutritional aspects of these vegetables.

Asparagus

Introduction

Asparagus (*Asparagus officinali* L.), a member of the lily family is related to onion, leek, garlic and tulip. This stem vegetable is a perennial with male (yellowish-green) and female (less conspicuous) fl wers on separate plants. The mature asparagus plant is dark green-fern-like foliage of about 3-ft (0.91 m) height. The edible portions of asparagus are the spears or the stems (cladophylls) that develop from the crown. Asparagus is known from early times as a vegetable and medicine, owing to its delicate fl vor and diuretic properties.

Asparagus can be white, purple, green, or a combination of purple and green. Exposure of the plants to ultraviolet light during cultivation causes depigmentation. European white asparagus is known as *spargel*. White asparagus is less bitter than the green and is popular in Netherlands, France, Belgium and Germany for its delicate fl vor and tender texture. Purple asparagus has high sugar and low fibe . It was originally developed in Italy and commercialized under the variety name *Violetto d'Albenga* (Kotecha and Kadam 1998; Robyn 2004; Anon. 2009a, 2009b).

Each country grows specifi types and varieties of asparagus suited to their particular climatic conditions and market needs. In the United States, the older asparagus cultivars such as *Mary Washington* are being replaced by higher yielding, all-male cultivars, such as *Centennial*, *Jersey Giant*, *Jersey Knight*, *Jersey General* and *Jersey King*. In Spain, *Ercole*, *Atlas* and *Jersey Deluxe* are high yielding green cultivars. Some of the white cultivars are *Rapsody*, *Ramada*, *Ravel*, *Rally*, *Ciprés* and *Thielim* (Kotecha and Kadam 1998; Cermeño et al. 2008).

Production and Consumption

Asparagus is commercially grown in many parts of Europe, Asia, Australia, New Zealand and North America. Although a temperate vegetable, it grows best when growing conditions provide high light intensity, warm days, cool nights, low relative humidity and adequate soil moisture. Direct seeding is rarely practiced in asparagus plantings; new plants are generated from vigorously growing clumps of roots called crowns that are about

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1 year old. The crowns are planted in spring when soil temperature is about 10°C. An asparagus crop does not reach full productivity for about 3 years, but once established, the plant can be productive for 15 years or more. Intercropping asparagus with other vegetables such as legumes or herbs is common; this also helps to reduce weed problems (Kotecha and Kadam 1998).

According to the Food and Agriculture Organization (FAO), the estimated world production of asparagus in 2007 was about 7 million metric tons (MMT). The top fi e asparagus producers were China (6.2 MMT), Peru (0.28 MMT), Germany (0.094 MMT), Mexico (0.053 MMT) and United States (0.05 MMT). Most of the asparagus produced in China is white and is exported as a processed product. The United States produces mainly green asparagus. The per capita availability of asparagus in the United States in 2009 was 1.38 lb (0.82 kilograms); of this, more than 80% was consumed as fresh, 10% as canned and 6% as frozen (USDA-ERS 2008a; Rich et al. 2009).

Harvest, Postharvest Handling and Storage

Asparagus spears begin as leaf buds below the soil surface; the spears grow above the ground during spring. Harvesting (firs cutting) of asparagus usually commences at this stage and it continues until spear quality deteriorates in the hot summer. When harvesting ceases, the spears are allowed to develop into leaves or ferns. During this stage, the plant photosynthesizes and replenishes its nutrient reserves in the crown for the next year's harvest.

The harvested spears are protected from sunlight and hydrocooled by immersing or spraying chilled water (3–5°C). They can be stored at 0–2.2°C for about 2–3 weeks under high (90–95%) relative humidity. Storage at subzero temperatures causes limp, mushy and discolored spears and high temperatures cause partially open bracts (feathering). Potential diseases and bacterial soft rot in asparagus can be minimized by dipping the spears in around 2% calcium hypochlorite or hydrogen peroxide solution.

Precooled, bundled spears are usually packed in fully waxed, paper-lined cartons as quickly as possible and stored at 0°C. The asparagus can be stored for about 10 days at this temperature, but can be subject to chilling injury if held longer. High humidity (~90–95%) during storage minimizes desiccation. A decline in tissue strength of asparagus spears held at 0 and 5°C was shown to correlate with a decrease in the ethylenediaminetetraacetic acid (EDTA) soluble pectin fraction (Kotecha and Kadam 1998; Robyn 2004; Herppich et al. 2005; Shou et al. 2007).

Storage of asparagus to an atmosphere of 5–9% CO_2 and 2% O_2 controlled atmosphere (CA) storage conditions for 24 hours retarded bacterial rots. However, 5% CO_2 was ineffective in controlling the growth of *Phytophthora* and 10% or higher concentrations of the same at 6.1°C causes development of pits. Chilling injury was not reported with 15% CO_2 at 1.7°C (Kotecha and Kadam, 1998). Current recommendations to extend shelf life of asparagus are modifie atmosphere packaging (MAP) and storage at 2–4°C (Fuchs et al. 2008). Three-stage hypobaric storage slowed respiration rate, loss of chlorophyll and vitamin C. It extended storage life to 50 days, compared to about 25 days in atmospheric cold condition and 6 days at ambient conditions (Li et al. 2006, 2008).

Physicochemical, Nutritional and Phytochemical Qualities

Texture

For fresh asparagus spears, texture is the main quality indicator. Good quality asparagus should not be fibrous woody, or stringy. Texture toughening has been related to lignificatio and modificatio of the cell wall composition. White asparagus cell walls contain

appreciable amount of phenolics, including ferulic acid and its dimers and trimers. An increase in storage temperature leads to a higher amount of cell wall phenolics; however, absence of oxygen in the storage atmosphere delays their accumulation. The degradation kinetics under these storage conditions indicate toughening of asparagus to be faster than chlorophyll degradation, which renders them unsuitable for human consumption (Renquist et al. 2005; Jaramillo et al. 2007).

Color

The spears are reported to retain color when stored in an atmosphere of $\geq$5% CO_2 in the dark and at $\geq$10% CO_2 concentration in the light. Even brief exposure to an atmosphere of 100% CO_2 prior to storage at ambient atmosphere is found to be very effective in color retention (Siomos et al. 2001, 2005).

Flavor

Good quality asparagus should exhibit full (not too mild) fl vor with a balance of sweet and bitter tastes. The fl vor profil of asparagus is influence by the cultivar, growing conditions and postharvest handling and storage (Hoberg et al. 2008). A total of 36 fl vors have been identifie in asparagus of which methanethiol, dimethyl sulfide dimethyl disulfide bis(methylthio)methane, dimethyl sulfoxide and dimethyl sulfone are noteworthy (Ulrich et al. 2001).

Chemical Composition and Nutritional Quality

Asparagus contains about 93% water, 4% carbohydrate, 2% protein, 2% fibe and 0.1% lipids. Table 25.1 gives typical nutrient values of raw, frozen and canned asparagus. As expected, freezing has protective effect on nutrients while canning causes loss of minerals and some water-soluble vitamins (USDA 2009).

Phytochemical Quality

Asparagus contains bioactive phytochemicals including hydrocinnamic acids (HCA), saponins, fl vonoids, sterols, alkaloids, polyphenols and fructans. Among the HCAs, 4-hydoxycinnamic acid (coumaric acid), 3,4-dihydroxycinnamic acid (caffeic acid) and 4-hydroxy-3-methoxycinnamic acid (ferulic

Table 25.1 Selected nutritional values of raw, frozen and canned asparagus

Nutrients/100 g	Raw asparagus (NDB 11011)	Frozen asparagus (NDB 11018)	Canned asparagus (NDB 11013)
Moisture (%)	93.22	91.82	94.32
Energy (Kcal)	20.0	24.0	15.0
Protein (g)	2.20	3.23	1.80
Fat (g)	0.12	0.23	0.18
Carbohydrate (g)	3.88	4.10	2.47
Dietary fibe (g)	2.10	1.9	1.0
Sugars (g)	1.88	NA	NA
Potassium (mg)	202.0	253.0	172.0
Sodium (mg)	2.0	8.0	284.0
Calcium (mg)	24.0	25.0	15.0
Iron (mg)	2.14	0.73	0.60
Vitamin A (IU)	756.0	948.0	526.0
Vitamin C (mg)	5.6	31.8	16.5
Niacin (mg)	0.978	1.202	0.851
Folate (μg)	52.0	191.0	85.0

Source: USDA 2009.
NA, not available.

acid) are the major phenolics in asparagus stalks. These are also conventional precursors of lignin, the concentration of which increases rapidly during storage above 10°C. Notable quantity (~0.01% fresh weight) of protodioscin, a saponin, is present in green asparagus spears. It is reported to possess strong cytotoxic effect against several cancer cell lines and increases levels of androgens. A moiety of protodioscin—diosgenin, also found in asparagus—has been found to reduce cholesterol and serum low-density lipoprotein (LDL) level. Asparagus also contains asparagin, coniferin and the glucoside vanillin (Kotecha and Kadam 1998; Liu and Jiang 2006; Chin and Garrison 2008; Guillén et al. 2008; Yingyan et al. 2008). A novel deoxyribonuclease with antifungal activity against *Botrytis cinerea* has also been isolated from the seeds of *A. officinali* (Wang and Ng 2001).

High dietary fibe powders obtained from asparagus spears has HCA content of 2.31–4.91 mg/g of fibe , 2.14–3.64 mg/g of saponins and 0.6–1.8 mg/g of fl vonoids. Sterols and fructans are present in minor amounts at 0.63–1.03 mg/g and 0.2–1.4 mg/g of fibe , respectively (Fuentes-Alventosa et al. 2009a, 2009b).

Rutin and its aglycone-quercetin, are also present in asparagus. Besides, two anthocyanins, cyanidin 3-[3′′(O-β-D-glucopyranosyl)-6′′ (O-α-1-rhamnopyranosyl)-O-β-D-glucopyranoside] and cyanidin 3-rutinoside have been isolated from the spear peels. Rutin in synergy with other antioxidative polyphenols can be used as an index for the medicinal value of asparagus. Light has a significan impact on the rutin and polyphenol content. The content of the polyphenols, rutin, ascorbic acid and chlorophyll contents as well as DPPH radical scavenging activity are known to decrease, if asparagus plants are grown in shade. The content of rutin is found to be significantl higher in leaves of asparagus than in roots and spears, whereas the activity of asparaginase is found to be higher in roots, compared to that in spears and leaves.

It has been demonstrated that pectinases decrease rutin content and, hence, antioxidant activity of asparagus while carbohydrases increase rutin content, soluble solid content and juice yield with high antioxidant activity. Laccase in pectinase is possibly the major cause of loss of rutin, which can be inactivated after heating the asparagus juice at 70°C for 90 seconds. However, rhamnosidase activity detected in pectinase can change rutin in asparagus juice to quercetin-3-glucoside, which has higher antioxidant activity than rutin. This may explain the increase of antioxidant activity of asparagus juice treated with heated pectinase (which retains some activity of rhamnosidase (Huang et al. 2006; Sun et al. 2007a, 2007b, 2007c; Ji et al. 2008; Yingyan et al. 2008).

Besides the above-mentioned compounds, asparagus also contains biothiols such as captopril, cysteine, *N*-acetylcysteine and glutathione which serve as antioxidants. However, hydrogen peroxide, commonly used as a disinfectant and sterilizer, is reported to markedly diminish these biothiols and develop oxidative stress in asparagus (Demirkol and Cagri-Mehmetoglu 2008; Demirkol 2009).

Asparagus shows higher antioxidant activity than broccoli since it contains more fl vonoids than broccoli. However, extracts from these vegetables and their juice products show no significan differences in total phenolic content (Sun et al. 2007d). Asparagus along with caulifl wer have cholesterol-lowering potential, which has been evaluated by determining the bile acid binding potential. The relative in vitro binding of bile acids by asparagus (4%) is significantl higher than that of caulifl wer (1%), but lower than that for broccoli (5%). Extracts from asparagus have been recently shown to increase the function of the enzymes (alcohol and aldehyde dehydrogenases) in the liver and boost the metabolism of alcohol (Kahlon et al.

2007a, 2007b; Sun et al. 2007d; Kim et al. 2009).

In the Indian system of medicine, *Asparagus racemosus* is an important medicinal plant and its root paste or root juice has been used in various ailments and also as a health tonic. Reports indicate that the pharmacological activities are principally due to its phytoestrogenic properties. The extracts from this plant are known to be effective in controlling depression and hypertension. Asparagus-P® is a traditional herbal medicinal product consisting of a combination of asparagus roots and parsley leaves in equal proportions which supports kidney function and combats inflammatory processes (Bopana and Saxena 2007; Dhingra and Kumar 2007; Dartsch 2008).

Although asparagus has potential health benefits preliminary investigations suggest several steroids isolated from the roots of *A. officinali* L. to have cytoxicity in human cells (Huang et al. 2008).

Processing

Minimal Processing

Minimal processing of white asparagus includes peeling, trimming, brief immersion in water (containing 50 ppm free chlorine), packaging in O_2-permeable polypropylene film and subsequent storage at 4°C. Semipermeable film with an adsorbent material (such as silica gel and alumina) and immersion in ascorbic acid solution extend shelf life of green asparagus in cold storage at 6°C (Albanese et al. 2006). Exposure to normal light accelerates deterioration of texture and color, promoting greenish hues in tips and reddish-brown hues in spears. However, blue-light illumination and use of packaging film of proper permeability with a blue-tinted color shows better preservation of minimally processed asparagus (Sanz et al. 2009).

A decrease in iron and manganese levels and an increase in copper and zinc are observed during processing of asparagus. These changes are due to peeling prior to processing (López et al. 1999, 2004; Siomos et al. 2008).

Canning

Canned asparagus is prepared from the edible portion of the stalks of asparagus. For canning, fresh asparagus is cleaned, prewashed and steam blanched to inactivate enzymes. The green and white portions of asparagus are separated and then immersed in 2.0–2.5% brine solution containing 0.2% citric acid. The cans are then exhausted, sealed and processed at 115–120°C for 15–30 minutes, depending on the size and grade of the cans. Subsequently, cans are cooled and stored. Canned white asparagus has been found to retain 73% of the initial crude fibe by dry weight (Martín-Belloso and Llanos-Barriobero 2001).

Freezing

Green asparagus is preferred to white ones for frozen storage because of its richer fl vor. Field-fresh asparagus should be frozen within 5–6 hours after cutting because it rapidly toughens, becomes stringy and acquires a bitter taste on standing at temperatures above 5°C. A thorough blanching by steam, water, or microwave is necessary before freezing. The collapse of frozen asparagus on thawing can be minimized if it is individually quick-frozen (IQF). These IQF products are not markedly different in appearance from the cooked, fresh asparagus (López et al. 1999, 2004).

Effects of Processing on Asparagus Quality

The fibe -rich powders obtained as by-products from asparagus are a potential source of dietary fibe . Heat processing and continuous stirring during processing have been found to affect the phytochemical composition (principally the fl vonoids) and antioxidant activity of the same. HCA content in

the fibe is also affected by the drying methods (Fuentes-Alventosa et al. 2009a, 2009b).

Vitamin C content, dietary fibe , chlorophyll and drip loss have been investigated in preblanched frozen asparagus spears. Loss in vitamin C content is found to be the least after microwave blanching compared to steam and water blanching. Although cryogenic freezing reduces drip loss significantl , the vitamin C, chlorophyll and dietary fibe in the frozen spears subjected to blast freezing or cryogenic freezing were reported to be similar (Kidmose and Kaack 1999).

Broccoli

Introduction

Broccoli *(Brassica oleraceae* var. *italica*) belongs to the Brassicaceae (formerly known as Cruciferae) family. The Brassicaceae includes more than 350 genera and 3,500 species, which include biennials and annuals, characterized by a wide adaptability to growing environments. Many cole crops such as caulifl wer, cabbage, kale, collards, bok choy and brussel sprouts belong to *B. oleracea.* Broccoli is a compact, fast-growing flora vegetable with a head of fles y tight fl wer heads (curds) or buds, usually green in color arranged in a tree-like fashion on branches sprouting from an edible stalk. It is a cool weather, slow maturing crop. Broccoli is native to the Mediterranean and Asia Minor. It has been popular in Italy since the Roman Empire. During the late twentieth century, its use and production has picked up in the United States (Rangavajhyala et al. 1998; Anon. 2009a).

There are fi e cultivar groups in broccoli—sprouting broccoli or Calabrese, Broccolini (a cross of broccoli with Chinese kale), purple broccoli, Chinese broccoli (also known as Chinese kale) and white fl wering broccoli. There are several varieties of broccoli. Examples of varieties grown in warm lowlands are *Greenbud*, *DeCicco* and *Spartan Early*; varieties such as *Waltham 29*, *Coastal Atlantic*, *Green Mountain* and *Premium Crop* are best adapted to cool uplands, above 2,000 ft elevation. Examples of fresh market varieties are *Arcadia*, *Buccaneer* and *Southern Comet*. The varieties used for processing are *Arcadia*, *Emerald City*, *Excelsior*, etc. (Rangavajhyala et al. 1998; Rahman et al. 2007; Anon. 2009c; Michelle et al. 2009).

Production and Consumption

Broccoli cultivation needs bright sunshine, rich, alkaline, well-drained soils with pH around 6.5–7.5. Soil pH over 6.8 is preferred to manage club root disease. Mulching to keep plants cool and moist is advantageous. The bed is prepared with manure and compost and extra nitrogen provided if the soil is sandy. Broccoli can be seeded directly or seedlings (4–6 inches high) can be transplanted into the field For good transplant production, temperatures below 29°C during the day and above 7°C at night are desired. The beds should be cultivated frequently to control weeds and to break up surface crusting to improve water penetration. Crucifer crops and related weeds such as wild radish and wild mustard should not be present in the fiel for at least 2 years before broccoli planting. Cultivation has to be shallow to prevent root injury. Broccoli forms its firs head in 85–90 days. After the primary head is picked, most varieties produce secondary shoots with much smaller heads all seasons long. An increase in the plant spacing beyond 45 cm can cause lower number of heads, while narrow spacing can cause competition among the plants leading to lower diameter and weight of curd (Madhavi and Ghosh 1998; Rangavajhyala et al. 1998; Rahman et al. 2007).

The data on world production of broccoli and caulifl wer are given together by the FAO. In 2007, the combined world production of these two vegetables was about 17.7 MMT. China (~8.0 MMT) and India (~5 MMT) were the leading producers of these two

vegetables. According to the United States Department of Agriculture's (USDA) *Vegetables and Melons Yearbook* data published by its Economic Research Service, the estimated broccoli production in the United States in 2008 was about 1 MMT. As a result of various studies linking consumption of broccoli with health benefits broccoli has emerged as one of the top utilized vegetables in United States. The per capita utilization of fresh and frozen broccoli in the United States in 2008 was about 2.7 kg and 1.2 kg, respectively (USDA-ERS 2008b, 2008c).

Harvest, Postharvest Handling and Storage

Broccoli is harvested when it has uniform, blue-green to green color and tight dome-shaped heads that stand above the leaves. Appearance of yellow petals indicates overmaturity. Side heads develop after the large central head is removed. Postharvest application of cytokinins has been shown to delay senescence of whole stalks of broccoli. Harvested broccoli heads are trimmed to approximately 6 inches and bunches weighing about 1.5 pounds are used for retailing. Like other vegetables, broccoli is highly perishable. After harvest, broccoli is hydrocooled to about 4.4°C to lower the respiration rate. Subsequently, it is packed with ice and stored under refrigeration at 0°C for about 3–5 days. This maintains broccoli in good salable condition and retains its fresh green color and vitamin C. Broccoli should not be washed before storage since the excess moisture renders it limp and moldy. For broccoli to be held above 4–5°C for more than 3 weeks, 6% CO_2 and 2.5% O_2 was reported to cause minimum physiological injury (Rangavajhyala et al. 1998).

MAP of broccoli was shown to increase chlorophyll and C-18 polyunsaturated fatty acids (PUFA) in broccoli floret within 96 hours of storage. It is recommended to cold (3–5°C) pack broccoli floret since packaging at warm (20°C) temperature caused color loss and rendered them unsuitable for consumption (Rangavajhyala et al. 1998; Ekman and Golding 2006).

Nutritional and Phytochemical Qualities

Nutritional Composition

Table 25.2 gives selected data on selected nutrients of raw, cooked and frozen broccoli. Broccoli contains about 90% water, 2.8% protein, 6.6% carbohydrate, 2.6% fibe and 0.4% lipids. It is a good source of vitamin C, vitamin A and potassium.

Refrigerated broccoli can lose some of its nutrients, especially vitamin B complex, vitamin C, Fe and Ca (Rangavajhyala et al. 1998; Podsędek 2007; USDA 2009).

Flavor

Important compounds responsible for fl vor of broccoli are ethanol, C5-C7 aldehydes, 2,3-butanediol and 3-hydroxy-2-butanone; the concentration of these compounds would vary depending on storage conditions and processing (Rangavajhyala et al. 1998; Podsędek 2007).

Phytochemical Quality and Antioxidant Capacity

Besides vitamin C and vitamin A, broccoli contains glucosinolates (GLS), polyphenols, carotenoids (β-carotene, lutein and zeaxanthin), vitamin E and sulfur-containing compounds. The nitrogen and sulfur-containing glucosides called GLS—mustard oil glucosides or thioglucosides—have drawn most attention. These GLS are a group of non-nutritional plant secondary metabolites, which are anions and occur in plants mostly as potassium salts. A generalized structure of GLS is shown in Figure 25.1. Table 25.3 shows various GLS commonly found in Brassica vegetables. The glycosyl component of

Table 25.2 Selected nutritional values of raw, cooked and frozen broccoli

Nutrients/100 g	Raw broccoli (NDB 11090)	Cooked broccoli (NDB 11091)	Frozen broccoli (NDB 11092)
Moisture (%)	89.30	89.25	91.46
Energy (Kcal)	34.0	35.0	26.0
Protein (g)	2.82	2.38	2.81
Fat (g)	0.37	0.41	0.29
Carbohydrate (g)	6.64	7.18	4.78
Dietary fibe (g)	2.60	3.3	3.0
Sugars (g)	1.70	0.08	1.35
Potassium (mg)	316.0	293.0	212.0
Sodium (mg)	33.0	41.0	24.0
Calcium (mg)	47.0	40.0	56.0
Iron (mg)	0.73	0.67	0.81
Vitamin A (IU)	623.0	1548.0	1034.0
Vitamin C (mg)	89.2	64.9	56.4
Niacin (mg)	0.639	0.553	0.470
Folate (μg)	63.0	108.0	67.0

Source: USDA 2009.

β-D-glucopyranose and all GLS have the anticonfiguratio with respect to the sulfate and R groups. The GLS content of purple broccoli has been found to be in the range of 72–212 mg/100 g (Rangavajhyala et al. 1998; Bellostas et al. 2007).

Epidemiological studies highlight an inverse relationship between consumption of Brassicaceae vegetables and cancer risks. The GLS compounds of *Brassica* possess low-antioxidant activity but the products of their hydrolysis have therapeutic, notably cancer-protective properties. Under moist conditions, GLS are hydrolyzed by the action of the coexisting endogenous enzyme myrosinase (thioglucoside glucohydrolase, EC 3.2.3.1), present in plant tissues to yield β-D-glucose, sulfate and organic aglycone moieties. Depending on the reaction conditions such as presence of proteins, pH and trace metals, these aglycones undergo intramolecular rearrangement and/or fragmentation to yield volatile and nonvolatile products such as hydrogen sulfide methanethiol, ethanethiol, propanethiol, dimethyl sulfide acetaldehyde, 2-methyl propanol, thiocyanates, isothiocyanates, oxazolindine-2-thiones, indoles, cyanides and nitriles. These compounds along with sulforaphane, released when caulifl wer and broccoli are chopped (or chewed), are

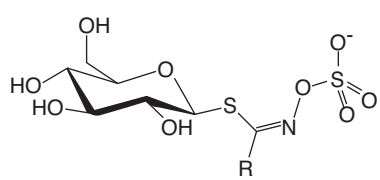

Figure 25.1 Structure of glucosinolate. Source: Rangavajhyala et al. 1998.

Table 25.3 The glucosinolate skeleton commonly found in Brassica vegetables

R(variable side chain)	Trivial name
Prop-2-enyl	Sinigrin
2-hydroxybut-3-enyl	Progoitrin
2-hydroxypent-4-enyl	Gluconapoleiferin
3-methylthiopropyl	Glucoiberverin
3-methylthiobutyl	Glucoerucin
3-methylsulfin ylpropyl	Glucoiberin
3-methylsulfi ylbutyl	Glucoraphanin
2-Phenethyl	Gluconasturtiin
Indolyl-3-methyl	Glucobrassicin
4-hydroxyindolyl-3-methyl	4-hydroxyglucobrassicin
2-methoxyindolyl-3-methyl	4-methoxyglucobrassicin
1-methoxyindolyl-3-methyl	Neoglucobrassicin

Source: Rangavajhyala et al. 1998.

responsible for sulfurous odors of these vegetables, the intensity of which increases with cooking time.

Among all these compounds, the products that possess the indolic side-chain have been associated with cancer defense presumably through the induction of mammalian (liver) phase II detoxificatio enzymes such as glutathione reductase, glutathione transferase, UDP-glucoronosyl transferase, epoxide hydrolase and NADPH: quinone reductase. These enzymes, in addition to protection against carcinogenesis, also prevent mutagenesis and other forms of toxicity of electrophiles and reactive forms of oxygen. A total of 11 GLS have been identifie in broccoli, of which glucoraphanin is found to be most abundant, representing 90% of the aliphatic GLS. Other aliphatic GLS include progoitrin, piprogoitrin, glucoiberin, napoleiferin, glucoalysin, glutathione, glucarate and gluconapin; the lowest concentration is that of the indole GLS of which glucobrassicin is the most abundant (Fahey et al. 1997; Nestle 1997; Heimler et al. 2006; Nilsson et al. 2006; Bellostas et al. 2007).

In the case of the breast cancer, broccoli is reported to play a role in the removal of estrogen. Indole-3-carbinol (a metabolite of glucobrassicin), 3,3′-diindolylmethane (produced from indole-3-carbinol), glucoraphanin (also known as sulforaphane glucosinolate, SGS), vitamin C and β-carotene (converted to vitamin A in the body) are the principal components that confer these protective properties along with selenium (Verhoeven et al. 1996; Heimler et al. 2006; Bellostas et al. 2007; Podsędek 2007).

Recent studies have confirme that the isothiocyanate sulforaphane is highly effective in protection against chemically induced cancers. Its anticarcinogenic activity has been well demonstrated in cases of cystic carcinoma, ovarian cancer and colorectal cancer. It is found to be a positive regulator of phase II detoxificatio enzymes and induces apoptosis and cell cycle arrest. It also enhances radiosensitivity in human tumor cells and, thereby, presents possibilities for a multitude of clinical applications for chemoradiotherapy. It has also been found to act as a dietary preventive agent against oxidative stress-induced intestinal injury (Chu et al. 2009; Nishikawa et al. 2009; Yeh et al. 2009; Yu et al. 2009). Other studies suggested protective effect of steamed and cooked broccoli on ischemia-reperfusion-induced cardiac injury through the redox signaling of sulforaphane (Mukherjee et al. 2010).

The Brassicaceae family is also known to contain fl vonoids, especially fl vonols. Flavonoids, phenolic acid and total polyphenol content (mg/g dry weight) are 3.04, 8.69 and 11.73, respectively, in broccoli. The phenolics include kaempherol, quercitin glycosides and hydrocinnamic esters. Many of the fl vonols identifie exist in both free and in conjugated forms in broccoli.

Predominant HCAs identifie in broccoli floret are 1,2-disinapoylgentiobiose, 1-sinapoyl-2-feruloylgentiobiose, 1,2-diferuloylgentiobiose, 1,2,2′-trisinapoyl gentiobiose, 1,2–disinapoyl-2-feruloylgentiobiose and 1-sinapoyl-2,2′-diferuloylgentiobiose. Total amounts of feruloylsinapoyl esters of gentiobiose and caffeic acid derivatives in several cultivars of broccoli vary from 0–8.25 mg/100 g and from 0–3.82 mg/100 g, respectively. Identifi cation of these classes of compounds together with the assessment of their antiradical activity is providing a good insight into the protective effects of Brassica vegetables against cancer and cardiovascular disorders (Kushad et al. 1999; Heimler et al. 2006; Podsedek 2007; Sultana and Anwar 2008).

Broccoli also acts as an antilithogen on prostatic stones and is preventive against interstitial cystitis and urinary tract infections. Along with spinach, it minimizes risk of cataracts. It is suggested that D-glucaric acid (3.5 g/kg) present in broccoli plays a role in reducing levels of serum cholesterol (Fahey et al. 1997; Rangavajhyala et al. 1998).

A protein in broccoli called epithiospecifie protein (ESP) plays a role in pushing the balance toward the sulforaphane. Heating the broccoli destroys the ESP, tipping the balance in favor of the beneficia sulforaphane. Research is under progress to ensure high levels of this beneficia compound by eliminating the genes in broccoli, which code for the ESP protein. Broccoli proteins have also been established to be potential rich sources of the vasoconstrictor enzyme (angiotensin I-converting enzyme, ACE, kinase II, EC 3.4.15.1) inhibitor, which has been identifie as a tripeptide (Try-Pro-Lys). Clinical trials with these high activity peptides have indicated them to be a possible treatment for hypertension (Fahey et al. 1997; Rangavajhyala et al. 1998; Lee et al. 2006).

At high intake levels, the GLS are associated with toxic effects, especially goiter development. Broccoli is also one of the leading producers of intestinal gas leading to flatu lence and it is, therefore, suggested to consume broccoli with ginger or garlic to reduce gas production (Fahey et al. 1997; Anon. 2009a).

Processing

Cooking

Broccoli should be cooked as soon as it is cut to retain vitamin C and fl vor. Pan-steaming method, also known as braising, is most preferred. Recent studies have shown superior cardioprotective properties of steamed broccoli over cooked broccoli. Overcooking is, however, not recommended for broccoli so as to minimize loss of its nutrients including the cancer protective compounds and to avoid the crowns becoming mushy and discolored (Hansen et al. 1997; Wachtel-Galor et al. 2008; Mukherjee et al. 2010).

Freezing

Freezing is the best way to preserve broccoli. It is frozen after scalding or blanching in boiling water or steam for 3–5 minutes to stabilize the green color and deactivate enzymes (peroxidases, catalases, polyphenoloxidases and ascorbic oxidases) which cause toughening, fl vor and nutrient loss during freezing. This is followed by cooling to 10–15°C, wrapping in plastic bags and, then frozen storage at −20°C (Rangavajhyala et al. 1998; Kmiecik et al. 2007; Podsędek, 2007).

Effects of Processing on Broccoli

Blanching and boiling of broccoli causes about 30% loss of GLS. Blanching broccoli in water results in loss of 8–9% solids compared to a minimal 2% solid loss when blanched in steam. Besides, steam blanching also results in better retention of total folate content than water blanching. Postblanching retention of vitamin C is about 60–62%. Antioxidant capacity and phenolic contents are found to be in the order of steamed > boiled > microwaved and decrease with longer cooking time, regardless of method. Conventional cooking in water causes leakage of vegetable antioxidants into the cooking water. Typically, steaming is the preferred cooking method to release or conserve antioxidant potential of Brassica vegetables (since it leads to retention of fl vonoids and phenolic compounds); microwave treatment should be avoided since it causes more losses of the same (Rangavajhyala et al. 1998; Cieślik et al. 2007; Podsędek 2007; Song and Thornalley 2007; Sikora et al. 2008; Wachtel-Galor et al. 2008).

The freezing preservation does not affect GLS significantl . Frozen broccoli after a 12-month storage at −20°C loses about 3–18% vitamin C. Freezing, however, may cause a greyish-brown discoloration and softening of the curd accompanied by water-soaked conditions. The loss of the green color is the major limiting factor in the shelf life of frozen broccoli. Investigations have also been carried out on the retention of minerals in broccoli post-processing and frozen storage for 12 months. Broccoli cooked in 2% brine, frozen- and

microwave-cooked retains ash, K, Na, Mg, Fe, Mn and P significantl (Rangavajhyala et al. 1998; Kmiecik et al. 2007; Podsędek 2007).

Cauliflower

Introduction

Caulifl wer *(Brassica oleraceae* L. var. *botrytis*) is considered as the most refine and delicate vegetable crop of the Brassicaceae family. Although a biennial, some varieties are grown as cool season annuals, requiring moderately cool climates for growth. The edible portion of the caulifl wer is a compact head or curd (thick undeveloped yellow to creamy white fl wers), which constitutes approximately 45% of the vegetable (Madhavi and Ghosh 1998; Sanders 2009).

There are four major types of caulifl wer. The *Italian type* can be white, green, purple, brown and yellow. They are considered the ancestral type from which other varieties have developed. The Northwest European biennial developed in the nineteenth century in France is grown during winter and early spring and includes the cultivars *Roscoff* and *Angers*. The Northern European annuals are grown in Europe and North America for summer and fall harvest. These were originally developed in the eighteenth century in Germany and include cultivars like *Erfurt* and *Snowball*. The Asian group formerly developed in India during the nineteenth century is the tropical caulifl wer grown in China and India and includes *Early Patna* and *Early Benaras* varieties. Other common varieties of caulifl wers include *Snowball*, *Hybrid White*, *Super Snowball*, *Snow Crown*, *Perfected Snowball*, *Early Snowball*, *Extra Early Snowball*, *Mayflowe* , etc. (Madhavi and Ghosh 1998; Jack et al. 2009; Sanders 2009).

Production

Caulifl wer like broccoli requires fertile, loose, moist, well-drained soil with signifi cant organic matter, good water-holding capacity and pH ranging from slightly acidic to neutral (5.5–7.0). Sandy loams are good for earlier crops while loams and clay loams are ideal for late crops. Caulifl wers require high magnesium levels for good growth. The planting and cultivation of caulifl wer is similar to broccoli (Madhavi and Ghosh 1998; Rahman et al. 2007; Sanders 2009). Separate data on caulifl wer production and utilization is given by the USDA's Economic Research Service. Accordingly, the production of caulifl wer in 2008 in the United States was 0.324 MMT and its per capita utilization as fresh and frozen was 0.72 kg and 0.22 kg, respectively (USDA-ERS 2008b, 2008c).

Harvest, Postharvest Handling and Storage

Heads of caulifl wers are harvested when the curd is regular in shape, medium size (15–25 cm in diameter), firm compact, globular and smooth in appearance. The time from tying the outer leaves to harvesting varies from 4–5 days during warm and 14–21 days during cool periods. Depending on the variety and the growing conditions, caulifl wer is ready for harvest after 90–120 days of planting. Late harvesting results in overmature curds, which appear loose with uneven spaces commonly known as ricy curds.

The curds are properly sorted out and stored in the shade to prevent browning (pale yellow to blackish-brown) due to sun's ultraviolet rays. It is customary to hydrocool the curds to 1–5°C immediately after harvest to remove fiel heat. Treatment of caulifl wer with α-naphthylacetic acid (NAA) or dichlorophenoxyacetic acid (2,4-D) prevents leaf abscission and increases storage life. Treatment with one of these chemicals and low-temperature storage retards yellowing of caulifl wer.

Postharvest senescence of caulifl wer is correlated with lipid peroxidation in which PUFA are preferentially degraded by reactive

oxygen species. Postharvest quality is reported to be better for caulifl wers grown under environmental stress conditions of low temperature and high water loss of plants. Under these conditions, the caulifl wers exhibited an increase in the fatty acid content, polyphenols and antioxidant activity. Late harvested caulifl wers showed increase in unsaturated fatty acids (Madhavi and Ghosh 1998; Scalzo et al. 2007; Sanders 2009).

CA is not recommended for caulifl wer storage as it produces soft curds and off-odors. A maximum level of 10% CO_2 can be used at 0°C; at higher temperatures, even 5% CO_2 causes severe injuries. The GLS content, however, increases during these conditions of storage (Madhavi and Ghosh 1998; Hodges et al. 2006). Studies on MA storage at 8°C of mixed floret of caulifl wer and broccoli has shown 1% O_2 + 21% CO_2 to be the best storage conditions for 7 days at 8°C. Under these conditions, external appearance and concentration of GLS are well maintained and off-odor prevented in the Brassica medley (Ekman and Golding 2006; Schreiner et al. 2006, 2007).

Physicochemical, Nutritional and Phytochemical Qualities

A comparative data on selected nutrients in raw, cooked and frozen caulifl wer is given in Table 25.4. Among the GLS, the concentration of aliphatic GLS is least in white caulifl wers, compared to the other members of the cruciferous family. Caulifl wer is also known to contain very high amount of fl vonols. Flavonoids, phenolic acid and total polyphenol content (mg/g dry weight) are 0.16–0.29, 0.09 and 0.38 in white caulifl wer and 2.10, 0.07 and 2.17 in green caulifl wer, respectively. Caffeic acid and sinapic acids are the major hydroxycinnamic acids in caulifl wers. Apigenin and luteolin are the principal fl vones in caulifl wers, which have not been detected in broccoli.

However, caulifl wers are known to contain goitrogens which interfere with the functioning of the thyroid gland and also purines which if taken in excess lead to gout and kidney stones (Madhavi and Ghosh, 1998; Nilsson et al. 2006; Podsędek 2007; USDA 2009).

Table 25.4 Selected nutritional values of raw, cooked and frozen cauliflower

Nutrients/100 g	Raw caulifl wer (NDB 11135)	Cooked caulifl wer (NDB 11136)	Frozen caulifl wer (NDB 11137)
Moisture (%)	92.07	93.00	92.51
Energy (Kcal)	25.0	23.0	24.0
Protein (g)	1.92	1.84	2.01
Fat (g)	0.28	0.45	0.27
Carbohydrate (g)	4.97	4.11	4.68
Dietary fibe (g)	2.0	2.30	2.30
Sugars (g)	1.91	2.08	2.22
Potassium (mg)	299.0	142.0	193.0
Sodium (mg)	30.0	15.0	24.0
Calcium (mg)	22.0	16.0	22.0
Iron (mg)	0.42	0.32	0.54
Vitamin A (IU)	NA	12.0	12.0
Vitamin C (mg)	48.2	44.0	48.8
Niacin (mg)	0.507	0.410	0.429
Folate (μg)	57.0	44.0	64.0

Source: USDA 2009.

Processing

Cooking

Caulifl wer is cooked longer than broccoli by steaming, boiling, or microwaving (Madhavi and Ghosh 1998; Sultana et al. 2006; Wachtel-Galor et al. 2008).

Drying

Thin-layer drying of fresh caulifl wer floret at 60°C in tray dryers shows best rehydration characteristics and sensory parameters. Hot-water blanching is recommended as a pre-treatment prior to drying (Thakur and Jain 2006; Mudgal and Pande 2007).

Pickling

Caulifl wer is often used as a component of mixed pickles. Curds are stored for several days in 5–16% brine until packaged and sold at retail markets (Madhavi and Ghosh 1998).

Freezing

Among processed caulifl wers, frozen form is the most common. Varieties of caulifl wers that produce large white heads with relatively smooth surfaces, tender texture and not too thick flore stalks are desirable for freezing. Rapid transport from fiel to freezer is crucial. The curds are broken into individual florets washed, blanched for 4–5 minutes in steam, cooled in water and placed on a conveyer with cold air blowing to cause rapid evaporative cooling. The cooled floret are either IQF-frozen or mechanically packed into cartons for freezing in plate or blast freezer (Madhavi and Ghosh 1998; Podsędek 2007).

Hurdle Technology

Caulifl wer, postblanching can be preserved by low-cost, low-energy processing technology (hurdle technology) involving different concentrations and combinations of salt (5, 10 and 15%), potassium metabisulfit (KMS) and citric acid (1%) up to 180 days. Among these treatments, caulifl wer samples steeped in 10 and 15% salt solutions containing 0.2% KMS were rated best at the end of the storage period (Madhavi and Ghosh 1998; Barwal et al. 2005).

Effects of Processing on Cauliflower

Blanching of caulifl wer results in about 2.7% loss of GLS. Boiling produced much greater losses in white caulifl wer (35%) compared to blanching. Fine shreds of caulifl wer–broccoli medley show 90% loss of GLS into the cooking water when boiled; however, steaming, microwaving and stir-frying does not produce significan loss of the same. Conventional cooking of violet-pigmented caulifl wers leads to loss of anthocyanin, while microwave heat treatment preserves the same. Thus, bioavailability of GLS and the antioxidants can be increased by avoiding prolonged boiling of caulifl wers during thermal processing (Madhavi and Ghosh 1998; Wachtel-Galor et al. 2008).

Contrary to the effect of cooking on antioxidants, cooking in water has beneficia effect on free phytosterol content of caulifl wers. Cooking in boiling water for 30 minutes increases the content of free phytosterols, principally sitosterol and campesterol in caulifl wers. Cooked caulifl wers are reported to provide better protection against cardiovascular diseases (Kaloustian et al. 2008).

Effects of freezing on caulifl wer are similar to that on broccoli. Freezing does not affect concentration of GLS significantl . Frozen caulifl wer after 12-month storage at −20°C loses 6–13% vitamin C (Madhavi and Ghosh 1998; Rangavajhyala et al. 1998; Kmiecik et al. 2007; Podsędek 2007).

Processing of caulifl wers produces a large amount of byproducts mainly leaves and stems, of which leaves constitute 50% of the total wastes. These residues are of environmental concern and have been traditionally

valorized for fibe and fuel production. Besides, caulifl wer leaves are an excellent unconventional feed for ruminants, equivalent to any conventional green fodder. Caulifl wer wastes have also found use in medium for production of glucoamylase using *Aspergillus niger*. A 30% supplementation of dried caulifl wer wastes has shown substantial increase in glucoamylase activity. Moreover, incorporation of caulifl wer waste in molasses at 15% w/w increases ethanol production by nearly 36% as compared to molasses alone. Peroxidase enzyme has also been isolated from caulifl wer and purifie to 19.3-fold (Wadhwa et al. 2006; Dhillon et al. 2007; Oberoi et al. 2007).

The caulifl wer byproduct extracts show significan free radical scavenging activity, ferric-reducing ability and capacity to inhibit lipid peroxidation. Caulifl wer by-products (trimmings) are sources of dietary fibe , antioxidants and proteins in cereal based ready-to-eat expanded snacks. Five to twenty percent of dried and milled caulifl wer wastes added to formulation mixes have been subjected to extrusion cooking which signifi cantly increased the level of phenolic compounds and antioxidants. However, prior to incorporation of these byproducts as a dietary complement or as a natural food antioxidant, toxicity, pesticide residues, in vivo activity and bioavailability of the same need to be investigated (Llorach et al. 2003; Stojceska et al. 2008).

Conclusion

The nutritional qualities of caulifl wer, broccoli and asparagus depend on genetic, environmental (biotic and abiotic factors), postharvest handling and storage and on processing. Conventional processing methods such as blanching, cooking and canning significantl influenc the nutritional value of these vegetables. Minimal processing of these vegetables may be helpful in preserving their nutritional qualities. Development of packaging materials to enhance storage life and utilization of by-products from these vegetables require further work.

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Chapter 26

Avocado: Production, Quality, and Major Processed Products

Tasleem Zafar and Jiwan S. Sidhu

Introduction

Avocado (*Persea americana*), a climacteric fruit is used primarily as a vegetable. Like olives, avocado is rich in monounsaturated fatty acid (oleic acid), health-promoting phytosterols, and phenolic antioxidants. Generally large-sized, good quality avocados are sold in retail markets. Avocados are processed as guacamole, frozen slices and sauces, puree, canned, dehydrated, and as avocado oil. Processing of avocado into guacamole or pulp has enabled the exporters to serve far and wide markets. This chapter reviews the production and consumption, postharvest physiology, storage and shelf life, physicochemical and nutritional characteristics, as well as the major value-added products made from avocado.

Production and Consumption

Background and Origin

Avocado seeds were found among the remains of many other species of cultivated plants in cave deposits in Tahuacan valley Puebla, Mexico. The oldest cotyledon from Coxcatalan Cave was found to be dated 10,000 BC by C^{14} determination and was not found to be morphologically different, to a significan extent, from the recent avocado pits (Smith 1966, 1969). The avocado is also known as butter pear after its buttery smooth texture and shape of a pear. Avocado is classifie as *P. americana*. It belongs to kingdom Plantae, family of Lauraceae, order Laurales, genus *Persea*, and species *P. americana*. The three major commercially important races are, var. *drymifolia* from the Mexican highlands, var. *guatemalensis* from Guatemalan highlands, and var. *americana* from the pacifi lowlands (Blumenfeld and Gazit 1974).

Avocado tree is dense, evergreen, and tall (∼20 m). It can grow in areas from central highlands of Mexico, where frost occurs, to lowlands of Central and South America, where the climate is without frost but with little wind to maintain the needed humidity. West Indian varieties do best in humid, tropical climates but get freezed at near 0°C. Mexican types thrive well in dry subtropical and Mediterranean climate whereas Guatemalan types are native to cool, high altitude tropics. Avocados adapt well to mild-winter conditions but not to the desert conditions. They grow in Florida and Hawaii and in the cooler parts of northern and inland California. The Hass cultivar can tolerate temperature down to −1°C. Avocado has been grown in California since 1871 (Blumenfeld and Gazit 1974, Anon 1999).

Cultivation

Avocados are commercially grown by grafting. Grafted trees not only produce fruit

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quickly in 1–2 years as compared to 8–20 years if grown from seeds (Blumenfeld and Gazit 1974), but the reproducibility of the fruit quality is also ensured. Avocado trees grow well in hilly sloping land with loose or sandy loam soil. These trees are never grown on a fla land or streambeds as a good drainage is important for success. Soil pH is adjusted according to the avocado cultivar (usually pH of 5.5–6.5), using lime or dolomite. The avocado tree requires regular irrigation to maintain high yields. Most orchards are supplied with mini sprinkler under each tree for irrigation. Mature trees are given nitrogenous fertilizer in late winter or early summer. For the young trees after 1 year of growth, feeding balanced fertilizer 3–4 times yearly is beneficial Iron deficien y is seen when the leaves turn yellow. Zinc deficien y is also common in mature trees. Mineral defi ciencies are usually corrected with trace minerals spray (Anon 1999).

Avocado fl wers appear in the months from January to March as 200–300 small yellow-green panicles before the firs seasonal growth. Each panicle will produce only one to three fruits, which is about less than 0.1% of the fl wers. Although the trees produce abundance of fl wers, because of the dichotomy in its fl wering, avocados are only partially self-pollinating making breeding difficult The fl wers are perfect, but unusual in the timing of the male and female fl wering phases (Lewis 1978).

Major Varieties

The three major races have different growing conditions and characteristics, which are stated as follows:

1. Mexican race (*P. americana* var. *drymifolia* Blake): This avocado variety is native to highlands of Mexico and Chile. Trees are planted in high elevation. They are resistant to cold thus called cold hardy. Leaves are anise scented. They bear small fruit that ripens in 6–8 months. The oil content is up to 30%.

   Some of the popular cultivars of the Mexican variety include Ganter, Mexicola, Mexicola Grande, Duke, and Topa.
2. Guatemalan race (*Persea nubigena* var. *guatamalensis* L. Wms.): This variety is native to areas from highlands of Central America to Ecuador and Mexico. Trees are cold hardy. They grow large fruit with rough skin that ripens in 9–14 months. The seeds are small and tight in cavity. The oil content is 7.5–18%.

   Various cultivars of Guatemalan race include Anaheim, Hass, Nabal, Pinkerton, Queen, Sharwil, Gwen, etc.
3. West Indian race (*P. americana* Mill. var. *americana*): This variety is native to lowlands of Central and South America. Being a summer variety, the trees are sensitive to cold. The size of the fruit is variable with thin and smooth skin that ripens in 6–9 months. The seeds are loose and shake in the fruit. The oil content is 5–7%.

   The popular cultivars are Lula, Lyon, etc.

Because of the geographical isolation, these species do not cross-fertilize. Hybrid forms exist among all three types or races. For example, Fuerte, an important cultivar, is a crossbreed of Mexican and Guatemalan subspecies, and Hass is a hybrid of Guatemalan with some influenc from Mexican subspecies. The other popular hybrid cultivars are Bacon, Creamhart, Jim, Reed, Ryan, Spinks, Whitsell, Wurtz, Zutano, Rincon, and Murrieta Green (Anon 1999).

Hass Avocado

Among seven different varieties grown in California, Hass is commercially the most important cultivar. It is oval in shape with a pebbly skin that changes color from green to black upon ripening (Figure 26.1). It has a small stone, good creamy texture with 19% oil

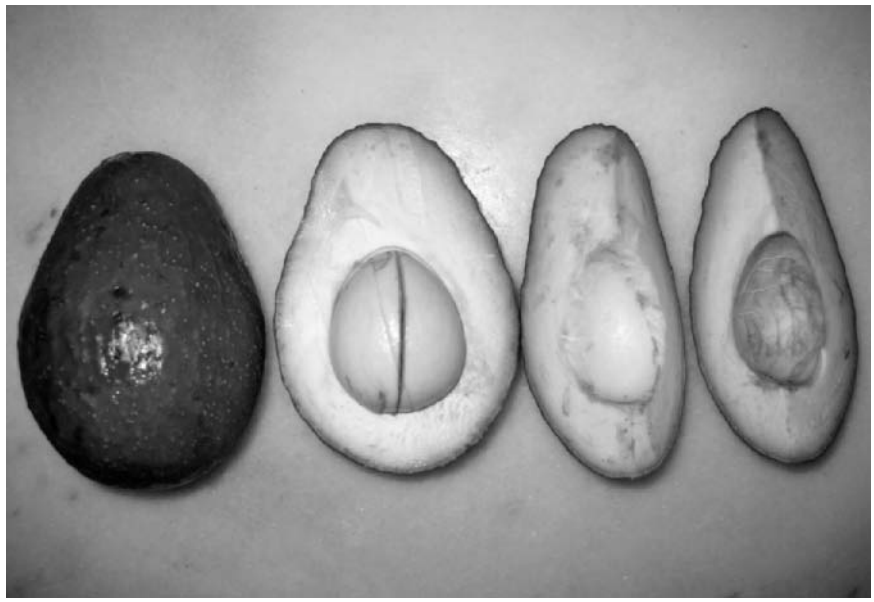

Figure 26.1 Fully mature, whole and cut avocado fruit. (Photo source: Prof. Jiwan S. Sidhu).

content. Hass accounts for almost 95% of the total crop. Southern Californian climate is perfect for growing Hass variety. Good soil, proper drainage, abundance of sunshine, and cool breezes from the ocean is all that is needed by the fruit. Hass is a late maturing variety and is tolerant to pests and fruit diseases (Thorp and Sedgley 1993).

World Production and Leading Producer Countries

Avocado has a long history of production and consumption especially in Mexico, and North and Central America. In 2004, the world production of avocado was 3,222,069 metric tons valued at $606,608,000 (FAO 2000/09). In 2007, the leading producer was Mexico followed by Indonesia and United States of America (Table 26.1) (FAO 2007).

Consumption and Market Trends

Mexico is the leading exporter and consumer of avocado in the world. The annual per capita consumption in Mexico is nearly 8 kg, whereas world average consumption range is 3–5 kg (FAO 2000/09). Consumption of avocado has gradually increased over the year throughout the world. However, where on the one hand, the consumption has risen steadily from 163,000 metric tons in 1995–1996 to 250,000 metric tons in 2006–2007 in Europe, the consumption has grown from 179,833 metric tons to 460,000 metric tons in United

Table 26.1 Major world producers of avocado

Rank	Country	Production-2007 Million Metric Tons (MMT)
1	Mexico	1.143
2	Chile	0.250
3	Indonesia	0.202
4	United States of America	0.188
5	Dominican Republic	0.184
6	Columbia	0.158
7	Brazil	0.154
8	Peru	0.122
9	Spain	0.120
10	Guatemala	0.114
	World (Total)	3.569

Source: FAO 2007.

States for the same time period. The average per capita consumption during 2006–2007 in Europe and United States was 500 g and 1,600 g, respectively. In Europe, however, where, France was a major consumer of avocado averaging about 1,800 g, the consumption in Germany was only 230 g. During the same period, the per capita consumption in Chile and Israel was 4,000 g and 5,000 g, respectively. For the year 2006–2007, the domestic production of avocado in the United States was 140,000 tons while the import volume was 320,000 tons, mainly from Mexico and Chile. Domestic production in Europe was 60,000 tons while the import volume was 190,000 tons, mainly from Israel, Chile, South Africa, Kenya, Mexico, and Spain (Naamani 2007). Avocado is not popular in Asia. With the exception of Australia, New Zealand, and Sri Lanka, no other country has improved avocado variety available for cultivation (FAO 2000/09).

Postharvest Physiology, Storage, and Shelf Life

Maturity Indices

Avocado is harvested when fully mature yet green and firm When harvested immature, it will not ripen properly, whereas an overripe avocado will decay rapidly after harvest. Typical maturity indices for fruits such as color, smell, or texture of the fruit are not reliable indicators for avocados (Gaete-Garreton et al. 2005). Both its color and smell change with ripening after harvest. Although color change (skin darkening) before harvest is observed in late season avocados, the fruit may still be unripe (Cox et al. 2004). Other maturity indices include assessment of oil content, dry matter, or percentage of moisture. Depending on the cultivar, growing conditions, time of harvest, postharvest handling, and method of determination, the oil content of 8–33% and dry matter of 17–21% are considered typical for commercial grade avocado (Morris and O'Brian 1980; Lee et al. 1983). In South Africa, percentage of moisture (complementary to dry matter) is used as a maturity index (Clark et al. 2003). Blakey et al. (2009) reported that the percentage of moisture content at harvest correlated well with the postharvest ripening ability of the fruit without shriveling.

Firmness correlates well with other parameters of maturity such as oil content and is a good predictor of expected storage time (Lewis 1978; Peleg et al. 1990). As the fruit matures and ripens, the firmnes measured by a penetrometer declines accordingly. Use of near infrared spectroscopy (NIRS) method is becoming popular for measuring dry matter and water content of avocados. It enables the producer to rapidly scan and sort not only the harvested fruit into different classes for further handling and processing (Clark et al. 2003), but also the measurement of dry matter or water content in fiel before the harvest (Blakey et al. 2009). Maturity can also be estimated by using specifi gravity or time of the fruit growth. For example, from bloom to fruit, the Mexican types take 6–8 months to ripe while Guatemalan types take 12–18 months (Lee et al. 1983).

Fresh Avocado Packaging and Shelf Life

Avocados are picked by hand using special clippers and ladders. Once picked, they are precooled overnight to remove fiel heat in the packinghouse to ensure the quality. Before packaging, avocados are washed, lightly cleansed, sized, and graded for quality. The highest grade is separated for supply to supermarket for raw consumption; others are used for processing. The packed avocados are maintained at optimum cool temperature to ensure ripeness and quality while awaiting shipment. Once picked, avocado ripens quickly at room temperature because of the production of ethylene gas during storage. All these steps from picking to grading take 5–9 days (Feng et al. 2000). Skin of avocado

changes color upon ripening; for example, Hass avocados change color from green to purple to black.

To enhance shelf life, most producers size avocados by weight or separate by firmness Heterogeneity in firmnes can cause variability in ripening and, thus, setting up of the climacteric process. It is important to sort avocados in lots of different ripening stages and employ postharvest measures to extend shelf life and quality, as ethylene production from some avocados in a lot can trigger ripening which once initiated, is hard to stop (Mizrach et al. 1991).

Physiological Disorders: Softening, Chilling Injury, Oxidation, etc.

Ripening of climacteric fruit involves a series of metabolic changes initiated by a surge in the production of the plant hormone ethylene after harvesting (Alexander and Grierson 2002). High ethylene production is a result of high respiration rate, which is partly responsible for altering the fruit's biochemistry, physiology as well as gene expression (Giovannoni 2001), thus causing softening of the mesocarp (pulp) as well as color and fla vor change. Softening is caused by several cell wall-degrading enzymes (Fischer and Bennett 1991). Early stages of avocado softening is based on the cellulase activity in the cell wall, which disrupts the polygalacturans in the wall matrix, and releases polygalacturanase for the fina fruit softening (Weemaes et al. 1999). The firmnes of avocado mesocarp at harvest changes from 80 to 100 N measured by nondestructive compression force to less than 5 N in a fully ripened fruit (Salvador et al. 2009).

Storage at lower temperatures is used to extend shelf life. However, a major limitation in storing avocados at low temperature is the development of external chilling injury (Woolf et al. 2003) expressed as mesocarp discoloration, skin blackening, and pitting. This occurs at a temperature of 3°C or less. Chilling injury is highly correlated with increased electrolyte leakage of the skin (Woolf et al. 2000). It is also associated with embryo growth and ethylene production during cold storage (Hershkovitz et al. 2009). It is suggested that during chilling stress, some tissues accelerate their ethylene production, resulting in ultrastructural changes in the membrane leading to disrupted ion balance, release of polyphenol oxidase (PPO) enzyme, and leakage of electrolytes (Lyons 1973). Besides an increase in electrical conductivity, PPO activity has been found to correlate with the mesocarp discoloration in cold storage (Hershkovitz et al. 2005). Development of dark brown spots on Fuerte fruit skin is an external physiological damage at cold storage temperatures of 4–5°C. The actual cause of the brown spot disorder is not clear; however, a significan increase in lenticels damage is observed when the fruit is picked wet or gets bruised in picking and the severity of the damage would vary depending on the season, location, and harvest (Zilkah et al. 1995).

Postharvest Handling and Storage

As indicated before, ethylene plays an important role in the ripening of avocado and its shelf life. Storage at low temperature delays ethylene production; however, storage at low temperatures can also cause chilling injury. Low storage temperatures generally range between 5 and 8°C but could be reduced to as low as 2–8°C in order to reach a distant market (Flitsanov et al. 2000). To prevent chilling injury in cold storage, ethylene absorption sachets are used to reduce levels of ethylene in the storage atmosphere (Adkins et al. 2005), or the avocados are treated with 1-methylcyclopropene (1-MCP), an inhibitor of ethylene action, before cold storing (Jeong et al. 2003). Feng et al. (2000) measured the potency of 1-MCP in delaying ethylene-induced avocado ripening at various concentrations using cultivars Ettinger, Hass, Reed, and Fuerte. Mature avocados were treated for 24 hours at 22°C with various

concentrations of 1-MCP after ventilation and exposing to 300 mL/L ethylene for 24 hours. Subsequently, they were stored in ethylene-free air at 22°C and assessed for ethylene production, fruit firmness color, cellulase, and galacturonase activity during ripening. It was observed that 1-MCP inhibited ethylene-induced ripening at very low concentration of 30–70 nL/L and delayed ripening up to 13 days.

Further, cultivars Fuerte and Hass (Barmore and Rouse 1976; Arpaia et al. 1990) were successfully stored for 5–9 weeks without chilling injury at 5–7°C in a controlled atmosphere (CA) storage of 2% oxygen and 10% carbon dioxide. Meir et al. (1995) reported that a combination of 3% oxygen and 8% carbon dioxide extended shelf life of Hass avocado at 5°C up to 9 weeks. This reduced ratio of oxygen in storage atmosphere resembles anaerobic respiration of fruit tissues producing acetaldehyde (AA) and ethanol. Accumulation of these endogenous respiration metabolites gives aroma to the fruit and inhibits ethylene production in plants. Application of exogenous AA vapor to avocados before storage also inhibited fruit ripening by reducing ethylene production and activities of cell wall-depolymerizing enzymes and chilling injury symptoms at low temperature of 2°C (Pesis et al. 2002).

Waxing is commonly used to prevent postharvest water loss. Jeong et al. (2003) investigated a combined effect of ethylene inhibitor (1-MCP) treatment and waxing on avocado's shelf life. As evaluated by fruit firmness color, ethylene production, and respiration rate, 1-MCP and wax combined had significantl delayed ripening in avocados at 20°C compared to either waxing or 1-MCP treatment alone. The firmnes of the control fruit declined from 100 to 20 N over a 7-day period at 20°C; fruit treated with either wax or 1-MCP decreased in firmnes at 20°C in 11 days, whereas the combined effect of waxing and 1-MCP required about 45 days to decrease softness to 25 N.

Chilling injury in Hass avocados can be reduced by pretreatments with hot air or water at moderated temperatures such as 38°C for 6 hours immediately prior to cold storage for 3 weeks (Woolf et al. 2004). This heat shock treatment of avocados not only prevented unfavorable effects of chilling injury but also protected against Mediterranean fruit fl eggs (Jang et al. 2001). Pretreatments of moderate heat (i.e., 38°C) also induce tolerance to much higher temperatures required for insect killing. This induced tolerance of fruits is suggested to be due to the induction of heat shock proteins (hsps) that are stimulated in fruit by postharvest heat treatments of avocado (Woolf and Lay-Yee 1997; Woolf et al. 1999). Similar induction of hsps gene expression was seen in avocados that were picked from trees facing the sun, which, therefore, exhibited reduced external chilling injury in cold storage as compared to those picked from trees facing shade (Woolf et al. 2003).

Physicochemical and Nutritional Qualities

Sensory and Flavor Quality

Avocado's soft delicately creamy texture and fl vor is attributed to the inherently high concentration of oil specificall , unsaturated fatty acids. The fruit is smooth and fatty but not sweet. The sugars glucose and fructose are present in negligible quantities, whereas sucrose, D-mannoheptulose, (a seven-carbon carbohydrate) and perseitol are comparatively abundant. Oil content increases with maturity of the fruit, enhancing the mouth feel and fl vor (Landahl et al. 2009). Because of its creamy texture and nonsweet fl vor, it is served mixed with white rice, or is added to soups, salads, and sandwiches. It is used on the side of chicken and meat as a popular Mexican dip, guacamole.

Once the fruit is cut, it becomes brown when exposed to air. This is because the avocado pulp is rich in PPO, an enzyme that

causes immediate oxidation and blackening of tissue exposed to oxygen (Kahn 1975). Therefore, in commercial products, application of AA to the cut surface of the fruit retards the progressive browning probably by inactivating the oxidizing enzymes (Burdon et al. 1996). Different tips are used to avoid darkening of avocado such as use of lemon or lime juice, vinegar, salt, or sugar that prevent contact of oxygen with peeled avocado surfaces. Soft whole avocados can be stored in refrigerator for 2–3 days before consumption. Cut avocados can be stored frozen for up to 5 months when mixed with a spoon of lemon per 2 pureed avocados.

Chemical Quality and Composition (Fatty Acid Profile)

Besides fat, other nutrients present in avocado are protein (highest among fruits), sugars including sucrose and 7-carbon carbohydrates such as D-Mannoheptulose, pigments, tannins, antioxidants, phytoestrogens, and fibe etc., (Naveh et al. 2002). The oil is mainly unsaturated consisting of both monounsaturated (oleic acid) and polyunsaturated fatty acids (linoleic acid and linolenic acid) (Pacetti et al. 2007). Oleic acid is the principal fatty acid comprising 71% of its total fatty acids (USDA 2007). Avocado oil is considered similar to olive oil in total fat content and fatty acid composition (Swisher 1988). Other fatty acids present include palmitic and palmitoleic acids with some lesser amounts of myristic, stearic, cinolenic, and arachidonic acids (Vekiari et al. 2004). During ripening, palmitic acid decreased and oleic acid increased. The lipid fraction of avocado is a rich source of polar lipids such as glycolipids and phospholipids, which are important components in cell membranes, functioning as second messengers for various cellular processes. These lipids are used as emulsifier to combine lipids and aqua solutions for making emulsions and, therefore, have a wide variety of applications in food, pharmaceuticals, and cosmetics industries (Table 26.2).

Table 26.2 Fatty acid profile of avocado oil vis-a-vis olive oil

Type of fatty acid	NZ avocado oil	NZ olive oil
	% Fatty acid	
Palmitic, 16:0	12.5–14.0	8.6–12.9
Palmitoleic, 16:1	4.0–5.0	0.3–0.7
Stearic, 18:0	0.2–0.4	2.1–2.8
Oleic, 18:1	70–74*	77.0–82.6
Linoleic, 18:2	9.0–10.0	4.6–7.5
α-linolenic, 18:3	0.3–0.6	0.5–0.7
Arachidic, 20:0	0.1	0.0–0.6
Gadoleic, 20:1	0.1	0.0–1.4

Source: Eyres et al. (2009).
*Includes 18:1 isomer (5%).

Avocado Enzymes: Polyphenol Oxidase, Lipooxygenase

Peroxidase or oxidase are present in most of avocado varieties but are absent in the green fruit. Fuerte has a negligible amount of oxidase and it does not turn black readily when cut surfaces are exposed to oxygen (Kahn 1976).

The activity of lipoxygenase enzyme is associated with fungal rotting, if the fruit is infected. In a mature fruit, fl vonoid epicatechin, a natural antioxidant, decreases while the fruit is ripening. Epicatechin is an inhibitor of lipoxygenase enzyme, thus its activity increases when the level of its inhibitor declines. These metabolic changes in the fruit also reduce the level of an antifungal compound, 1-acetoxy-2-hydroxy-4-oxo-heneicos 12, 15 (antifungal diene, AFD) resulting in activation of quiescent *Colletotrichum gloeosporioides*. *Colletotrichum gloeosporioides* is a phytopathogenic fungus that attacks a wide variety of tropical and subtropical fruits including avocado. Unripe avocado is resistant to this fungus because of its high content of the epicatechin and lower concentration of lipoxygenase enzyme (Guetsky et al. 1995).

PPO is a copper-containing enzyme which catalyzes two different reactions in the presence of oxygen such as hydroxylation of monophenols to o-diphenols and subsequently o-diphenols to o-quinones. O-quinones then polymerize nonenzymatically with other o-quinones, phenolic compounds or amino acids and form red to brown to black pigments (Espi'n et al. 1997). Inhibition of brown coloration can be achieved by inactivation of these enzymes by high temperature, pressure, or both or other treatments such as removal of oxygen, etc.

Bioactive Compounds

Together with fibe (5.2 g/100 g), high β-sitosterol (a phytosterol) (Duester 2001; Naveh et al. 2002; Plaza et al. 2009) and fatty acid, oleic acid, avocado is suggested to improve lipid profil in healthy and mildly hypercholesterolemic subjects by reducing total cholesterol, low-density lipoprotein (LDL) cholesterol, and triglycerides while increasing high-density lipoprotein (HDL) cholesterol (Ledesma et al. 1996). Research studies on Mexican populations show that people consuming avocado have decreased serum total cholesterol, LDL cholesterol, and triglycerides while increased HDL cholesterol compared to control diet (Alvizouri-Munoz et al. 1992; Ledesma et al. 1996).

Adding avocado to meals increases the feeling of satiety resulting in reduced food intake and, thus, better body weight management. Body weight correlates positively with reduced risk of coronary heart diseases or stroke and diabetes (Lu et al. 2005). Partial replacement of carbohydrate foods with avocado extract in the diet of type-2 diabetic subjects showed a remarkable improvement in the lipid profil and plasma glucose concentration (Gallagher et al. 2003).

Avocado is rich in antioxidants such as tocopherol and carotenoids including zeaxanthin, cryptoxanthin, α-carotene, and β-carotene) and lutein; lutein is 70% of the measured carotenoids, which is highest in avocado among fruits. The acetone extract of avocado containing tocopherol and carotenoids was capable of inhibiting growth of both androgen-dependent (LNCap) and androgen-independent (PC-3) human prostate cancer cell lines in vitro (Lu et al. 2005). Lutein has been shown as an anticarcenogenic carotenoid (Park et al. 1998); however, acetone extract of avocado had a greater inhibitory effect of the above-mentioned prostate cancer cell lines compared to purifie lutein, which suggests the involvement of a combination of factors rather than lutein alone (Lu et al. 2005). Other studies showed that chloroform extract of avocado selectively induced apoptosis in human oral cancer cells but not in normal oral epithelial cell lines (Ding et al. 2007; Ding et al. 2009) or human breast cancer cell line (Roberts et al. 2007).

Therapeutic value of avocado is realized in Mexico folk medicine. Its fruit, oil, and leaves are used to treat a wide variety of diseases. For example, the oil from its seed is considered a useful treatment for rashes, scars, or dysentery (Argueta-Villamar et al. 1994). Avocado leaves are not only used by Mexicans but also by people in Brazil, Panama, Jamaica, Nigeria, and Indonesia to treat hypertension (Adeboye et al. 1999).

- *Nutritional Quality*

Avocado contributes minerals including magnesium, potassium, iron, copper, and phosphorus, and vitamins such as vitamin C, thiamin, ribofl vin, niacin, folic acid, vitamin E, and β-carotene (Rainey et al. 1994). The nutritional composition of avocado is given in Table 26.3.

Using avocado as a spread on sandwiches replacing butter, cream cheese, and fatty mayonnaises can help reduce intake of calories, saturated fat, sodium, and cholesterol. Phytonutrients are better absorbed in the presence of fat, and avocado is abundant in both fat and phytonutrients. Research study in humans showed that avocado added to salsa enhanced

Table 26.3 Avocado raw edible portion nutrient composition and percent daily values for vitamins and minerals

Nutrients	Per 100 g edible portion
Energy	160 Kcal (670 KJ)
Carbohydrates (g)	8.53
Sugars (g)	0.66
Dietary fibe (g)	6.7
Fat (g)	14.66
Saturated (g)	2.13
Monounsaturated (g)	9.80
Polyunsaturated (g)	1.82
Protein (g)	2.0
Vitamins:	
Thiamin (mg)	0.067
Ribofl vin (mg)	0.130
Niacin (mg)	1.738
Pantothenic Acid (mg)	1.389
Vitamin B6 (mg)	0.257
Folate (μg)	81
Vitamin C (mg)	10
Minerals:	
Calcium (mg)	12
Iron (mg)	0.55
Magnessium (mg)	29
Potassium (mg)	485
Phosphorus (mg)	52
Zinc (mg)	0.64

Source: USDA nutrient database.

lycopene and β-carotene absorption by 4.4 and 2.6 times compared to control salsa without avocado. Addition of either 150 g avocado or 24 g avocado oil to salad enhanced α-carotene, β-carotene, and lutein absorption by 7.2, 15.3, and 5.1 times, respectively compared to avocado-free salad (Unlu et al. 2005.)

Major Products

Fresh-Cut Avocado

Enzymatic browning of sliced avocados is a serious problem in the preparation of fresh-cut products. Using Hunter color values as indicators of browning, Gomez-Lopez (2003) investigated various browning inhibitors. Ascorbic acid and sodium sulfit were effective browning inhibitors when combined with citric acid. Other reports (Soliva-Fortuny and Martin-Belloso 2003; Illeperuma and Nikapitya 2006) indicated retention of texture (firmness when avocado slices were dipped in citric acid and ascorbic acid solutions, and stored under modifie atmosphere. Maftoonazad and Ramaswamy (2009) reported that pectin-based coating extended shelf life of avocado for more than 1 month at 10°C.

Frozen Avocado

Kurlaender (2004) reported that commercial processing of avocados started in the United States in 1964 at the Frigid Foods, Inc., Escondido, California, by Calavo Growers. The company developed frozen avocado halves and slices by immersing in liquid nitrogen (−196°C). Later on, frozen avocado sauce (guacamole dip) was also developed (Urbanek 1966). The processing potential of avocado cultivars at different stages of fruit maturity was investigated by Pauker et al. (1992). The composition of edible part of avocado fruit (mesocarp) varied depending upon the cultivar and harvest season. They reported various constituents such as dry matter (19.18–30.29%), fat (8.3–16.75%), protein (2.1–2.3%), carbohydrates (6.8–8.1%), and mineral ash (0.7–1.2%). Fruits harvested near to the end of harvesting season gave the highest values for these constituents. Olaeta and Rojas (1987) have also reported the effect of cultivar and maturity on the quality of frozen (−40°C) avocado pulp stored at −18°C. Of the fi e cultivars tested, Edranol gave the best quality frozen product. A minimum of 15% oil content was required in these cultivars at their maturity level to obtain an acceptable quality frozen avocado pulp product. Stephens et al. (1957) have prepared an acceptable frozen guacamole base using 100 parts of avocado fles with 5 parts of lemon juice, 4 parts of chopped onions, and 1 part of salt. This product when packed with minimum headspace in glass jars or tin cans had a shelf life of 7 months at −18°C (0°F).

Bower and Dennison (2003) developed a process to produce both fresh-cut and frozen

avocado halves, slices, and chunks. The major problems related to product browning, as well as taste and texture of the fruit, were addressed. They suggested the use of antioxidants (ascorbic acid) to prevent browning during defrosting process. Biochemical properties of PPO enzyme in two selected avocado cultivars have been investigated by Kahn (1977). Calcium ions play an important role in the browning of avocado fruit (Rensburg and Engelbrecht 1986). To prevent enzymatic browning during frozen storage and thawing, Scutamore-Smith (1984) coated the frozen avocado slices with ascorbic acid solution (0.5%) or half strength lemon juice or citric acid solution for 1 minute. The correct use of antioxidants, modifie atmosphere packaging (MAP), and frozen storage conditions will decrease the potential for microbial growth and will enhance the marketability of fruit products in a wider area (Pao and Petracek 1997).

In case of fresh avocado fruit, off-taste develops due to tissue collapse. Even the frozen product on defrosting develops off-fl vor. Bower and Dennison (2004) investigated the use of MAP with decreased oxygen and increased carbon dioxide levels. They used a carbon dioxide shock treatment to modify the phenolics and pasteurization process to prevent fruit softening. They concluded that MAP was not necessary if oxygen is present in the mix. However, pasteurization process was helpful in eliminating frozen fruit collapse after defrosting, browning discoloration, off-taste development, and the use of citric acid as antioxidant. According to their findings frozen halves and slices were reported to be the most acceptable products from avocado. In another study, Bower and Dennison (2005) developed a process to prevent browning of frozen avocado halves and chunks. They ripened the avocado fruit to correct softness, cleaned it externally with a disinfectant, peeled, and sliced. The slices were dipped in boiling water for sufficien time to inactivate the PPO, as well as to leach phenolics from the cut surface of the slices. The slices were frozen in liquid nitrogen. These steps enhanced the fl vor of the product and eliminated bitterness associated with the storage of frozen avocado products. Ramirez-Martinez and Luh (2006) reported that ascorbic acid-treated frozen avocado chunks did not darken when kept at -26°C. The darkening of color of frozen chunks correlated well with the disappearance of most phenolic compounds, except the simple cinnamic acid derivatives.

Valdivia et al. (2002) investigated the use of ^{60}Co gamma rays (doses 0.5–2.5 kGy) on the quality of frozen avocado pulp. The *Listeria monocytogenes* was reduced by 1–4 log cycles without adversely affecting the hydrolytic or oxidative rancidity at any of the doses for 120 weeks of frozen storage. Even the highest radiation doses did not produce any off-fl vor or affect the green color (chlorophyll) of the product.

Dehydrated Avocado

During dehydration, many quality characteristics such as color, texture, fl vor, porosity, and the rehydration ratio, are affected (Jayaraman and Das-Gupta 1992; Tsami and Katsioti 2000). Drying of avocado has a few special problems. Avocado is dried either by the spray drying or by the drum drying technique. These drying techniques produce a product that has only pale green color and has a chalky off-fl vor, which does not have a big market. By adding a few spices, the off-fl vor can be masked and a ready mix of guacamole is produced. The dehydrated avocado may fin use in pet food manufacture as an ingredient rich in oil (Kurlaender 2004).

A number of patents have been issued for dehydrated avocado pieces (Schlager and Fedelli 2009), powdered compositions (Phillips 2007), avocado concentrate (Carre 2004), and osmotic drying (Koyazounda 2002). Grajales-Lagunes et al. (1999) spray-dried avocado paste and studied the effect of

synthetic and natural antioxidants on the oxidative stability and palatability of stored avocado powders at temperatures ranging from 6 to 40°C. During storage, peroxide value was measured and the development of rancidity was determined by sensory evaluation. Tertiary butylated hydroxyquinone (0.05%) + citric acid (0.1%) mixture coupled with nitrogen packaging were found to be the most effective in extending the shelf life of spray-dried avocado powder during ambient storage. Lee et al. (2006) developed a mathematical model based on one-dimensional, steady state to suitably describe the rehydration behavior.

The effect of variety, storage time, temperature, and atmosphere on the chemical and organoleptic quality of freeze-dried avocado puree and guacamole has been studied by Gomez and Bates (1970). Significan differences among the rate of lipid oxidation (peroxide value) were observed among the varieties evaluated. Use of the antioxidant butylated hydroxyanisole (BHA) reduced the rate of peroxide formation in samples stored in air at 21°C but not at 38°C. They found no use of peroxide value in predicting product acceptability, as deterioration in sensory quality was observed without significan increase in peroxide value. Vergara-Balderas et al. (2005) reported manufacture of high quality freeze-dried guacamole and Mujica-Paz et al. (2005) investigated the hygroscopic properties of freeze-dried guacamole during storage.

Guacamole

The value-added product, guacamole, is prepared from a fully ripe fruits by blending the pulp with herbs, spices, lemon juice, and salt for fl voring (Ramtahal et al. 2007). The process outline for preparing guacamole from ripened avocado fruit is described in Figure 26.2. After the ripening is completed, the fruit is chilled to 5°C. The fruit is dipped in 200 ppm hypochlorite solution to lower the microbial load on the surface. Avocado stems are removed, fruit is cut into halves, and the seed is removed. The pulp is removed from peel either by ricing machine or manually (Kurlaender 2004). All the remaining spices and other ingredients (as per formulation) are added to the pulp and blended to obtain a uniform-fl vored guacamole. The product is fille into containers, vacuum-sealed (or nitrogen-flushed) and stored frozen (−22°C). Low initial counts of microorganisms of the ripened fruits are very important for the production of guacamole, as any heat given to the pulp causes color and fl vor deterioration (Ahmed and Barmore 1980).

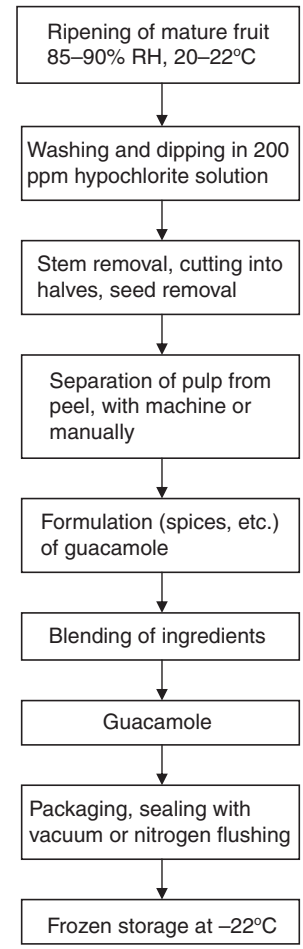

Figure 26.2 Typical process for the production of avocado guacamole.

Arvizu-Medrano et al. (2002) collected samples of guacamole from a number of restaurants in the Queretoro city, Mexico and tested for the presence of pathogenic organisms. They also inoculated the guacamole pulp with *Salmonella* spp., *Staphylococcus aureus*, and *Escherichia coli* O150:H7 to study the behavior of these pathogens. A wide variation observed for the pathogen counts in guacamole samples correlated well with the sanitary conditions observed in catering establishments, with higher numbers from street vendors. No growth of pathogens was observed in guacamole stored at a temperature of 4–7°C. A few patents have been issued for the preparation of guacamole (Griebel and Kargel 2004), use of hurdle technology for shelf-stable guacamole (Palaniappan et al. (2008), and avocado fruit fles processing (Yoshiaki et al. (2008).

Avocado Puree (Sauce)

The process for avocado puree or sauce is similar to guacamole up to pulp extraction step. The nest step consists of high shear blending of pulp with water, gums, thickeners, and spices. A thick sauce should have an apparent viscosity of 8,000–12,000 centipoises as measured by a Brookefiel viscometer using spindle number 4. The sauce is then fille into polyethylene jars, and frozen stored at −18°C (Kurlaender 2004).

The use of traditional heating of avocado puree produces off-fl vors and, therefore, use of an alternative process of high temperature-short time (HTST) heating using microwave energy has been investigated by Guzman et al. (2002). According to their findings use of 120 ppm of zinc chloride and 12 ppm of copper chloride during microwave heating of avocado puree resulted in preservation of color for 7 days at refrigerated storage. In another study, use of microwave heating of avocado puree at high energy level for 180 seconds brought only 60% reduction in PPO activity (Jimenez et al. 2001). Soliva-Fortuny et al. (2002) have investigated the kinetics of PPO activity and browning of avocado puree preserved by antibrowning agents (ascorbic acid, or EDTA) and antimicrobial agents (sorbic acid). They proposed a fractional conversion model to predict the shelf life of minimally processed avocado puree in terms of visual appearance. The avocado puree when added to the sausage formulation had no adverse effect on the acceptability of this meat product (Rueda-Lugo et al. (2006).

Elez-Martinez et al. (2007) investigated effect of α-tocopherol and sorbic acid on development of oxidative rancidity in avocado puree. As expected, α-tocopherol reduced the rancidity of lipid fraction in avocado puree stored under different MAP conditions. Sorbic acid used as an antimicrobial agent in puree had a moderate prooxidant effect and enhanced the oxidative rancidity of lipid fraction of puree. Lipid oxidation is one of the major phenomena that limits the shelf life of avocado products. Use of 100 ppm of α-tocopherol and 200 ppm of ascorbic acid has been reported to have beneficia effect on the stability of lipid fraction of avocado puree (Elez-Martinez et al. 2005). The use of microwave energy in the preparation of avocado puree also has a tremendous potential to retain better color and fl vor in the finishe product. The effects of microwave heating of avocado puree on the volatile components as influ enced by the heating times, pH values, and addition of avocado leaves have been studied by Lopez et al. (2004). The addition of avocado leaves had a positive effect on the fl vor of puree. According to their results, the optimum values for the processing of avocado puree were microwaving for 30 seconds at pH 5.5 and addition of 1% avocado leaves. Guzman-Geronimo et al. (2008) have also studied the effect of microwave heating time, pH, and addition of avocado leaves on the volatile profil of puree and obtained similar results.

Soliva-Fortuny et al. (2003) studied role of storage temperature, pH, water activity (a_w),

MAP, and addition of chemical preservatives to extend the shelf life of avocado puree. According to their findings 300 ppm of sorbic acid was sufficien to inhibit yeast and fungi responsible for the spoilage of avocado puree. This product can also be preserved without sorbic acid addition by combining vacuum packaging and storage at 4°C. Use of maltose to reduce a_w gave slightly more stable product, but the effective use level of maltose affected the sensory quality of puree adversely.

Avocado Oil

Avocado oil is known to be rich in many bioactive substances that can prevent and control hyperlipidemia (Takenaga et al. 2008). Because of its unique nutritional quality, avocado oil has been named as the new wonder oil (Anon 2001). Meyer and Terry (2008) developed a rapid method for the sequential extraction and subsequent estimation of fatty acids and sugars from avocado mesocarp tissues. The fatty acid composition and phytosterols present in avocado oil are similar to olive oil (Polana et al. 1999; Salgado et al. 2008). Depending upon the season and location of orchard, the oil content in Hass variety of avocado can vary from 16 to 30% (Human 1987; Eyres et al. 2009). Not only the late season fruits have more oil, but also it is easier to extract oil from the idioblast cells that contain fat. A typical composition of the avocado fruit is: (1) flesh 65%; (2) seed, 20%; and (3) peel, 15% (Eyres et al. 2009). However, several avocado varieties from Venezuela have been reported to have low (6.73–8.07%) to very low (3.0–6.70%) oil content (Gomez-Lopez 1998; Gomez-Lopez 1999).

Avocados oil can be extracted by one of the three methods: (1) solvent extraction from dehydrated avocado pulp (gives nearly complete recovery of oil); (2) hydraulically from dried avocado fla es (yields are very low); and (3) centrifugation from soft fruit (recovery only 50% of the oil present). The crude oil, thus, extracted from the avocado is further refined Refinin process removes the off-fl vors, free fatty acids, most of the chlorophyll, phosphatides, and waxes. The refinin process consists of alkali treatment, bleaching, deodorization, and winterization (Kurlaender 2004). The modern "cold-press" method involves maceration of fruit fles by a high-speed grinder. Then, oil, water, and pulp solids are separated by decanting. The oil fraction goes thru Alfa Laval olive oil processing equipments. Depending upon the season, the typical oil yield comes between 10 and 18% of the whole fruit (Werman and Neeman 1987).

Eyres et al. (2009) produced refined bleached, and deodorized (RBD) oil that meets the extra virgin oil standards. The RBD oil has fatty acid composition similar to olive oil (Table 26.2) and find use in cooking as well as in cosmetics industry. Bizimana et al. (1993) developed avocado oil extraction technology suitable for the developing countries. Highest recoveries (70–80%) were obtained at water to avocado ratio of 5:1, pH 5.5, and centrifugal force of 12,300 × g. Use of 5% calcium carbonate or calcium sulfate eliminated the requirement of organic solvents during extraction process. Processes for extra virgin oil from avocado pulp (Dorantes-Alvarez and Ortiz-Moreno 2006) and for the manufacture of refine avocado oil rich in triglycerides (Msika and Legrand 2007) have been granted US patents. Mostert et al. (2007) studied the effect of fruit ripeness and method of fruit drying on the extractability of avocado oil with hexane and supercritical carbon dioxide. Oil extraction yield was higher from ripe than unripe fruits. Oil extraction from freeze-dried avocados was higher than oven-dries samples. Hexane proved to be better solvent for oil extraction than supercritical carbon dioxide.

Besides triglycerides, avocado oil also contains a small but significan amount of unsaponifiabl components. Farines et al. (1995) have identifie nine unsaponifiabl components through chromatographic fractionations and spectroscopic analysis. These products

have a homogenous structure, having a furyl nucleus with position 2 substituted by an aliphatic, mono-, or polyunsaturated chain of 13–17 carbon atoms (always odd carbon numbers). The presence, identification and characterization of pigments (Ashton et al. 2006), glycolipids and phospholipids (Pacetti et al. (2007), and furan lipid-rich unsaponifi able materials (Piccirilli and Legrand 2008) in avocado oil have been reported.

High-Pressure Processing of Avocados

As described elsewhere in this book, in this method, the food is subjected to a very high pressure in the range of 200–900 MPa with or without heating. The objective is to inhibit spoilage microorganisms and pathogens, inactivate enzymes, and retain sensory and nutritional qualities (Wouter et al. 2003; Ramaswamy et al. 2005). The ultrahigh-pressure (UHP) food processing technology by Avomax (TX, USA) has been applied for the production of avocado pulp and guacamole (Anon 2000; Khurana and Karwe 2009). Palou et al. (2000) studied the application of HPP with pressures of 689 MPa for the processing of guacamole by measuring its effect on microbiological quality, sensory properties, color, catechol oxidase, and lipoxygenase activities. Lipoxygenase was inactivated completely by treatment at 689 MPa for 15 minutes, whereas 4 cycles of 5 minutes at 689 MPa inactivated catechol oxidase. The standard plate counts decreased from 12,000 to 13,000 CFU/g to $<$10 CFU/g. The HPP did not affect the sensory properties or color of guacamole significantl . The pressure-treated guacamole had a shelf life of 30 days at 25°C, but the untreated/control sample spoiled within 5 days.

Although the HPP-treated avocado guacamole had fresher taste than the frozen; the HPP-treated product was inferior in appearance and color, as the enzyme PPO was still active in the product (Lopez-Malo et al. 1998; Weemaes et al. 1999). The HPP treatment is not capable of eliminating the PPO activity completely, which causes the avocado products to turn brown, once the vacuum packed product is opened.

Standards for Processed Avocados

The Codex (Stan 197-1995) gives defini tion and classificatio of avocados, size codes, and requirements for quality, contaminants, hygiene, packaging, marketing, and labeling. For more information, the readers are referred to the list of Codex Standards (Anon 2005) on the Codex Alimentarius (http://www.codexalimentarius.net).

Avocado By-Products

The avocado lipids contain small amounts of unsaponifiabl components, which have been found useful in the treatment of osteoarthritis (Eli and Lockwood 2008). Lee et al. (2008) investigated the antioxidative activity (in vitro) of polyphenols extracted from the sarcocarp, seed, and peel of avocados. The methanol extracts from the peel of avocado showed higher free radical scavenging activities than the sarcocarp and seed and increased apoptosis in MDA-MB-231 cells. A patent (Barclay 2008) reported the production of fats rich in ω-3 unsaturated fatty acids by growing microalgae, *Thraustochytrium*, *Schizochytrium*, or their mixture, on fla seed, rapeseed, soybeans, and avocado meal.

Avocado honeys (Anon 2002; Terrab and Heredia 2004; Terrab et al. 2005) produced in Spain showed high pH, ash, and total mineral content, potassium being the most abundant (73% of the total minerals). Perseitol, a sugar, was suggested as an indicator of the degree of purity of avocado honey (Dag et al. 2006).

Conclusions

Avocado has healthy lipid composition. In addition, it is rich in minerals, vitamin E,

and health-promoting phytochemicals. As indicated in this review many processed forms of avocado can extend use of this important produce and improve the nutritional quality of our diet.

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Chapter 27

Dry Beans: Production, Processing, and Nutrition

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Introduction

Beans belong to legumes, which play a significan role in human nutrition. Out of approximately 13,000 species of legumes, only about 20 are commonly consumed. The common dry bean (*Phaseolus vulgaris* L.) has undergone wide production distribution from its origins in Mexico and Central America, and has been utilized in a variety of food applications (Uebersax et al. 1989). Historians believe that ancient Peru and Mexico were the homes of common beans, where they were domesticated firs and then slowly introduced to other parts of the world. A diverse range of dry bean varieties is grown in many parts of the world. Table 27.1 lists different regions and countries of the world where dry beans are grown and consumed. In North America, native Americans grew beans, which were later adopted by the settlers (FAO 2004). By the 1880s, American bean production started to boom. Michigan was the center of bean growing, and the crop soon attracted new growers in Idaho, Colorado, Montana, New Mexico, Nebraska, and Wyoming.

The various types of beans are a staple food and a low-cost source of protein in many countries where protein energy malnutrition is prevalent widely (Van Heerden and Schonfeldt 2004). They provide a good source of protein, which is two to three times that of cereal grains, and are a rich source of dietary fibe and starch (Osorio-Diaz et al. 2003). Dry beans are a good source of vitamins (thiamine, ribofl vin, niacin, vitamin B6, and folic acid) and certain minerals (Ca, Fe, Cu, Zn, P, K, and Mg). Dry beans also contain about 1% of polyunsaturated fatty acids, especially linoleic and linolenic acids (Augustin and Klein 1989; Kutos et al. 2002). Dry beans are rich in nonnutrient components, such as phenolics, and antioxidant compounds too (Amarowicz and Pegg 2008; Xu and Chang 2008). While offering many nutritional benefits dry beans have several undesirable characteristics as well such as long cooking times, "beany" fl vor, and the presence of enzyme inhibitors and hemagglutinins that must be removed for safe consumption (Sathe et al. 1984; Gupta 1987). Nonetheless, the nutrient-dense, common beans are less expensive than animal food products. This chapter discusses production, processing, and nutritional and health benefit of dry beans, and potential for expanding their use.

Breeding, Production, and Harvest

Variety development and evaluation is an important part of overall dry bean producing operation. Centro Internacional de Agricultura Tropical (CIAT) in Colombia has been conducting and coordinating research to increase bean productivity through improved cultivars

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Table 27.1 Dry bean producing countries in different regions of the world

Region	Countries
East Asia:	China, Cambodia, Indonesia, Japan, Korea Rep., Myanmar, Philippines, Thailand, Vietnam
South Asia:	Bangladesh, India, Nepal, Pakistan, Sri Lanka
West Asia/ Middle-East:	Iran, Israel, Jordan, Lebanon, Saudi Arabia, Turkey, Yemen
North America	U.S.A., Mexico, Canada
Central America and Caribbean:	Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Nicaragua, Panama
South America:	Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela
Europe:	Albania, Austria, Benelux, Bulgaria, France, Germany, Greece, Hungary, Ireland, Italy, Poland, Portugal, Romania, Spain, Sweden, United Kingdom, former USSR (Russia)
East Africa:	Burundi, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, Uganda, Zaire
West Africa:	Algeria, Egypt, Morocco, Tunisia
South Africa:	Angola, Lesotho, Madagascar, Malawi, Republic of South Africa, Swaziland, Zimbabwe

Source: FAOSTAT (2009); FAO (2004).

and natural resource management practices in partnership with national programs and regional networks (CIAT 2009). In the United States, different bean-growing states, with assistance from the United States Department of Agriculture (USDA), have their own breeding and quality evaluation programs. For example, in Michigan the variety development and improvement program at Michigan State University has been conducting research for many decades. The varietal evaluation assesses both raw dry beans and canned products quality, as canned beans are major portion of processed products.

The dry bean production operations are diverse across different regions of the world. In the developed countries, highly mechanized systems of production and harvesting are employed. While in Latin America, except for Argentina where beans are produced on large holdings with high technical input, most dry beans productions are on small farms with resource-poor farmers; same is the case mostly in Asia and Africa (Van Schoonhoven and Cardona 1986; FAO 2004). For mechanized harvesting, the plant needs to be uniform and upright with pods off the ground. Breeding for an improvement in plant architecture would help mechanized harvesting become more efficien and cut down on losses (FAO 2004).

For harvesting, the bean pods in a fiel need to be ready at the same time. After the harvest, the bean seed continues to ripen; thus, biochemical reactions occur, which can deteriorate the quality. There are two types of mechanized dry bean harvesting: conventional undercutting, winnowing then combining; and the direct harvest system requiring only one pass of the combine. Using the firs method, after pulling and winnowing, the plant is usually left in the fiel for several hours to dry in the sun. Later, a gathering mechanism lifts the bean plants into a combine where they are thrashed. The moisture levels should be about 13–15% (Schwartz and Pastor-Corrales 1989; FAO 2004; MBC 2009a). In developing countries, harvesting is mostly manual, where careful harvesting is important to not only the bean yield but also its quality during drying and storage.

Dry Bean Classes

The common dry bean classes, many of which are region- and country-specific along with their characteristics and uses are described below (MBC 2009b):

Black Bean: The glossy black color is actually dark purple. Black beans are medium- to small-size, oval-shaped

beans with a shiny black coat or skin, a small white eye or spot (called a "keel"), a creamy white interior, and a pleasant mushroom-like fl vor, which some cooks have described as "earthy" or "meaty." Black beans are widely used in salads, dips, and stews, and in thick soups, especially in Cuba, Puerto Rico, Brazil, and Spain. Commonly processed products are canned in brine, soups, or paste.

Cranberry Bean: These are medium-sized, oval, and creamy white beans with red speckles and streaks with an earthy fla vor. These beans are commonly used in Italian dishes with vegetables, in salads, with meat, in soups and stews.

Great Northern Bean: Great Northern beans are large, oblong-shaped, and plump with a white skin. They are popular throughout North America and bring a slightly nutty fl vor to dishes. Commonly processed as canned in brine, these are frequently served mixed with Pinto beans and can even be substituted for the smaller Navy bean in any recipe.

Red Kidney Bean: The name of the Kidney Bean is derived from its shape. Whether the light red variety or the dark red variety, their size and bright color make them a good addition to nearly any dish. The Kidney beans are processed as canned in brine, meat-based chili products, or acidifie bean salad pack. They can be used in a variety of dishes including soups, salads, sandwiches, and dip.

Navy Bean: Navy beans get their name because of the frequency with which they were served to sailors at sea. Navy beans are small in size and are often used by commercial baked bean manufacturers. Navy beans are processed as canned in brine or tomato sauce, baked with sugar/molasses, or as condensed bean soup. They are used in a variety of forms, such as baked beans, soups, salads, casseroles, or ethnic dishes.

Pinto Bean: Pinto means painted in Spanish; these beans get their name from their mottled beige and brown skin. This medium-sized bean is a staple in the diets of Mexico and the southwestern United States. Pinto beans are processed as canned in brine or refried bean products, and can be found in chili, refried beans, and many dips.

Small Red Bean: The Small Red beans are often used interchangeably with Kidney beans; their color is burgundy red, but their size is small and round. Small Red beans are used in chili, baked beans, spicy Cajun recipes, or any recipe that calls for a Kidney bean.

Production and Consumption

World Production

The world dry bean production in 2008 was 20.39 million metric tons (MT), which reflect an increase of 48.74% over the 1980 production. The world dry beans total production and yield data, for selected years from 1980 to 2008, are shown in Figure 27.1. The dry bean yield during this period increased from 0.54 MT/hectare in 1980 to 0.73 MT/hectare in 2008. The improved production technologies in the last three decades have resulted in 35.55% boost in the yield/unit area, which demonstrate that, of the total increase (48.74%) in dry bean production since 1980, only about 13% can be attributed to increases in area under beans cultivation. The leading dry bean producing countries, ranked by production are listed in Table 27.2. India, Brazil, Myanmar, United States, and Mexico are the top fi e producers of dry beans, accounting for about 60% share of the total world production. The bean classes produced in different countries are quite diverse; e.g., chickpeas (or garbanzo beans) are a major crop in India, whereas Pinto and Navy beans are the predominant bean classes being produced in the United States.

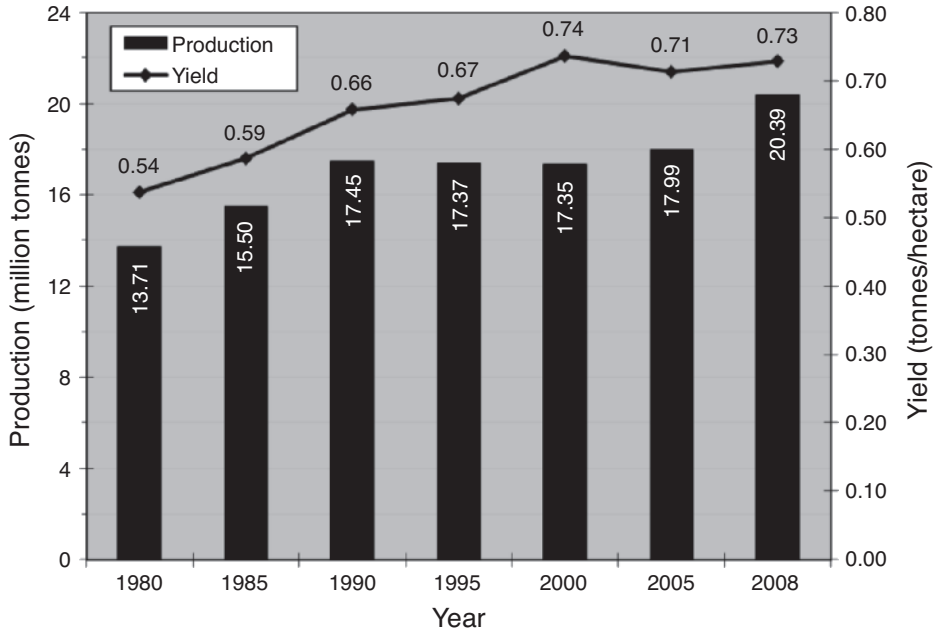

Figure 27.1 World production and yield/hectare of dry beans, metric tons (1980–2008). Source: FAOSTAT (2009).

US Production

North Dakota, Michigan, Nebraska, Minnesota, and Idaho are ranked as the top fi e dry beans producing states in the United States. Table 27.3 shows production data for dry beans based on state productions. Historically, the production has seen significant changes with respect to the individual states (USDA-ERS 2009). For example, from 1980 to 2008, dry bean production in Nebraska and Minnesota increased almost fourfold and threefold, respectively, whereas California saw about 75% decrease over the same time period. Similarly, in Idaho and Michigan, dry bean production has dropped by over 50% during these three decades.

The different classes of dry beans produced in the United States are listed in Table 27.4. Pinto and Navy beans continue to be the leading two dry bean classes produced in the United States. Garbanzo beans (chickpeas) have seen a significan growth from 3,404 MT in 1980 to 55,782 MT in 2008. Similarly, Black bean production has doubled during those years. The growth in Garbanzo bean production can be attributed to changing demographics in the United

Table 27.2 Leading dry bean producing countries of the world (2008)

Rank	Country	Production (Metric Tons)	World share (%)
1	India	3,930,000	19.27
2	Brazil	3,460,867	16.97
3	Myanmar	2,500,000	12.26
4	U.S.A.	1,159,290	5.68
5	Mexico	1,122,720	5.50
6	China	1,121,151	5.50
7	Tanzania	480,000	2.35
8	Uganda	440,000	2.16
9	Argentina	336,779	1.65
10	Indonesia	320,000	1.57
11	Korea, DPR	300,000	1.47
12	Kenya	265,006	1.30

Source: Adapted from FAOSTAT (2009).

Table 27.3 Leading dry bean producing states in the United States (1980–2008)

State	Production (Metric Tons)			
	1980	1990	2000	2008
North Dakota	136,051	254,270	386,765	510,471
Michigan	393,826	276,623	209,563	183,247
Nebraska	138,693	254,219	163,586	146,567
Minnesota	49,076	89,820	121,928	143,671
Idaho	169,124	180,859	87,178	74,274
California	193,713	155,356	104,604	48,771
Washington	54,867	46,333	32,514	44,961
Wyoming	45,266	49,025	38,712	35,816
Colorado	117,965	217,184	100,590	33,530
Others	59,338	121,267	102,521	77,119

Source: USDA-ERS (2009).

States, mainly due to population increases in people of Hispanic and Asian/South Asian origins. In contrast, Pink, Lima, Great Northern, and Black Eye beans have seen significan drop in production figure in the corresponding period. Regardless of these increases or decreases, the overall dry bean production in the United States has remained steady. Almost one-fourth of the dry beans produced in the United States are exported (USDA-ERS 2009). The main classes of dry beans being exported are Pinto, Navy, Black, Great Northern, Lima, and Red Kidney; Mexico, Canada, Dominic Republic, Japan, Angola, and Spain are the major importer of US beans. The US imports of dry beans have seen about 700% increase since 1980; Black beans are the leading imported bean class that was not imported prior to 1990.

US Consumption Trends

The per capita dry beans consumption in the United States was 6.51 pounds/year in 2007 (Figure 27.2), the latest year for which the data was available. Although this is about 20% higher than that in 1980, during the 1990s, per capita consumption was in the range of 7.23–7.81 pounds/year, which was the highest consumption level during the last four decades. The lowest recorded per capita

Table 27.4 Different classes of dry beans produced in the United States (1980–2008)

Dry bean class	Production (Metric Tons)			
	1980	1990	2000	2008
Pinto	524,949	693,464	547,557	521,088
Navy	290,442	334,945	242,382	230,748
Black	73,715	55,477	67,873	148,498
Red kidney (Light + Dark)	89,261	119,083	120,200	101,606
Great Northern	107,754	143,367	126,449	81,184
Lima (Baby + Large)	61,218	52,327	49,736	28,247
Garbanzo	3,404	1,372	67,771	55,782
Small red	32,819	32,920	15,901	41,455
Pink	88,906	60,710	16,257	28,297
Black eye	35,461	47,552	19,407	20,016
Others	49,990	103,740	74,935	41,506

Source: USDA-ERS (2009).

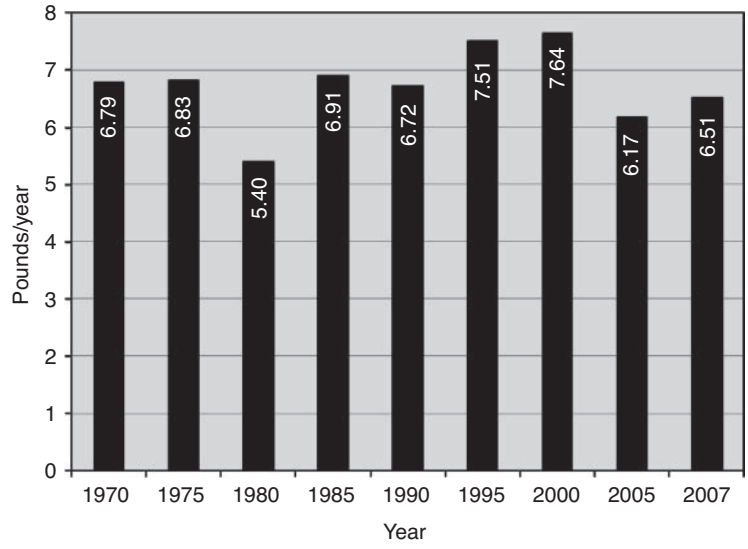

Figure 27.2 Per capita consumption of dry beans in the United States (1970–2007). Source: USDA-ERS (2010).

consumption was 5.41 pounds/year in 1978 (USDA-ERS 2010).

Nutritional Profile and Health Benefits

Nutrients Composition

Beans are one of the most nutritionally complete foods available. As compared to common grains (wheat, oats, corn, etc.), dry beans have significantl higher amounts of protein, dietary fibe , iron, potassium, and folate, whereas carbohydrates and fat content are lower (Table 27.5). Nutritional profil of dry beans is summarized below:

Proteins: The most important role of legumes including dry beans in the diet is as an inexpensive protein source. Dry beans are relatively rich in essential amino acids, particularly lysine and threonine (Sahasrabudhe et al. 1981), whereas cereal grains are deficien in lysine. Only methionine and cysteine (sulfur amino acids) are limiting in dry beans (Carpenter 1981; Sahasrabudhe et al. 1981). Because legumes are looked upon

Table 27.5 Comparison of nutritional profiles of dry beans with other grains (per 100 g)

	Dry beans	Wheat	Oat	Corn	Sorghum
Energy (Kcal)	333	339	389	361	339
Protein (g)	23.58	13.7	16.89	6.93	11.3
Carbohydrates (g)	60.01	72.57	66.27	76.85	74.66
Dietary fibe (g)	24.9	12.2	10.6	7.3	6.3
Fat (g)	0.83	1.87	6.9	3.86	3.3
Iron (mg)	8.2	3.88	4.72	2.38	4.4
Potassium (mg)	1406	405	429	315	350
Folate (μg)	394	44	56	25	0

Source: USDA-NAL Nutrient Database (2009).

as a good source of protein in vegetable-based diets, much effort has been spent in investigating the protein quality of legumes. Bressani and Elias (1980) and Kay (1979) reported that the predominant class of proteins present in *Phaseolus* beans is salt-soluble globulins, of which three distinct proteins have been identified i.e., phaseolin, phaselin, and conphaseolin. The protein efficien y ratio (PER) of raw and cooked legumes is approximately 0 and 1.2, respectively (Rockland and Radke 1981).

Carbohydrates: Beans are rich in complex carbohydrates, with starch being the most abundant nutrient. The carbohydrate content in dry beans ranges from 50–60% by weight (Sathe et al. 1984), with any variations observed are due to different cultivars. Dry beans have the best type of carbohydrates because they are considered to be low glycemic index making beans a suitable food for diabetics. Monosaccharides and some oligosaccharides are also present in dry beans but these make a minor contribution to the total carbohydrate. Soluble sugars are present in the range of 5.5–8% (Reddy et al. 1984). Those present in greatest concentration are sucrose and stachyose along with raffinos and verbascose. Raffinose-containin oligosaccharides constitute from 31–76% of the total sugar fraction in dry beans (Naivukul and D'Appolonia 1978; Akpapunam and Markakis 1979).

Dietary fibe : Dietary fibe constitutes about 25% of the dry beans by weight, which is twice as high as that in wheat and corn (Table 27.5). The indigestible residue of dry beans is an important component and makes up from 8 to 9% of the total carbohydrate fraction (Reddy et al. 1984). The most prevalent fibe components present are cellulose, hemicellulose, and lignins, but pectin is also present. Dry beans contain approximately 13% water-insoluble fibe and 11% water-soluble components (Asp and Johansson 1981). Soluble fibe forms gel, increasing the viscosity of intestinal contents, which may affect glycemic index (Roberfroid 1993). The importance of dietary fibe in human nutrition has received significan attention in recent years from scientists and consumers (Olson et al. 1987; Hughes and Swanson 1989; Hughes 1991). Numerous health benefit have been associated with consuming adequate amounts of dietary fibe , including lower blood cholesterol, reduced risk of heart disease (Schneeman 1986), increased fecal bulk, decreased intestinal transit time, reduced risk of colon cancer, and improved glucose tolerance, which is especially beneficia for diabetics (Toma and Curtis 1986).

Lipids: Common beans contain from a low amount of <1% to no more than 3% lipids, depending on the variety, with the majority of the fatty acids in dry beans found being unsaturated (Patte et al. 1982; Sathe et al. 1984). The total lipid content of dry bean depends on the variety, origin, location, climate, environment conditions, and the type of soil in which they are grown. The oleic, linoleic, and linolenic are the major unsaturated fatty acids, ranging from 64% to 87% of total lipids. The polyunsaturated fatty acids, such as linoleic and linolenic, cannot be synthesized by animals and humans, and these two fatty acids are required for normal growth, cell structure, functions of all tissues, and prostaglandin synthesis (Sathe et al. 1984). The linoleic and linolenic help to lower blood cholesterol too (Mahadevappa and Raina 1978).

Minerals: Dry beans are rich in minerals, such as iron, potassium, and folate. Hosfiel and Uebersax (1980) measured ash content in 34 varieties of dry beans

and reported an average ash content of 3.94%. Considerable decrease of the ash content after cooking has been observed by many researchers due to leaching of the minerals into cooking water (Koehler and Burke 1981). The mineral content of beans should be considered in conjunction with its bioavailability (Sathe et al. 1984). Phytic acid and proteins can complex with dietary essential minerals, such as calcium, zinc, iron, and magnesium, and render them biologically unavailable for absorption; therefore, physicochemical modification of bean proteins to produce desired functional properties may alter the binding of minerals to food components, thereby influencin the mineral availability (Sathe et al. 1984).

Vitamins: Dry beans provide water-soluble vitamins including: thiamine, ribofl vin, niacin, and folic acid, but very little ascorbic acid (Uebersax et al. 1989). Vitamin content in dry edible beans is folic acid (0.171–0.579 mg/100 g), thiamine (0.86–1.14 mg/100 g), ribofl vin (0.136–0.266 mg/100 g), niacin (1.16–2.68 mg/100 g), and vitamin B6 (0.336–0.636 mg/100 g). However, beans provide less than 30 International Units (IU) of vitamin A/100 g of raw beans. Variability of vitamin content is high; Augustin et al. (1981) suggested that geographic location of growth appeared to have had a significan effect on this variability.

Phytochemicals/Antioxidants

Antioxidants, chemicals that destroy free radicals, are found to be very high in many types of beans. Wu et al. (2004) investigated the oxygen radical absorbance capacity (ORAC) of over 100 common foods consumed in the United States. Their data showed that among the foods analyzed, dry beans (Small Red, Red Kidney, Pinto, and Black Beans) were found to be a good source of antioxidants (Table 27.6).

Table 27.6 Top-20 sources of antioxidants among fruits, vegetable, and nuts per serving size

Food item	Serving size	ORAC (μmol of TE)
Small red bean (uncooked)	*Half cup*	*13,727*
Wild blueberry	1 cup	13,427
Red kidney bean (uncooked)	*Half cup*	*13,259*
Pinto bean (uncooked)	*Half cup*	*11,864*
Blueberry (cultivated)	1 cup	9,019
Cranberry	1 cup (whole)	8,983
Artichoke (cooked)	1 cup (hearts)	7,904
Blackberry	1 cup	7,701
Prune	Half cup	7,291
Raspberry	1 cup	6,058
Strawberry	1 cup	5,938
Red Delicious apple	1	5,900
Granny Smith apple	1	5,381
Pecan	1 ounce	5,095
Sweet cherry	1 cup	4,873
Black plum	1	4,844
Russet potato (cooked)	1	4,649
Black bean (uncooked)	*Half cup*	*4,181*
Plum	1	4,118
Gala apple	1	3,903

Source: Wu et al. (2004).
TE, Trolox Equivalent; ORAC, oxygen radical absorbance capacity.

The heightened awareness of consuming antioxidant-rich foods has resulted in a significan increase in research on the antioxidant properties of dry beans. In recent years, numerous studies have reported total phenolics (Luthria and Pastor-Corrales 2006; Dong et al. 2007, Lin et al. 2008), fl vonoids (Dinelli et al. 2006; Onyilagha and Islam 2009), and antioxidant capacity (ORAC) of dry beans (Madhujith et al. 2004; Oomah et al. 2005; Xu and Chang 2008). Similarly, many studies have reported on the effect of processing or storages conditions on antioxidants in dry beans (Korus et al. 2007; Granito et al. 2008; Machado et al. 2008; Xu and Chang 2009).

Health Benefits

A diet high in beans can potentially reduce the risk of developing a chronic disease (Wu et al. 2004). Chronic diseases are conditions that typically take many years (10–30 years) to develop and include certain types of cancers, type-2 diabetes mellitus, heart disease, and other diseases of the blood system. These diseases are the most common causes of death in the United States and they significantl lower the quality of life for millions (Geil and Anderson 1994). The inclusion of dry beans and other legumes in the daily diet has many beneficia physiological effects in controlling and preventing various metabolic diseases such as diabetes mellitus, coronary heart disease, and colon cancer (Tharanathan and Mahadevamma 2003; Flight and Clifton 2006; Dilis and Trichopoulou 2009; Raju and Mehta 2009).

It has been reported that the protective effects of dry beans in disease prevention, such as against cancer, may not be entirely associated to dietary fibe , but to phenolics and other non-nutritive compounds too (Oomah et al. 2006), as polyphenols from dry beans can act as antioxidants, hindering the formation of free radicals (Boateng et al. 2008). In addition, legumes belong to the food group that elicits the lowest blood glucose response. The general consensus on healthy eating habits favors an increase in the proportion of legume-based polymeric plant carbohydrates including starch in the diet. The role of legumes as a therapeutic agent in the diets of persons suffering from metabolic disorders has been reported in the literature (Shehata et al. 1988; Pittaway et al. 2008). The large amount of water-soluble fibe is particularly effective in lowering cholesterol in the blood, whereas the water-insoluble fibe provides bulk, pushing food through the digestive system at a faster rate. Common beans are low in sodium (Augustin and Klein 1989; Buttriss and Stokes 2008); this could be a healthy food choice for persons on low-sodium diet. Regular consumption of dry beans in the United Status, where obesity is on the rise, has been suggested to improve the diet quality signifi cantly (Mitchell et al. 2009).

Limiting Factors/Anti-Nutrients

In spite of many dietary benefits there are a number of limiting factors, which limit increased beans consumption (Jourdan et al. 2007; Boniglia et al. 2008; Oomah et al. 2008). Among these factors, the followings are the major ones (Uebersax et al. 1989): bioavailability and digestibility; antinutritional factors such as enzyme inhibitors and lectins, and raffinose-containin saccharides that may contribute to flatu production. Bressani (1975) categorized the toxic substances present in legumes into several groups: trypsin inhibitors, hemagglutinins or lectins, goitrogenic factors, cyanogenic glucosides, lathyric factors, and compounds that cause favism. Of these factors, trypsin inhibitors and hemagglutinins are of primary concerns for the processors and the consumers (Uebersax et al. 1989; Sathe 2002), the presence of flatulence-causin oligosaccharides also contribute to the negative image of beans.

One of the most important nutritional problems of dry beans is low protein digestibility. The apparent protein digestibility values of different beans are significantl lower than that of animal protein. Possible factors that influenc protein digestibility of lightly cooked beans include lectins and protease inhibitors (Sathe 2002). Trypsin inhibitors, as the name indicates, are protein fractions that strongly inhibit the enzymatic activity of trypsin in the intestine (Gomes et al. 1979), thereby reducing the digestion of proteins and hence absorption of their constituent amino acids. Leiner (1975) reported that the proteins of unheated beans resist proteolysis in the intestine; after heating, true digestibility increases and trypsin inhibitory activity decreases. Uebersax et al. (1989) reported that soaking

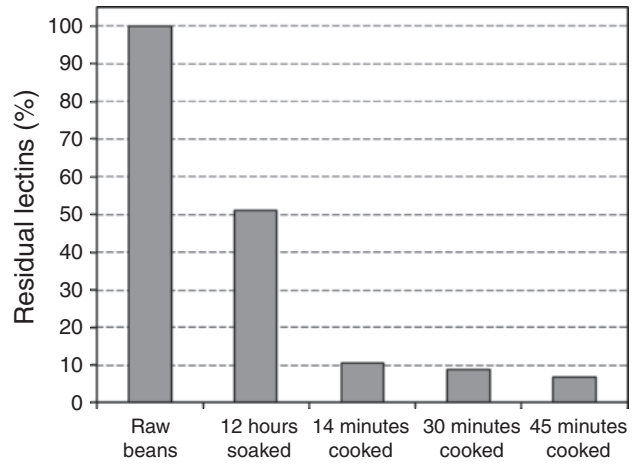

Figure 27.3 Effect of soaking and cooking on the lectins in red kidney beans *(Soaking at initial temperature of 77°C, end temperature 24 ± 1°C; cooking at 99.3°C).* Source: Siddiq et al. (2006).

and heating processes improve digestibility of bean protein in two ways: (1) by denaturation which makes the proteins more susceptible to enzymatic action; and (2) by destroying trypsin inhibitors.

Hemagglutinins, commonly referred to as lectins in beans, can also be destroyed by heat. Lectins are carbohydrate-binding proteins (or glycoproteins) of nonimmune nature, and bind reversibly to specifi mono- or oligosaccharides (Sharon 1993; Boniglia et al. 2003; Wong et al. 2010). They play an important role in the plant's defense against insect pests, and have been found to be toxic to viruses, bacteria, fungi, insects, and higher animals (Van Damme 2008). These compounds cause agglutination of red cells and impair absorption (Leiner 1975). Adequate cooking of raw beans can destroy lectins' activity (Shimelis and Rakshit 2007; Yasmin et al. 2008). Coffey et al. (1985) reported that slow cooking Red Kidney beans at 82°C for 160 minutes resulted in a 1-log reduction of bean lectins; this activity was shown to decrease with a linear response at 70°C (Coffey et al. 1993). Siddiq et al. (2006) reported a significan reduction in lectin after 12 hours of soaking (at an initial temperature of 77°C, equilibrating to room temperature at the end of soak), which can be attributed to higher than ambient initial soak temperature of 77°C. Cooking, after 12-hour soak, in boiling water for 45 minutes reduced lectins by a total of over 93%, with very little or no differences between 14-, 30-, or 45-minutes cook times (Figure 27.3).

The presence of oligosaccharides, which cause flatulenc after consuming beans, has played perhaps a major role in the rather limited popularity of beans among some consumers. The bean oligosaccharides can be reduced (by leaching) by adequate soaking and cooking regimes. A significan reduction in raffinos (80.8%) and stachyose (83.4%) after 12 hours of soaking (elevated initial temperature of 77°C, equilibrating to room temperature at the end of soak) was reported by Siddiq et al. (2006). Cooking can further reduce oligosaccharides to a varying degree (Figure 27.4).

Dry Bean Processing

After harvest, beans delivered to the elevators are checked for quality, color, foreign material, and moisture content. The following

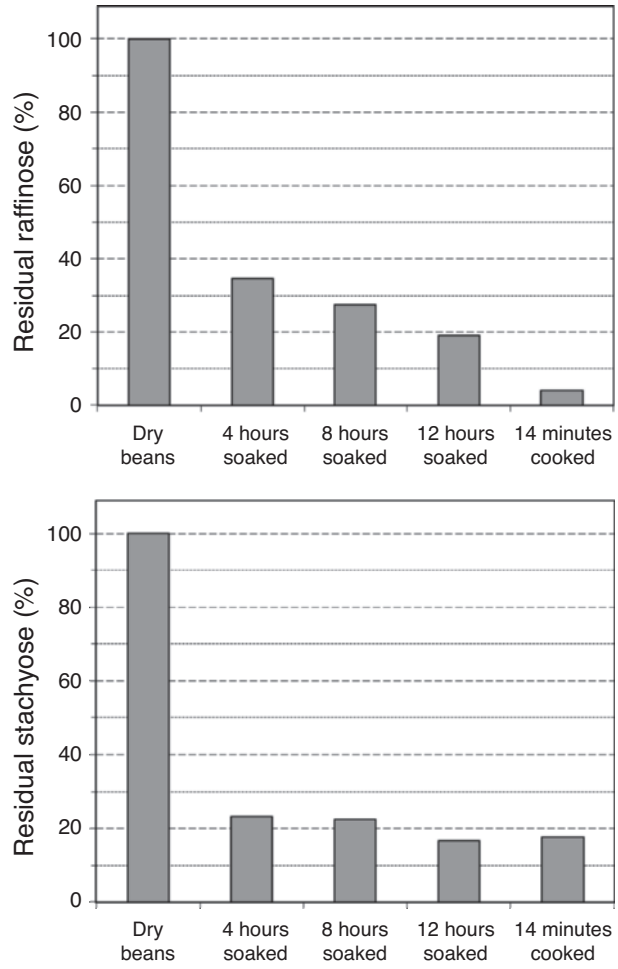

Figure 27.4 Effect of soaking and cooking on the raffinose and stachyose content in red kidney beans *(Soaking at initial temp of 77°C, end temp 24 ± 1°C; cooking at 99.3°C).* Source: Siddiq et al. (2006).

steps are taken before shipping beans to the processing plant: (1) clipper mills clean the beans by separating any pods and other foreign material through a series of screens; (2) gravity separators use the density and weight of the beans to separate lower quality beans; (3) electric eye scanning devices ensure that foreign materials are removed. This includes magnets and metal detectors, which remove any metal that may have inadvertently become mixed with the beans; and (4) beans are passed through a machine to remove stones (MBC 2009b).

Canned Beans

Canning is the most common processing procedure used to manufacture a variety of beans products. These include beans processed in brine or sauce, in combination with meat stews, chili, etc.; a brief description of canned bean products follows (Uebersax et al. 1989): (1) *canned kidney beans*—hydrated kidney beans covered with a sugar and salt brine containing ethylenediaminetetraacetic acid (EDTA) to stabilize the red color; may be utilized in acid (i.e., snap

bean packs) termed "three bean salad"; (2) *canned chili beans*—contains kidney or pink beans, tomato sauce, beef, spices, and condiments. Generally, beans are cooked separately to achieve the desired tenderness and then added to the meat sauce prior to filling (3) r*efried beans*—hydrated cooked pinto beans are mashed to form a flui paste and heated with lard in a kettle prior and thermal processing. Commercially prepared dehydrated products are also available; (4) c*anned pork and beans*—hydrated navy beans are packed in seasoned tomato sauce with small chunks of cured jowl. The sauce is typically prepared from concentrate and may incorporate starch, sugar, salt and seasoning; and (5) c*anned baked beans*—Navy beans processed with sufficien sugar and molasses for increased development of browning pigments and fl vor compounds. Baking may be traditionally accomplished in open kettles and ovens for several hours, or by continuous infrared heating prior to filling

A variety of canned bean products, as mentioned earlier, are commercially processed; this section describes one specifi type of processed product—canned Red Kidney beans. Figure 27.5 shows a schematic of a typical bean canning process; a brief description of various steps, as reported by (Downing 1996), unless noted otherwise, is given below:

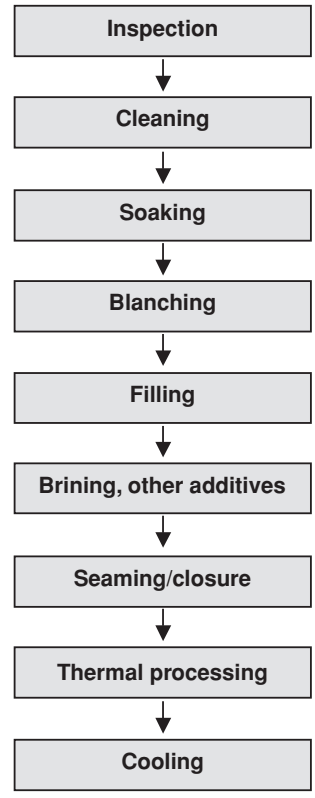

Figure 27.5 Flowchart of a typical dry bean canning process. Adapted from Downing (1996).

Inspection and Cleaning

Beans are inspected for any off-color, broken seeds, or otherwise unsatisfactory characteristics. Moisture content is also determined, which should be in the range of 12–14%. If the beans have not been previously cleaned, they are passed through a clipper cleaner or similar grain winnowing mill before use, in order to eliminate loose dirt and small pieces of foreign material.

Soaking

The quality of bean soaking water is important; soft water should be used as hard water may result in a product which will require a longer cook to make it tender. On the other hand, completely soft water can result in bean splitting. Uebersax et al. (1989) reported that dry beans are traditionally soaked for 8–16 hours at room temperature, or soaked at elevated temperatures (82–100°C) for 20–40 minutes. Either procedure is designed to provide beans with a fina moisture range of 53–57%. The high temperature short time soak is generally preferred since it reduces labor costs and floo space requirements, and reduces potential bacteriological problems that may occur during a long soaking period. Soaking at elevated temperature was shown to reduce lectins and oligosaccharide (Siddiq et al. 2006).

Many additives have been employed in soak water by researchers and include EDTA,

sodium bicarbonate, sodium hexametaphosphate, sodium chloride, sodium carbonate, sodium bisuluite, oxalic acid, ammonium oxalate, citric acid, malic acid, acetic acid, hydrochloric acid, and sulfates and chlorides of calcium and magnesium (Uebersax et al. 1989; Rehman et al. 2001; Pujola et al. 2007). Downing (1996) suggested that it is advantageous to control the soaking period so that the soaked beans will be delivered to blanching and canning lines with a moisture content as constant as possible in order that the proper fil may be obtained without the necessity of frequent changes in blanching schedule and fill-i ratio of beans to liquid.

Blanching

Typical blanching is done at 180–200°F (82–93°C) for 3–5 minutes. Conventional pea and bean blanchers are used for this operation. Optimum blanching is necessary as overblanching can cause splitting of the skins. Instead of the conventional long soak and short blanch, a long blanch method is used by some processors, where beans may be given a short soak or no soak but blanched at 170–212°F (77–100°C) for 10–40 minutes. The long blanch method requires careful checking of moisture content of both raw and blanched beans, and a careful control of fillin weights, sauce formula changes, and cooking time, in order to compensate for lower moisture content of beans when fille and their greater swell in the cans during processing. After blanching, the beans should be washed in cold water immediately. Rod reels or shaker washers equipped with cold water sprays are commonly used for cooling blanched beans. Any split beans or skins are separated prior to fillin bean into cans.

Filling, Brining, and Closing

Blanched beans are fille into cans using high-speed fillers a desired quantity of beans is fille into each can followed by the addition of brine. It is to be noted that sufficien brine must be added to cover all beans because beans that protrude above the brine into the headspace area are subject to dark discoloration after processing. If there are any variations in the soaking or blanching schedules, or any other factors which result in variable bean hydration, this should be taken into due consideration and the fil weight must be adjusted accordingly. Salt and sugar brine is commonly used for kidney beans; there is considerable variation in brine formulae used by various canners, but usually the formula consists of approximately 20 lbs (9.08 kg) of salt and 30–45 lbs (13.6–20.4 kg) of sugar per 100 gal (378.5 L) of brine. The brine must be added to the cans at a temperature as close to the boiling point as possible. The FDA (US Food and Drug Administration) food additive regulations allow an addition of 165 ppm of Na_2 EDTA to preserve color. The best method to incorporate EDTA treatment is through the use of combination salt tablets containing 1.6% Na_2 EDTA and 2.0% $CaCl_2$, with continuous agitation. Filled can must be sealed above 140°F (60°C) to attain a high vacuum. If the temperature of the can content is below 140°F, steam-fl w closure may be used to secure proper vacuum.

Thermal (Retort) Processing

Thermal processing is done using continuous retorts. Beans in brine in No. 2 1/2 (401 × 411) cans at an initial temperature of 100–140°F (38–60°C) are processed for 45, 30, or 20 minutes at 240°F (116°C), 245°F (118°C), or 250°F (121°C), respectively. In order to obtain the desired tenderness in beans packed under various canning conditions, it may be necessary to increase the process time from 10 to 50% above the processing times required for sterilization. After retorting, the cans must be immediately cooled to 95–105°F (35–41°C) by immersion in or a spray of cold water; this is necessary to minimize spoilage from the growth of thermophilic bacteria.

After cooling, cans are dried, labeled, and cased for warehousing and shipment.

Canned Beans Quality

Raw bean stored under adverse conditions may undergo hardening and lose their ability to hydrate, resulting in a bean which is termed hard-to-cook (HTC) and has low end-product yields for processors or home users. HTC beans have poor soaking imbibition and, despite prolonged cooking times, do not attain adequate texture, due to a failure of cotyledon cells to separate upon cooking. A survey on major consumer bean quality characteristics identifie cooking time as one of the most important factors, followed by the HTC defect (Garcia et al. 1998). Sgarbieri and Whitaker (1982) reported that texture is not the only quality attribute of beans that is affected by HTC, the nutritional value is also impaired by a loss of vitamins and decreased protein availability.

Textural (tenderness) and sensory aspects are the most important quality attributes of canned beans. Some quality problems encountered in canned bean products are discoloration, hardness of the beans, and breakage of the seed coat after the canning process. When the seed coat splits, it affects more than just the appearance; it can also result in starchiness and excessive viscosity in the fina product. Canners are often very particular about specifi qualities of the beans (Wassimi et al. 1990). The high standards quality expected by the canners and customers force bean producers to actively participate in breeding programs. Thus, the breeders have to be concerned with not only the yields of the cultivars, disease resistance, weather tolerance ability, and growth period, but also the culinary quality of the bean products as requested by the consumers (Wassimi et al. 1990). Balasubramanian et al. (2000) reported that processing variables, particularly the level of calcium in the soak water, blanch water, and brine, markedly affect several canning quality traits.

Textured/Hydrolyzed Protein Products

Textured or Texturized Vegetable Proteins

Textured vegetable protein (TVP) is a versatile ingredient, different forms allowing it to take on the texture of whatever ground meat it is substituting. Using TVP, a variety of different consumer food products can be made, such as vegetarian or vegan versions of traditional meat dishes such as chili, spaghetti, tacos, burgers, or burritos. TVP, also known as textured soy protein (TSP), is made from defatted soy flou , a by-product obtained while making soybean oil. It is quick to cook, high in protein, and low in fat. Rehydrated TSP can completely or partly replace ground beef in most recipes. It can also replace a minimum of 33% "tuna" fis in tuna salad. It is high in protein and low in fat and sodium. It is also a good source of fibe and isofl vones (Macedo-Silva et al. 2001; SANA 2009). The TSP is made by forming a dough of defatted soy flou with water in a screw-type extruder. The dough is extruded through a die into various possible shapes like granules, fla es, chunks, goulash, etc., and dried in an oven. By weight, TSP made from soy flou contains 50% protein and needs to be rehydrated before use. However, TSP, when made from soy concentrate, contains 70% protein. It is usually rehydrated with cold or hot water, but small amount of vinegar or lemon juice can be added to quicken the process (SANA 2009). Figure 27.6 shows dry TVP fla es and textured soy chunks available commercially. The nutritional profil of TVP and SPI is summarized in Table 27.7.

Soy protein isolate (SPI) is a dry powder food ingredient that has been separated or isolated from the other components of the soybean, making it 90–95% protein and almost carbohydrate- and fat-free. SPI provides

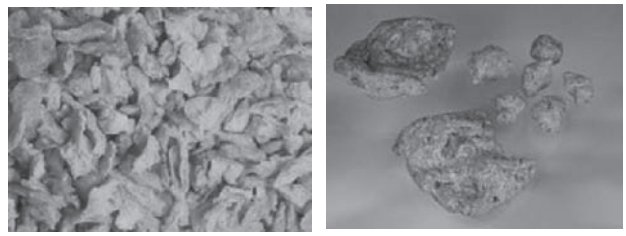

Figure 27.6 Commercially available TVP flakes and textured soy chunks. Source: SANA (2009).

a high quality protein that contains all essential amino acids. Nutritionally, SPI is comparable to animal products but unlike animal products contains no cholesterol and little or no saturated fat. Advances in processing technology have led to a variety of ways SPI can be produced. Generally, SPI is made from defatted soybean fla es that have been washed in either alcohol or water to remove sugars and dietary fibe (SANA 2009). SPI is used throughout the food industry for both nutritional and functional reasons.

Hydrolyzed Vegetable Protein

The TVP or SPI should not be confused with hydrolyzed vegetable protein (HVP), which is produced by boiling cereals or legumes, such as soy, corn, or wheat, in hydrochloric acid and then neutralizing the solution with sodium hydroxide. The acid hydrolyzes the protein in vegetables into their component amino acids. The resulting brown powder contains, among other amino acid, glutamic acid, which consumers are more familiar with in the form of its sodium salt, monosodium glutamate, or MSG—a fl vor enhancer in many processed foods. It is recommended that because of the high levels of MSG, people sensitive to MSG should avoid HVPs (Anon 2009).

Aaslyng et al. (1998) produced three protein hydrolysates (HVPs) from untoasted defatted soy by acidic hydrolysis (aHVP), enzymatic hydrolysis (eHVP), and enzymatic hydrolysis followed by a heat treatment with glucose (eHVP-ht). The three HVPs were characterized by amino acid analysis, identificatio of volatile compounds, and sensory profiling The aHVP had a higher degree of hydrolysis compared with eHVP and eHVP-ht, which still contained peptides composed mainly of the smaller and the acidic amino acids. A total of 29 volatile compounds were identifie by GC−MS. Furans and sulfide were primarily found in the acidic HVP. The multivariate analysis of the sensory profil showed that the acidic HVP had increased intensity in the bouillon, soy, and overall taste characteristics compared with the two enzymatic HVPs.

Table 27.7 Nutritional composition of textured soy protein and soy protein isolate

Composition	Textured soy protein* (per 0.75 oz, 29.3 g)	Soy protein isolate† (per 1.0 oz, 21.3 g)
Total fat	0	1 g
Total carbohydrates	6	2 g
Protein	11	23 g
Cholesterol	0 mg	0 mg
Sodium	3 mg	285 mg
Dietary fibe	4 g	1.5 g
Calcium	68 mg	50 mg
Potassium	192 mg	23 mg
Phosphorus	155 mg	220 mg
Folate	64 mcg	50 mcg

*American Soybean Association (www.soygrowers.com).
†USDA-NAL Nutrient Database (2009).

Table 27.8 Consumer panel* sensory scores of cooked Red Kidney beans coated with sugar syrup

	Sensory scores† of sugar-coated beans		
Sensory attribute	20% Syrup	35% Syrup	50% Syrup
Color	6.15a‡	6.00a	6.01a
Texture	5.78a	5.73a	6.10a
Flavor	5.59b	5.95ab	6.30a
Sweetness	5.48b	6.03a	6.27a
Overall acceptance	5.46b	5.85ab	6.19a

Source: Siddiq et al. (2006).
*N = 105; 33 males, 72 females.
†Scoring scale of 1–9: 1-dislike extremely, 9-like extremely.
‡Means sharing the same letter in rows are not significantl different from each other (Tukey's HSD test, $p < 0.05$).

Other Products

A number of products prepared from dry beans have been reported in the literature; bean flou (Sathe et al. 1981; Anton et al. 2009; Siddiq et al. 2010), extruded products (Korus et al. 2007; Rocha-Guzman et al. 2008; Siddiq et al. 2008), minimally processed sugar-coated beans (Dolan et al. 2006, Siddiq et al. 2006), spaghetti (Gallegos-Infante et al. 2010), pasta (Granito and Ascanio 2009), tortillas (Anton et al. 2009), snack bars (Durkee et al. 2006), use in beef sausages (Dzudie et al. 2002), and intermediate-moisture food (Figuerola et al. 2008). A 105-member consumer panel showed a fairly good acceptability for minimally processed sugar-coated Red Kidney beans (Table 27.8); on a scale of 1–9 (1, dislike extremely to 9, like extremely), the overall acceptability score ranged from 5.46 to 6.19 (Siddiq et al. 2006).

Most bean-based products utilize bean flou processed by different methods. Dry bean flour can be used as functional ingredients to improve the nutritional quality of a variety of processed food products (Horax et al. 2004). The application of various technological processes to legumes or dry beans can increase their use as an ingredient in manufactured food products. Processing improves the nutritional quality of dry beans by reducing the content of anti-nutritional factors and, at the same time, diversifie their use as ingredients by altering their functional properties. It is to be noted that production and use of these products is on a somewhat limited scale or in the research and development stages; nonetheless, the potential uses of dry beans products continue to be explored and expanded.

Another area where dry beans can be utilized is the gluten-free products. The fact that dry beans, apart from being nutrient-rich, are gluten-free offers significan opportunities for exploiting bean flou use in different food systems. The number of new gluten-free products introduced in the United States increased by over 6-fold, from 135 in 2003 to 832 in 2008 (Clemens and Dubost 2008). They further reported that the sales of gluten-free products are projected to grow at an annual rate of 25% for the next several years.

Summary

Common dry beans are a nutrient-dense vital food resource. Dry beans supply protein, complex carbohydrate, fibe , and essential vitamins and minerals to the diet, yet are low in fat and sodium and contain no cholesterol. Beans traditionally require soaking and heating to facilitate softening. Open kettle cooking over fir or gas stoves has commonly been used in developing countries, while canning

is the primary method of preparation in industrial nations. Cooked beans are served with a variety of sauces and may be used as the main dish or as a vegetable side dish. Including dry beans in a health-promoting diet is especially important in meeting the major dietary recommendations to reduce risk for chronic diseases such as coronary heart disease, diabetes mellitus, obesity, and cancer. New processing opportunities for improved utilization of dry beans continue to be investigated, especially utilizing flou from different bean varieties.

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Chapter 28

Carrots

B. C. Sarkar and H. K. Sharma

Introduction

The carrot (*Daucus carota* var. Sativa; family: *Umbelliferae*, genus: *Daucus*, species: *Carota*) is one of the important root crops grown throughout the world, and is grouped as: (i) biennial temperate carrots and (ii) annual tropical carrots which are red and juicy, with a bigger core and a heavier top (Bose and Som 1986). Carrots are grown for human consumption and as feed, particularly for horses. They are consumed as vegetables (fresh, canned, and dehydrated), salad, juice, soups, pickle, cake mix, etc. (Kalra et al. 1987; FAO 1990). Nutritionally, carrots are known for their high concentration of provitamin A (carotene). This chapter reviews the production, quality, and processing aspects of carrots.

Production

Production

China is the leading producer of carrots in the world (Table 28.1; Figure 28.1). The FAO production estimates combine carrot and turnip together, and accordingly the world production of these vegetables in 2000 and 2007 was 21.44 and 27.22 million metric tons, respectively (FAO 2007).

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Cultivation and Harvesting

Carrot, a cool-season crop, is cultivated throughout the world. Its color varies from orange to deep red, light purple to violet, yellow, or white. The shape of carrots makes them easy to handle during harvesting, cleaning, shipping, and distribution. Their effective root length at harvest is about 10 cm, and the root diameter and length can range from 2 cm to 6 cm and 6 to 30 cm, respectively.

Carrots are harvested when the roots are about 2 cm or longer in diameter. The soil may be loosened with a special plough (carrot lifter) or an ordinary plough. The fiel is irrigated a day before to facilitate harvesting. Carrot tops can be cut mechanically (Ryall and Lipton 1972), but 20–30% visible damage due to mechanical harvesting has been reported (Kalra et al. 1987). Machine harvesting, however, did not significantl affect chemical or sensory qualities of carrots when compared with hand-harvested carrots (Seljasen et al. 2007). Late harvest was reported to cause lesser weight loss, reduced respiration, higher sucrose-to-monosaccha ride ratio, and higher carotene content during storage of carrots at 0–1°C and 95% relative humidity (RH). However, the firmnes was not affected by the harvest date (Weichmann and Kaeppel 1977).

The growth and composition of carrot roots may depend upon the soil, climate, and cultural practices (sowing, fertilization, irrigation, etc.). Regardless of harvest date, the yield, quality, and carotene content are

Table 28.1 Leading carrot-producing countries in the world

World Rank	Country	Production-2006 (metric tons)
1	China	8,395,500
2	Russian Federation	1,730,000
3	United States of America	1,601,790
4	Poland	935,000
5	Ukraine	706,500
6	United Kingdom	677,144
7	Italy	641,558
8	Japan	630,000
9	Germany	555,000
10	Netherlands	430,000
11	France	417,800
12	Turkey	380,000
13	Mexico	378,517
14	India	350,000
15	Belgium	320,000

Source: http://www.carrotmuseum.co.uk/statistics.html.

reported to increase and incidence of misshapen roots is reported to decrease with the increase in level of organic matter applied to the soil (Parraga et al. 1995). Further, use of nitrogen fertilizers is reported to increase the phenolic compound concentrations (Smoleń and Sady 2009).

Varieties and Classification

Some selected commercial varieties of carrots are: Amsterdam, Barlikuner, Chantenay, Royal Chantenay, Delattya, Emperador, Flakker, Gold Pak-28, Honey sweet, Karotena, Pusa Meghalli, Pusa Kessar, Pusa Yamadagni, Berlicum, Sperton Fancy, Panter, and Yukon. The important carrot varieties in the United States are Imperator, Gold Spike, and Gold Pak, having long slender roots with a smooth exterior. The Royal Chantenay, Red Cored Chantenay and Autumn King are popular varieties used in processing; however, the highly fl vored French or Chantenay varieties are not considered for juice-making because of off fl vor development (Rodriguez et al. 1975; Kotecha et al. 1998). As would be expected, the variety of carrot has an effect on its color and sugar content (Baardseth et al. 1995).

The major Indian carrot varieties are Chantenay, Danvers, Nantes, Early Horn, and Early Gem. A hybrid variety, Pusa Kesar is cultivated throughout India. This may be due to its good adaptability to the Indian climatic conditions with desirable quality attributes (Ghosh 2002). Table 28.2 gives classificatio of carrots based on color, size, and shape.

Postharvest Handling and Storage

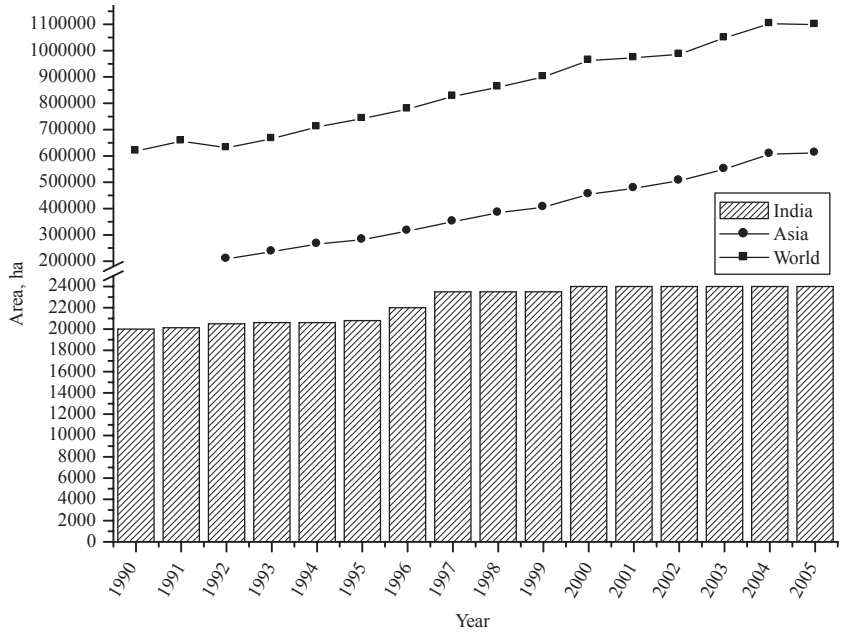
Sorting and Handling

Freshly harvested carrots are cleaned, screened, sorted, and graded to remove fiel soil and defective, undersized, cut/broken, diseased, discolored, misshapen, split/cracked, and sunburned carrots. Careful handling is necessary to minimize bruising and tip breakage. Depending upon the market requirements, the carrot roots are topped (washed, graded, and packed) or bunched (tops left on). Bunched carrots respire faster, and therefore deteriorate faster, than topped carrots. Topped carrots have a storage life of about 9 months at 0–1°C and 98–100% RH. After harvesting, size-grading is generally carried out by divergent rollers or belts (Burns 1997). The roots in the range of 2.5–3.5 cm in diameter are selected for canning.

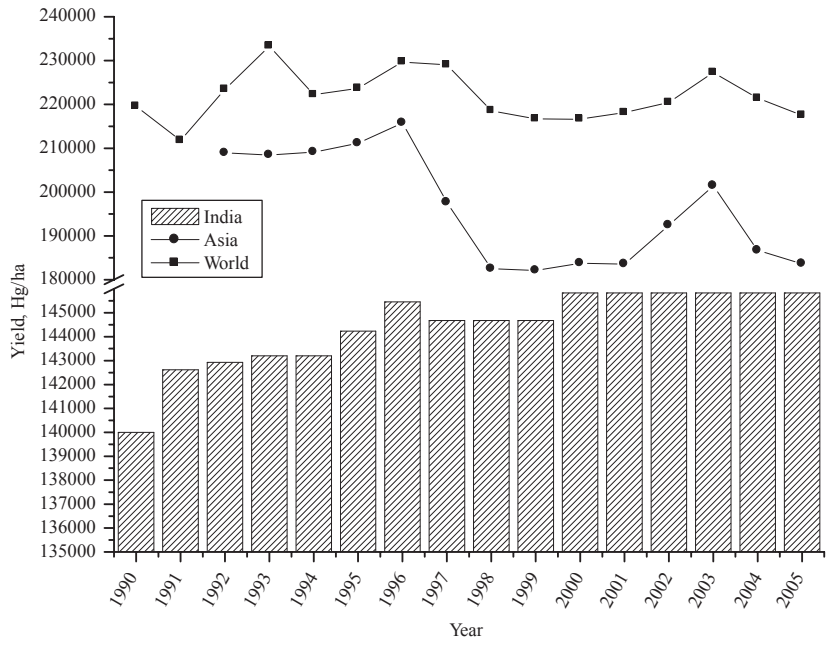
Postharvest shaking to remove moisture is reported to increase respiration rate and ethylene production, as well as ethanol and 6-methoxymellein generation, and decrease terpenes and sugars (Seljasen et al. 2007).

Preconditioning and Precooling

Toivonen et al. (1993) reported that preconditioning for four days at 1°C signifi cantly reduced weight loss of carrots when placed in simulated shelf conditions (temperature 13°C and RH $>$ 95%). Preconditioning enhances deposition of suberin on the surface



(a) Area under carrot cultivation



(b) Carrot yield

Figure 28.1 Carrot cultivation data of India, Asia, and the world.

Table 28.2 Characteristics of selected carrots based on color, size, and shape

Color	
Orange	Contains β-carotene with small amount of alpha carotene, both of which are orange pigments; high in Vitamin A; originates from Europe and the Middle East.
Yellow	Contains xanthophylls, similar to β-carotene pigment; origin: the Middle East.
Red	Contains lycopene; origin: India and China.
White	Lacks pigments but contains phytochemicals; origin: Afghanistan and Iran.
Size/Shape	
Nantes	This is a popular carrot with a sweet taste. Nantes carrot is almost cylindrical in shape, and round rather than tapering at the end. It has a small core and a larger outer cortex. Sugars accumulate in the cortex, giving Nantes their sweet taste. Nantes cannot be stored for very long. It matures in early to mid-summer, and is usually eaten fresh.
Imperator	This is the most commonly grown carrot because of its high yields and long storage potential. Imperators are long and tapered. They are a late-maturing variety, and generally have a larger, more fibrou core; therefore, they do not have the sweet taste like other varieties of carrots.
Chantenay	Shape-wise, Chantenays are considered as an intermediate variety between a Nantes and an Imperator. They are tapered like the Imperator, but the bottom rounds off somewhat like the Nantes. Chantenays are sweet like the Nantes.

of the periderm and the lignificatio of subsurface cell layers. These two changes are suggested as possible mechanisms for reduction of weight loss and discoloration of carrots, which occur under shelf conditions. However, carrots stored below 0°C for prolonged periods are susceptible to chilling injury, and carrots exposed to ethylene during storage develop a bitter fl vor; thus, it is important not to store carrots with ethylene-producing commodities.

Prepackaging

Carrots packed in either perforated polyethylene bags or in crates lined with polyethylene film were reported to hold well for 8–9 months at 0–1°C (Umiecka 1981). During storage of carrots in polyethylene bags for 5–7 months at −1°C to +1°C with 92–96% RH, the loss of ascorbic acid (2.2–5.4 mg/100 g), carotene (1.1–4.0 mg/100 g), and pectic substances (0–1.1 mg/100 g) was lower than that in the control carrots (Kalra et al. 1987).

Postharvest Storage

Carrots are considered to be highly susceptible to moisture loss, leading to wilting, limping, and loss of fresh quality. The degree and speed of changes depend on the temperature and relative humidity of the environment.

Storage Temperature

Mature topped carrots can be stored for 7–9 months at 0–1°C with an RH of 98–100%. However, even under these conditions, 10–20% of the carrots may show some decay after 7 months. The deterioration in quality during the storage is due to the loss of sugars (Apeland and Hoftun 1974). The optimum storage temperature for carrots as recommended by International Standards Organization is 0–1°C with 95–98% RH. Air circulation should be particularly vigorous in bulk-stored carrots (ISO 1974).

Modified and Controlled Atmosphere (MA, CA) Storage

Modifie atmosphere (MA) storage retarded whitening of carrots but had a detrimental effect on firmnes (Lafortune et al. 2005). Bohling and Hansen (1981) reported that controlled atmosphere (CA) (high CO_2 and low O_2) was not beneficia for whole carrots as it led to the growth of rootlets and shoots. However, carrot slices, sticks, and shreds stored in

CA of 0.5% O_2 and 10% CO_2 at 0–10°C, had reduced respiration rates. Further, at 0°C, cut carrots could be held in fil bags at the above gaseous atmosphere without any deleterious effect (Izumi et al. 1996). Gomez-Lopez et al. (2007) investigated the use of gaseous chlorine dioxide as a promising alternative to prolong the shelf life of grated carrots.

Quality of Carrots

The quality of fresh carrots used for consumption or processing depends on their texture, color, and sweetness. Measurement of Hunter "a" value has been reported as a simple and reliable method to evaluate carrot color quality (Park-Se-Won et al. 1995). Fresh carrots can be distinguished from canned carrots on the basis of carotenoid content as the latter are reported to have higher carotenoid than fresh carrots (Edwards and Lee 1986). Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) studies in fresh and stored (4 months at 8°C) carrots (*Daucus carota* L.) indicated a reduction of lipid droplets and starch grains within the chromoplasts in the stored carrots (Grote and Fromme 1978).

Quality Changes During Storage

During storage at 1°C and 98% RH, total sugar was reported (Simon 1984) to be almost constant, whereas the ratio of nonreducing sugars to reducing sugars decreased. The sweetness increased during storage in air atmosphere but reduced in the presence of ethylene. The total phenol content of carrots stored at 3 ± 1°C in 100 μl/l ethylene-containing atmosphere was higher than that of the control samples kept in air. There was an increase in the pre-existing phenols, particularly isochlorogenic acid, and also a *de novo* synthesis of four compounds, two of which were identifie as 3-methyl-6-methoxy-8-hydroxy-3,4-dihydroisocoumarin and 5-hydroxy-7-methoxy-2-methylchromone, not normally present in carrots (Sarkar and Phan 1979). Ethylene concentration (0.1–5 ppm) and temperature (1–15°C) were reported to increase respiration and also favored a more rapid formation of isocoumarin (Lafuente et al. 1996). Harvested carrots accumulated an antifreezing protein in their cell walls, reaching a maximum level after 12 weeks of storage at 0°C, followed by a gradual decrease. The presence of the antifreezing protein suggested that structural changes leading to changes in mechanical properties during the firs 12 weeks of storage may be associated with a cold-acclimation process (Gómez et al. 2003).

Nutrient Composition

Carrots are a rich source of β-carotene. A carrot root is also considered as a good source of minerals and carbohydrates (Table 28.3). Besides being used in various forms such as juice, frozen, canned, and dehydrated, carrot puree is used extensively in baby foods because of its nutritional values and appealing sensory properties (Francis 1999).

Carrot Processing

As per the USDA per capita availability data for in 2007, about 78% (4.1 kg) of carrots were used as fresh, 12% (0.6 kg) as frozen, and 10% (0.5 kg) as canned (USDA 2007). The minimally processed or fresh-cut carrots, frozen carrots, and carrot soups are available commercially. However, the processing for these forms of carrots is similar to that described in other chapters in this handbook and will not be discussed here. Baby carrots are another product which is ready-to-eat.

In this section, we describe the effects of pretreatments and other aspects of carrot juice processing. Table 28.4 shows important constituents and the juice yield from selected carrots.

Table 28.3 Selected nutrients in raw carrots

Content (unit)	USDA*	Gopalan et al. (1989)
Moisture (%)	88.3	86
Protein (%)	0.93	0.9
Fat (%)	0.4	0.2
Carbohydrates (%)	9.6	10.6
Total Sugars (%)	–	–
Dietary fibe	2.8	1.2
Total ash (%)	0.97	1.1
Calcium (mg/100 g)	33.0	80
Iron (mg/100 g)	0.30	2.2
Phosphorus (mg/100 g)	35	53
Sodium (mg/100 g)	69	35.6
Potassium (mg/100 g)	320	108
Magnesium (mg/100 g)	12	17.2
Copper (mg/100 g)	0.04	0.1
Zinc (mg/100 g)	0.24	0.36
Carotenes (μg/100 g)	11,762	1,890
Thiamine (mg/100 g)	0.066	0.04
Ribofl vin (mg/100 g)	0.058	0.02
Niacin (mg/100 g)	0.983	0.6
Vitamin C (mg/100 g)	5.9	3.0
Energy value (Kcal/100g)	41	48

*www.nal.usda.gov/fnic/foodcomp/search, accessed on June 25, 2010.

Pretreatments

As with other vegetables, blanching is helpful in retaining quality during subsequent processing and storage as it inactivates enzymes, removes raw fl vor, stabilizes the color and texture, and reduces microbial load. Depending on the quality of the raw product, different time/temperature combinations can be used for blanching (Anastasakis et al. 1987). Blanching of carrots before freezing caused 26.4% increase in β-carotene, while the carrots frozen without blanching had a 7.3% loss of β-carotene. Further, during storage at −40°C for 4 months, blanched frozen carrots lost about 24.5% β-carotene as compared to 38.1% loss in unblanched frozen carrots (Shaheen et al. 1977).

Bao and Chang (1994) reported that as compared to the unblanched carrots, blanched

Table 28.4 Carrot juice yield vis-à-vis composition of selected carrot varieties

	Carrot varieties			
Content/100 g (fresh weight basis)	Pusa kesar	Local red	T-29	Nantes
Water content, g	88.65	91.2	87.32	89.89
Protein, total, g	0.6	0.5	0.4	0.8
Fat, g	0.285	0.183	0.337	0.215
Carbohydrate, g	9.665	10.	10.87	8.97
Total sugar, g	4.51	5.15	3.74	4.42
Dietary fibe , g	5.16	5.16	7.13	4.55
Ash, g	0.8	0.7	0.9	0.82
Total carotenoids, μg	8645	7458	9457	9764
Pectin, g	1.375	1.196	1.575	1.421
Juice yield, g	66.58	63.8	58.95	62.36

Source: Sharma 2006.

carrots had higher redness and β-carotene but lower ascorbic acid after drying, but non-enzymatic browning (NEB) was unaffected by blanching. However, during storage of dehydrated carrots, a decrease in β-carotene and ascorbic acid content with an increase in NEB values was reported by Negi and Roy (2001).

Effects of various pretreatments (osmotic, microwave, sulfite water-blanching, and steam-blanching) on the tristimulus color parameters have been investigated (Krokida et al. 2000). Untreated and microwave pretreated carrots showed extensive browning during drying, manifested by a significan reduction in the Hunter "L" value and a corresponding increase in the "a" and "b" values. The pretreatments suppressed browning during drying, resulting in constant, or only slightly increased, "L", "a", and "b" values.

Carrot Juice Extraction and Processing

Typically, carrot juice, used either in blends or specialty products, contain approximately 10% soluble solids with a titratable acidity of about 0.15% and a pH of 6.1 (Ghosh 2002). A general fl wchart for the production of vegetable juice is given in Figure 28.2. Hydraulic, screw, and belt presses can be used to express juice. Washed and trimmed carrots are comminuted in a mill and juice is extracted. It is then given a preliminary heat treatment at 82.2°C to coagulate all materials unstable to heat. The mixture is then homogenized to prevent separation of the insoluble material during further heat treatment. The juice is preheated to 71.1°C, fille in cans, and processed at 121.1°C for 30 minutes.

A detailed process for carrot juice processing is shown in Figure 28.3. The juice thus processed and stored refrigerated (4 ± 1°C) for 6 months was acceptable in quality without significan loss of color and carotene content Goyal (2004).

An acceptable carrot juice may also be prepared by blanching the carrot in boiling water for 15 minutes and pressing in a hydraulic press. However, deep orange juice obtained from carrot by milling and pressing in a hydraulic press gave unsatisfactory fl vor and yield. Juice of a better fl vor was obtained from mature carrots rather than from young carrots. The bitterness associated with the stem and skin is minimized by peeling before milling and processing (Chadha et al. 2003).

Carrot juice obtained from the carrots unsuitable for fresh markets, discolored and clarifie quickly unless the carrots were

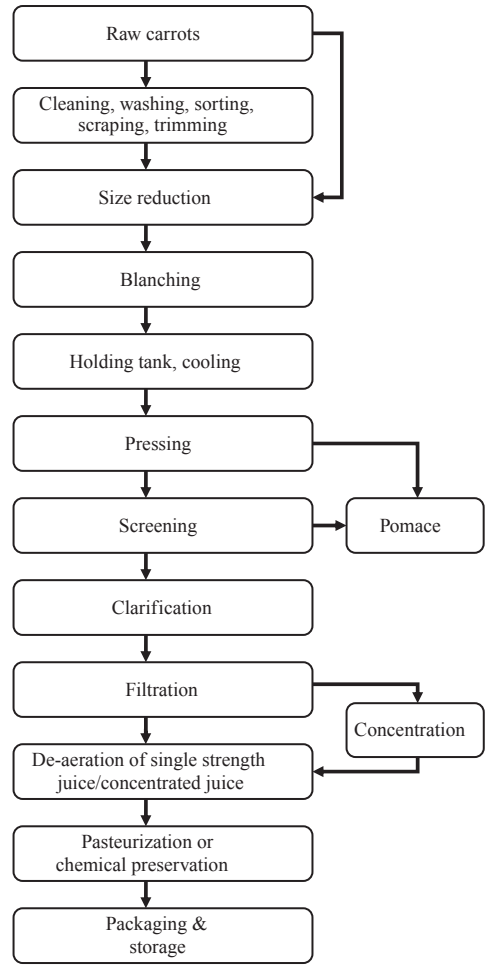


Figure 28.2 General flowchart for juice expression process.

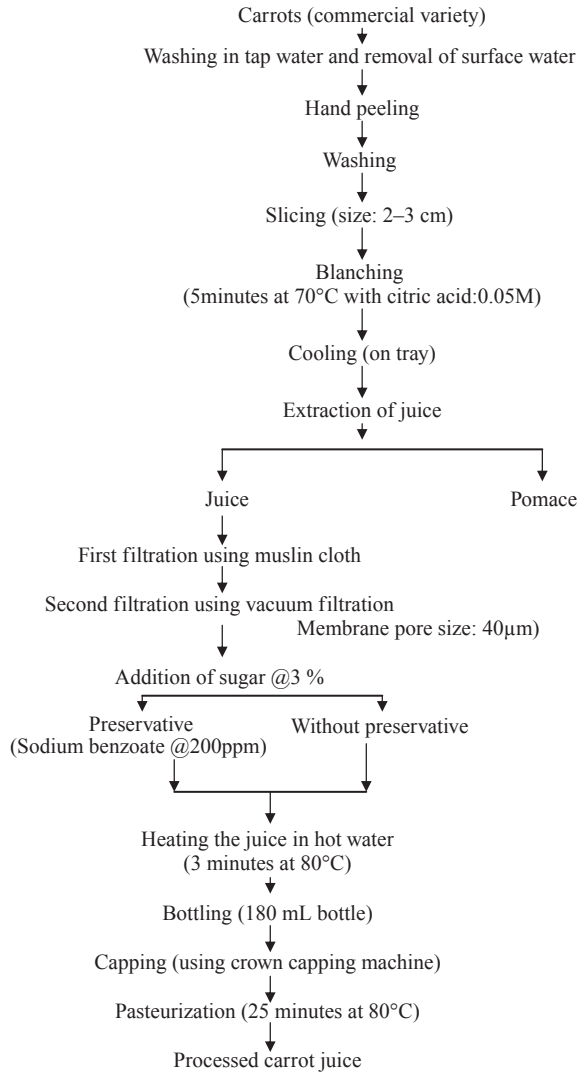


Figure 28.3 Flow diagram of carrot juice processing steps.

heated (90–95°C) prior to juice extraction. Heating whole carrots was more effective than heating milled carrots for improving color retention, but juice from carrots heated whole tended to clarify quickly if citric acid was not added. The addition of citric acid prior to juice extraction (acidificatio from pH 6 to pH 5 or pH 4) significantl improved color and cloud stability. A commercial pectinase/hemicellulase preparation added before extraction also improved juice color. The overall extraction of β-carotene into the juice was low (approximately 20%) (Sims et al. 1993).

Enzymes in Juice Processing

The use of pectinases and hemicellulases in juice extraction from plant tissues enables (i) increased juice yield and soluble solid;

(ii) better quality in terms of color, fl vor, and aroma; and (iii) reduced viscosity, the juice can be further concentrated without any issues such as gel formation.

The pectic enzymes of importance are pectinesterase and polygalacturonase. Pectinesterase deesterifie pectin molecules attached to the plant cell, giving rise to low-ester pectins and pectic acid. By single chain mechanism, the pectic acid creates regions of free polygalacturonic acid, in which the polygalacturonase enzyme depolymerizes pectic acid into polygalacturonic acid (Rombouts and Pilnik 1978). Cellulose is long unbranched chain of β-1, 4-linked glucose residue. The chains in plant cell exist in parallel sheet structure stabilized by inter-chain hydrogen bonding to form cellulose fibe (Gardner and Blackwell 1974). In plant foods, crude fibe refers to combination of cellulose and lignin. The pectins present in the primary cell wall are generally present in glycosylated form (Dea et al. 1977). The cellulase enzyme is important in the breakdown of complex cellulose molecule into glucose units as an ultimate end product. Some of the extracellular pectic enzymes are: pectate lyase, pectin lyase, exopolygalacturonate lyase, polygalacturonase, α-D-galacturonosidase (Collmer et al. 1988), which may be used singly or in combination.

The enzymes and their specifi usage in vegetable juice technology have been reported by various researchers (Table 28.5) (Fantozzi et al. 1977; Baumann 1981; Bhat 2000; Sharma 2006). The enzymatic hydrolysis has been applied for increasing juice yield and better clarification Enzymatic processing of carrot juice by various researchers is summarized in Table 28.6.

Various researchers have studied the effects of enzyme concentration from 0.2% to 0.5%. Increasing the enzyme concentration to 2 × produced the same result half the time, and vice versa. The selection of enzyme and the mode of usage are very important, besides the concentration. Typically enzyme solution in cold tap water or clear carrot juice can be added through a metering pump to the mashed carrots. The enzymes can attain their full effect only if uniformly distributed in the mash. Slow stirring has been used by many processors to induce interaction between the enzyme and substrate. During maceration, excessive agitation is detrimental to mash structure and pressability; it is preferable to stir intermittently at low rates (100–800 rpm). Effect of heating time on the composition and structure of carrot cell wall, which is rich in pectic polysaccharides, revealed that hydrolysis of the pectic polysaccharides by pectinases was facilitated by the presence of cellulases, which were necessary for a complete liquefaction of the tissues (Massiot et al. 1992).

Table 28.5 Applications of various enzymes in juice production

Enzyme	Uses
Cellulase, hemicellulase	Color; juice yield
Cellulase, pectinase	Juice yield; filterabilit
Cellulase, hemicellulase, protease	Liquefaction
Naringinase, limonase (with or without pectinase)	Debittering
Polygalacturonase	Juice viscosity reduction
Pectinesterase, pectinases	Juice yield; fl vor enhancement
Amylases, arabinases	Starch reduction
Pectolytic enzymes (mix)	Depectinization; haze reduction; improve extraction
Glucose oxidase	Elimination of oxygen; prevent browning; fl vor and color preservation

Juice Yield and Quality

The juice yield by press method was suggested to be related to the protopectin and lignin content of the raw material in addition and some physiological characteristics (Flaumenbaum et al. 1986).

Table 28.6 Enzymatic carrot juice processing

Enzymes	Pre-treatment	Process conditions				Results	Reference
		Temp °C	Time (minutes)	Concentration	pH		
Pectinglucosidase	Slicing blanching maceration	–	–	–	–	Higher color density and stability of juice.	Schmitt (1983)
Cellulase & pectintranseliminase	do	–	–	–	–	Juice recovery was more than 80%; extracted cellulose fibr was improved and can be used in high-fibe foods	
1. Cellulase (Maxazyme CL–2000)	Maceration milling	45	50–60	0.5	4	*Results from 4 treatments:*	Traversi et al. (1988)
						# Yield (%) TSS	
2. Pectolytic enzyme	do	do	do	do	do	1. (71.5) 7.5	
3. Combination of 1 & 2	do	do	do	do	do	2. (74.2) 9.8	
4. Controlled (untreated)	do	do	do	do	do	3. (80.0) 9.6	
						4. (68.5) 7.6	
Cellulase	Maceration	–	–	–	–	Volume yield, pH, viscosity, and TSS of juice showed that Rohment PC (4) was most effective	Anastasakis et al. (1987)
Hamicellulase		–	–	–	–		
Pectinesterase		–	–	–	–		
Cellulase & pectinglycosidase		–	–	–	–		
Endopolygalacturonase	Pasteurization (65–95°C, 5 minutes)	22	–	–	2–7	Adequate preservation of nutrients, color, and organoleptic properties of juice in both the cases	Szilagyi-Toth et al. (1985)
Phylendonase			–	–	–		
NK	Pasteurization at 85°C, 30 mg of vitamin C added	22	–	–	–	Vitamin C loss during pasteurization was 2.7%. Vitamin A & C content of juice declined slowly during storage of more than 210.	Nagyne-Gasztonyi et al. (1984)

Pectinase (Commercial)	Maceration, blanching	25–48	–	0.2 g/kg	6.0	Increased yield to 88–92% with corresponding increases in TS, ash, viscosity, and color, and decrease in juice pH	Munsch et al. (1986)
Pectinase/Hemicellulase	Heating, acidficicatio	–	–	–	–	Improved juice color, but not juice yield.	Sims et al. (1993)
Crude pectolytic enzyme (from *T. viride*) and crude cellulolytic enzyme (from *A. fumigatus*)	Blanching, mashing	35–55	50–90	0.2–0.4	–	Increased juice yield as high as 70%, viscosity decreased, amount of soluble solids increased. Color index and pH increased with increasing parameter levels.	Chadha et al. (2003)
Crude pectolytic enzyme (from *A. foetidus*) and crude cellulolytic enzyme (from *T. reesi*)	Grating, blanching	25–65	30–150	50–650 mg/kg	–	Enzyme-treated grated carrot showed increased juice recovery. Under the optimal conditions, juice recovery was 74.3%, having viscosity 1.07 cP, corresponding to the increase in yield by 13.95% and decrease in viscosity by 0.45cP.	Sharma et al. (2005).

do, as above; TSS, total soluble solids.

Carrots pretreated to combinations of pH, temperature, and time were expressed (in a hydraulic press using a wooden set-up) and the juice so obtained was characterized for various physicochemical parameters. The study indicated that carrots exposed to the different pretreatment conditions gave higher yield than the control carrots. The yield was about 78% under optimum conditions (Sharma et al. 2006).

Repeated pressings have been reported to be more effective in dewatering, than a single pressing when the pressing was done between two fla plates (Chancellor 1964). The experiments related to juice squeezing revealed that juice separation was a linear function of the residual volume, compressive force, and the time of compression. A relationship was developed on the basis of dry matter content of input and output materials. The dry matter content of the juice remained constant irrespective of the quantity of juice expressed and was independent of the compression time (Holdron et al. 1972).

Effect of Treatments and Storage on Carrot Juice Quality

Carrot juice samples were prepared and stored at room and refrigerated temperatures to study the effects of treatments on its quality (Bawa and Saini 1987). Two different sets of samples were prepared as: (i) pasteurized at 80°C, cooled, 600 ppm of sodium benzoate added, and bottled; and (ii) pasteurized at 80°C, hot fille in 160 ml glass bottles, corked, heat processed in boiling water for 15 minutes, and cooled. Subsequently, the juice samples were stored at room (22–35°C) and refrigerated (2–5°C) temperatures for 6 months and analyzed for physicochemical characteristics at monthly intervals. The soluble solids, acidity, and pH remained constant during storage at both temperatures. However, in both sample sets stored at room temperature, there was an increase in the reducing sugars. In sample set (ii), acidity decreased with increase in pH at room temperature. Pretreatments and storage temperatures had little effect on the consumer acceptability of the juice (Bawa and Saini 1987).

Storage of carrot juice under air was compared with storage under N_2, He, or CO_2. The deaeration of carrot juice by He or N_2 bubbling, followed by flus packaging, did not affect shelf life of the carrot juice, in comparison to storage under air. A prolonged shelf life was obtained by carbonating the juice and by decreasing the pH to less than 4 (Alklint et al. 2004).

Stability of carotene was studied in pure carrot juice to which citric acid-sodium citrate was added to adjust the pH (3.5–6.1) and to which Fe^{2+} (0–30 ppm), Fe^{3+} (0–30 ppm), and ascorbic acid (0–0.1%) were added. The juice was exposed to sunlight or stored under shade and treated in a vacuum of 0–0.08 MPa for 5–15 minutes. The carotene concentrations were significantl lower in vacuum-treated juice. The effects of sunlight and pH were insignificant However, ascorbic acid showed a protective effect against carotene degradation (Chen et al. 1995).

Nonthermal Processing of Carrot Juice

A combined treatment of high-pressure carbon dioxide (HPCD) and high hydrostatic pressure (HHP) was investigated as a nonthermal processing technique to enhance the safety and shelf life of carrot juice. Aerobes were completely inactivated by a combined treatment of 4.90 MPa-HPCD and 300 MPa-HHP. A combined treatment of 4.90 MPa-HPCD and 600 MPa-HHP effectively inactivated enzymes; the residual activities of polyphenol oxidase (catechol oxidase), lipoxygenase, and pectin methylesterase were less than 11.3%, 8.8%, and 35.1%, respectively. The cloud and color of the juice were affected by HPCD, but not by HHP. The activities of enzyme and the total color difference had positive correlation with pH, which was

Table 28.7 Selected quality data on fresh and dried carrot pomace

Products	Moisture (%, wet basis)	Crude fibe (%, dry basis)	Ash (%, dry basis)	Ascorbic acid, (mg/100 g, dry basis)
Pomace, fresh	85.62	15.89	2.80	23.44
Dried (at 60°C, 7.5 hours)	9.31	18.35	6.20	22.95
Dried (at 65°C for 6.0 hours)	8.85	18.37	6.21	20.62
Dried (at 70°C, 5.5 hours)	8.19	18.38	6.22	17.12
Dried (at 75°C, 5.0 hours)	7.68	18.38	6.22	13.53
Dried (at 80°C, 5.0 hours)	7.51	–	–	–
Sun-dried (48 hours)	11.37	–	–	11.90

Source: Upadhyay et al. 2008.
–, not given.

dependent on the pressure of CO_2 (Park et al. 2002).

Carrot Pomace

Carrot pomace is a by-product of the carrot juice industry. Approximately one-third of the raw material used to produce carrot juice remains as pomace which is normally used as feed or fertilizer. However, pomace can be a valuable source of fibe and carotenes. It can be dried for use in other food applications. Upadhyay et al. (2008) reported the effects of temperature and drying time on the quality of dried pomace (Table 28.7). As expected, the ascorbic acid content of the dried pomace decreased with the increase in drying temperature. Fiber and ash content remained almost unaffected with varied drying temperature. The percent moisture of the sun-dried pomace (11.37%) was higher than the heated air-dried pomace. The drying profil of pomace at different temperatures is shown in Figure 28.4.

The β-carotene content of the fresh pomace was about 14.4 mg/100 g (dry weight basis or db) versus 55.3 mg/100 g (db) in fresh carrots. Upon drying of pomace to different temperatures (65–80°C), its β-carotene ranged from 10.8 mg/100 g to 9.4 mg/100 g (db) (Upadhyay et al. 2008). Previous studies (Machewad et al. 2003;

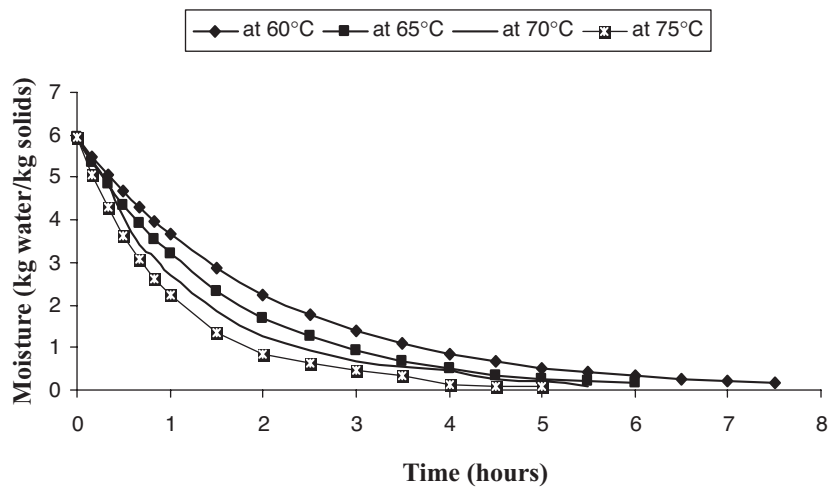
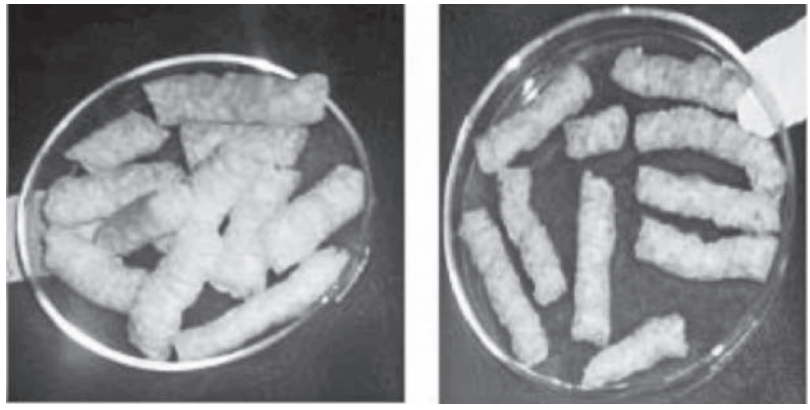


Figure 28.4 Drying rates curves at different drying conditions (Upadhyay et al. 2008).



(a) (b)

Figure 28.5 Drying rates curves at different drying conditions (Upadhyay et al. 2008).

Sagar et al. 2004) also reported that drying temperatures >75°C had adverse effect on β-carotene in carrots. Sun drying was not desired as a choice for pomace drying as it produced a low-quality dried product and took a long time to dry. Among the different drying temperatures (Table 28.7), drying pomace at 65°C gave optimum retention of ascorbic acid and β-carotene.

Carotene-Rich Functional Ingredient Based on Carrot Pomace

Stoll et al. (2003) described an optimized process for carotene-rich functional ingredient from carrot pomace consisting of grinding a suspension of carrot pomace in a colloid mill, enzymic hydrolysis, finishin (mesh, 0.5 mm) homogenization, and concentration of the carrot pomace hydrolysate. For the enzymic hydrolysis, Pectinex Ultra SP-L (PU; pectinase with hemicellulolytic activities) was combined with either Cellubrix L or Cytolase CL (CE and CY, respectively; cellulolytic activity) and tested at various incubation temperatures. The viscosity was reduced effectively (at 45–50°C) when the enzymes PU and CY were combined. The optimum enzyme concentration and the pH were 1,500 ppm and 4, respectively. Addition of 1,000 ppm Ca^{2+} markedly accelerated viscosity reduction within 1 hour under these conditions. The total carotene content of the hydrolysate obtained by this optimized method was 64 mg/kg (Stoll et al. 2003). The use of carrot pomace in different food preparations as a carotene supplement was also supported by Stoll et al. (2001).

Extruded Products Made from Carrot Pomace

Rice and gram flou mixed with carrot pomace powder were used to make extruded products (Upadhyay 2006; Upadhyay et al. 2010). The use of about 5% carrot pomace powder produced acceptable quality extruded product as shown in Figure 28.5.

Conclusion

This chapter briefl discussed the production, quality, and processing, especially juice making, aspects of carrots. Carrots are an excellent and relatively inexpensive source of provitamin A, carotene, and other important minerals and vitamins, fibe , and plant-based sugars. However, much work remains to highlight and realize the benefit of eating carrots, especially in countries where people lack nutritive foods.

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Chapter 29

Chili, Peppers, and Paprika

Lillian G. Po

Introduction

Capsicum peppers, available in various colors, shapes, sizes, and pungency, are a well-known spice and condiment worldwide. The increasing popularity of ethnic foods and emerging fusion cuisines in the United States and Europe has created an increased demand for peppers. This demand, coupled with globalization and trade, has translated into greater availability of a wider variety of peppers in mainstream food stores. There is also an interest in *Capsicum* peppers because of their high antioxidant constituents, like Vitamins C and A, phenolic acids, and fl vonoids.

Three types of *Capsicum* peppers cultivated worldwide are discussed in this chapter: (a) the mild to highly pungent *chili* peppers; (b) bell and sweet peppers utilized as vegetables; and (c) paprika, primarily traded as a spice. The objective is to provide an overview of *Capsicum* pepper's production, utilization, quality characteristics, processing, and food safety issues.

History and Nomenclature

The terms "chili, peppers, and paprika" refer to the fruit of a dicotyledonous group of fl wering plants belonging to the genus *Capsicum* and the family *Solanaceae*. Peppers have long been cultivated by the natives of the New World (Americas) from northern Mexico through South America, where it originated. Columbus and the Spanish explorers found pungent berries used for seasoning food in the New World which reminded them of black pepper, hence the name "pepper." Although the term "peppers" is still used for both *Capsicum* and the genus *Piper* (black and white peppers of the *Piperaceae* family), the two are not related (Andrews 1984; Somogyi and Luh 1988; Buckenhuskes 2003). For purposes of this chapter, the terms "chili, peppers, and paprika" refer only to *Capsicum* peppers.

Andrews (1984) provided a detailed account of the origin of *Capsicum* peppers. Spanish explorers in Jamaica found dried berries which resembled oversized black peppercorns and labeled them *pimiento* after the black pepper *pimienta* (*pimenta*). In Mexico, explorers heard the Nahuatl (language of the Aztecs) term *chili* (*chil* refers to the chili plant meaning "red"). *Chile* refers to the Mexican long green/red chile. Other names used interchangeably include chili, paprika, or red pepper. Dried peppers often have different names (e.g., *chipotles* are smoke-dried *jalapeños*).

World Production and Consumption

World Production

World production of fresh chilies and green bell peppers in 2007 was 27 million tons (MT) (FAOSTAT 2009). Figure 29.1a shows top world producers in 2007. China (14 MT) accounted for a little over 50% of the world

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

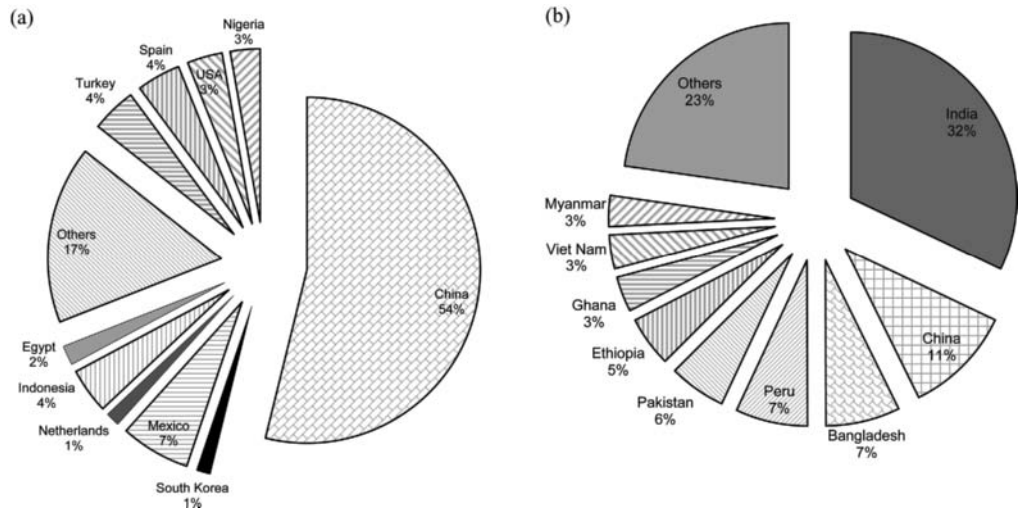


Figure 29.1 Top ten world producers of bell and chili peppers for 2007: (a) fresh; (b) dry (Source: FAOSTAT 2009).

production, followed by Mexico (1.89 MT), Turkey (1.76 MT), Indonesia (1.13 MT), Spain (1.06 MT), United States (0.86 MMT), and Nigeria (0.72 MT).

However, Asian and African countries produced most of the dry chili and green bell peppers in 2007. India led with 1.2 MT, followed by China (0.25 MT), Peru (0.17 MT), Bangladesh (0.15 MT), Pakistan (0.13 MT), Ethiopia (0.12 MT), and Ghana (0.08 MT) (Figure 29.1b).

A substantial quantity of chili exports is in the form of chili oleoresins, with India as the major producer. Spain, Hungary, and Morocco are the other major producers of paprika oleoresin.

World Consumption and Utilization

Chilies account for one-third of the total world consumption of *Capsicums*, while paprika comprises two-thirds (Thampi 2003). The 2003 pimento-consuming (includes peppers and allspice) countries were headed by India, followed by Bangladesh, Ethiopia, China, Pakistan, and the United States (FAOSTAT 2003). The difficult of accurately assessing consumption data of spices should be pointed out, where figure tend to be lumped with the consumption of other spices and data from developing countries are not easily available.

Capsicum peppers can be classifie according to (a) its use: vegetable (bell peppers) or spice (paprika); (b) the degree of pungency: nonpungent (sweet peppers) or hot (Cayenne); (c) shape (elongated, squat, heart-shaped); or (d) color of the fruit (green, red, etc). Utilization of *Capsicum* peppers is dictated by three types of market—retail, institutional, or industrial uses. Table 29.1 summarizes various ways of utilizing peppers worldwide. Mildly bitter pepper plant leaves are utilized as greens in Japanese and Filipino cuisines, in Korean *kimchi*, and in Japanese *tsukudani* style for preservation.

US Imports and Consumption of Capsicum Peppers

In 2007, the US imports of fresh chilies, dried jalapeño and Anaheim chile peppers, and canned pimiento were primarily from Mexico, while Peru was the major supplier of dried sweet (non-bell) peppers. The import of dried

Table 29.1 Popular *Capsicum* peppers (species, common names), pungency, fruit description, and utilization worldwide

Region	Species	Common name	SHU	Fruit description and utilization
Mexico	*Capsicum annuum*	*Ancho*		Dried *poblano*; deep red-brown, wrinkled, fruity, sweet, slightly hot; toasted and ground for sauces; stuffed; available as blocks of paste.
	C. annuum	*Cascabel*		Round, brown-red, smooth, translucent skin; lightly acidic, smoky, moderately hot fl vor; nutty after toasting and blended with tomatillos to make salsa; crumbled in stews.
	C. annuum	*Chilaca*		Thin, deep red, shiny, vertical ridges. Licorice fl vor. Roasted, peeled for vegetable dishes and sauces. Pickled.
	C. annuum	*Chipotle*		Smoke-dried jalapeno. Tan to coffee-colored, wrinkled, leathery; smoky, sweet, chocolate smell and taste, used to fl vor soups and stews; Soaked, peeled for sauces; Pickled.
	C. annuum	*De arbol*		Seldom found fresh. Bright red when dried. Slender, curved, pointed with thin fles and smooth skin. Searingly hot and tannic fl vor. Soaked and pureed in stews; used as table sauce.
	C. annuum	*Guajil-lo*		Long, slender, with blunt point; maroon with brown tones; smooth, tough skin; high acidity, tangy, pleasant sharp taste. Soaked, blended for enchilada sauces; crumbled in stews.
	C. annuum	*Guero*		Pale yellow, smooth, long, and pointed, with thin flesh light flora mild to medium-hot taste; fresh salsas, *moles*.
	C. annuum	*Jalapeno*	5,500	Bright green with dark patches; torpedo-shaped; crisp, thick flesh roasted and peeled; medium-hot; sweeter when fully red ripe; canned *en escabeche* (pickled); condiment.
	C. annuum	*Mulato*		Chocolate brown; full-bodied taste with notes of dried cherries; mild to medium-hot; toasted and ground for sauces.
	C. annuum	*Pasilla*		Dried chilaca. Slender, wrinkled, and almost black; astringent, rich fl vor that is complex and long-lasting. Toasted and ground; table sauces; cooked sauces for fish
	C. annuum	*Poblano*		Dark-green, shiny, with a ridge around the base of the stem; triangular, tapering; thick flesh roasted, peeled, stuffed, fried; rich fl vor. Pairs with corn and tomatoes.
	C. annuum	*Serrano*	25,000	Mid-green, ripens to bright red; cylindrical; crisp; concentrated grassy fl vor; pungent seeds and veins; sauces.
	Capsicum chinense	*Habanero*	150,000 to 210,000	Lantern-shaped, mid-green ripening to yellow, orange, and deep red; thin-fleshe and fruity. Mostly used in Yucatan; roasted to fl vor beans, hot sauces (with salt, lime juice).
South-west United States and Caribbean	*C. chinense*	*Jamaican hot*		Bright red; squat with thin flesh tastes sweet and very hot; used in salsas, pickles, curries.
	C. chinense	*Scotch bonnet*		Yellow-green to orange-red; similar to *habanero* but wrinkled top and flattene base; very hot with deep, fruity, smoky fl vor; in Caribbean hot sauces, jerk seasoning.

(*Continued*)

Table 29.1 *(Continued)*

Region	Species	Common name	SHU	Fruit description and utilization
	Capsicum frutescens	*Tabasco*	120,000	Thin-fleshed yellow, turning orange or red when ripe; sharp, biting taste with hint of celery; in Tabasco sauce.
Latin America	*Capsicum baccatum*	*Aji Amarillo*	17,000 (escabeche)	Common in Peru, both fresh and dried (*cusqueno*). Pointed and hot with raisiny aroma; used with potatoes, root vegetables, guinea pig, *ceviche*.
	C. annuum	*Aji Dulce*		Sweet, mild, musky, herbal-like; used with beans in Central America, Colombia, Venezuela.
	C. frutescens	*Malagueta*		Pale or mid-green, thin-fleshed tapered, tiny; Native to Bahia, Brazil; used in Afro-Brazilian cooking as condiment; Venezuelan name for small hot chilies pickled in vinegar.
	C. annuum	*Mirasol*		Popular in Peru and Mexico where dried form is called *guajillo*; used green, yellow or ripe, red-brown stage; fruity; colors dishes; good with meats, beans, vegetables.
	C. chinense	*Rocotillo*		Mild Andean chili pepper, bright red and squashed-looking; condiment with corn, beans, root vegetables, roast meats.
	Capsicum pubescens	*Rocoto*		Native to the Andes; plump, rounded; yellow to orange-red; fresh in sauces, condiments, vegetable, stuffed (meat, cheese).
Europe	*C. annuum*	*Banana*		Yellow-green, ripening to red; curved, waxy skin; mild chili related to hotter Hungarian. Used fresh in salads, stews; roasted whole with legumes or potatoes; pickled; as garnish.
	C. annuum	*Cherry*		Orange to deep red when fresh, mahogany when dried; thick flesh lots of seeds; fruity, mild to medium-hot; pickled.
	C. annuum	*Guindilla*		Brick-red; smooth; long, tapering Spanish chili used dried; large pieces soaked and added to a dish for extra piquancy.
	C. annuum	*Nora*		Mild and earthy; used to fl vor rice dishes, stews; essential to romesco sauce and for sweet paprika; larger, bell-shaped *choricero* used to fl vor chorizo, meat products.
	C. annuum	*Piment d'Espelette*		Bright red; wide-shouldered, tapering; sweet, fruity, mildly piquant; dried whole or as a powder; puree or *coulis*; from Basque country.
	C. annuum	*Peperoncino*		Slender, wrinkled, and often curved, with thin flesh sweetish fl vor; used fresh, green, or red in pickles and tomato-based dishes.
	C. annuum	*Peri peri*		Orange to deep red when fresh, mahogany when dried; thick flesh lots of seeds; fruity fl vor, mild to medium-hot; often pickled.
Asia	*C. frutescens*	*Bird*		Tiny green, orange, and red chilies; fiercel hot; used whole to give a "finishing fl vor to a dish.
	C. annuum	*Kashmir*		Deep red. Sweet notes yet distinct bite. Called *lal mirch*.
	C. annuum	*Korean*		Bright green, curved; related to Thai; used in fish meat, stir-fries, vegetable stew; fried.
	C. annuum	*Thai*	60,000	Used fresh and dried; slender; dark green or bright red; meaty fles and lingering heat; used in curries, stir-fries, pastes, and dips.

Source: Norman 2002; Andrews 1984.

bell peppers was mainly from China, and the major suppliers of canned bell peppers were Spain, Turkey, Chile, Peru, and Greece. The increased US imports of *Capsicums* could serve as an indication of increased pepper consumption, reflectin the continuing popular trend for ethnic foods which heavily utilize peppers.

However, the US availability of chile peppers for canning slightly decreased from 6.4 pounds (∼2.90 kg) in 2006 to 6.1 pounds (∼2.77 kg) per capita per year in 2007, implying less market for canned products compared to fresh and other processed forms. For bell peppers, per capita availability slightly decreased from 7.0 pounds (∼3.18 kg) in 2006 to 6.8 pounds (∼3.08 kg) in 2007 (ERS-USDA 2009).

Cultural Practices

Pepper is a warm season crop. However, temperature extremes can adversely affect germination, growth, and fruit set. Optimum germination is achieved at 29–32°C, and takes about a week. However, as temperature decreases to 15°C, germination can take as long as 25 days, and if the temperature is lower than 15°C or higher than 35°C, germination may not occur. Pepper seeds are light weight, and for a projected plant population of 30,000 per hectare, about 150 grams planting material (assuming a 10% germination failure and 10% casualty rate of seedlings at transplanting time) is required (Berke et al. 2005). After germination, seedlings grow best with a day and night temperature combination of 24°C and 18°C, respectively. Seedlings are ready for transplanting when leaves develop in about 4–5 weeks. Soil nutrient and irrigation of peppers can range from pure guesswork to adherence to area-specifi recommended best management practices (Simonne 2006). Peppers start fl wering in about 60 days after planting. Successful pollination through bees, ants, or even a strong wind will lead to fruit set, ready for harvest in about a month.

Varieties

Table 29.1 summarizes the major domesticated *Capsicum* species and their common names. There are wide variations in sizes and shapes among and within *Capsicum* species (Figure 29.2). A database of *Capsicum* peppers and varieties worldwide can be accessed on the internet, containing colorful photos of the fruits: http://www.g6csy.net/chile/database.html.

Andrews (1984) captured minute details of domesticated *Capsicums* from specimens with her colored illustrations of the plants and fruits.

Diseases

Throughout the pepper's life cycle, it is subject to pest and disease attack; so, growers have to take into consideration susceptibility, resistance, or tolerance to locally known pests and diseases when choosing varieties. It is a common practice to coat pepper seeds with pesticides to maximize survival rate during germination, and to granulate pesticides on holes in the fiel where transplants are placed. Scouting and monitoring the specifi type of disease or pest affecting the proper functioning of the pepper crop remains the most ideal way of preventing current infestation from rising beyond a predetermined action threshold. Diseases vary in different locations, but the problematic ones include the following (Andrews 1984; Goldberg 1995):

- *Bacterial leaf spot and leaf spot* (fungal, *Cercospora capsici*): more damaging to sweet peppers and are seed-borne; leaves drop off, leaving the fruit unprotected and sun-scalded.
- *Damping off* (fungus, *Rhizoctonia, Pythium*): soil-borne, common to moist soil; rotting the seed or killing seedlings.
- *Phytophora blight* (fungus, *Phytophthora capsici*): soil-borne disease, destructive during wet weather. Irrigation water can carry spores to several plants in a single

Figure 29.2 Varied shapes and sizes of *Capsicum* peppers.

row, infecting both stem and fruit, causing a sudden wilt.

Southern blight (fungus, *Sclerotium rolfsii*): fungus attacks plant near the soil line, causing it to wilt and die.

Ripe rot (fungus, *Alternaria calotopsicum*): fungus causes thick-fleshe *Capsicums* to rot in the fiel and in packing cases during a seasonal glut.

Mosaic (viruses): aphid-borne viruses affect *Capsicums* either singly or in combination. Common symptoms are mottling, curling, stunting, and distortion of leaves.

Goldberg (1995) described the parasitic and nonparasitic diseases that affect chile peppers and the general control practices for growing disease-free chile.

Harvest

As peppers continually go through the process of fl wering and fruit set, harvest can be done in 1–2 week intervals. Whether the

fruits are harvested at green or ripe stage will be dictated by the market. The proper time to harvest would vary depending on the variety, but in general, the fully mature ones should be either all green or yellow, and completely ripe ones should be totally colored, usually "red." The optimum maturity stage for harvest based on highest vitamin C and carotenoid content is the red ripe stage (Marin et al. 2004). Most peppers are harvested by hand. In countries like Mexico, India, and Hungary, where the practice is to hang pods for sun drying, the pods are picked with the stems attached. Harvesting peppers in the fully developed but green condition enables a higher yield as it stimulates production of more fl wers. A study on pectolytic enzymes (Jen and Robinson 1984) in sweet bell peppers showed that polygalacturonase activity increased during ripening, accompanied by softening of texture, while pectin esterase activity declined.

Postharvest Practices and Storage

Curing

Curing is the process of converting fresh red ripe fruits with thin pericarp into dried pods. Ripe peppers are plucked with their stalks and cured by piling them indoors for 3–4 days to enable full ripening and uniform color development. The curing practices differ according to different climatic conditions of production areas and the inherent characteristics of the cultivar. Pods left to ripen and partially wither on the plant took even shorter time for curing, and were found to be superior in pungency, initial color, and color-retention properties compared to those picked when fully colored. The curing step can be skipped for green chilies that are to be dried.

Pretreatments

Pricking: Pricking the skin longitudinally helps reduce total drying time and retains color and overall quality.

Pretreatments with 2% sodium carbonate: Chilies and paprika are steeped in a 2% sodium carbonate solution for about 10–12 minutes to retain red color. Treatment with an antioxidant also stabilizes the red color (Pruthi 2003a).

Pretreatment with MeSA and MeJA: Methyl salicylate (MeSA) and methyl jasmonate (MeJA) vapors were reported to increase resistance against chilling injury in freshly harvested green bell peppers (*Capsicum annuum* L. *cv Century*) (Fung et al. 2004).

Storage

The storage life of green peppers can be extended up to four weeks under low temperature and high relative humidity (RH) conditions.

For dried red peppers, loss of color is the major concern. Color retention has been found to correlate with the levels of ascorbic acid and tocopherol. However, these constituents vary with cultivars. Drying and storage temperatures also affect color; high storage temperatures increased degradation of pigments, although increased RH minimized degradation (Yogeesha and Gowda 2003). The vitamin C content for green mature peppers stored at room temperature (20°C) increased up to 10 days of storage, similar to that obtained for red peppers which have been harvested directly from the plant. However, red ripe peppers showed 25% and 15% loss of Vitamin C during storage at room temperature and at 4°C for 20 days, respectively (Martinez et al. 2005).

Physicochemical and Nutritional Qualities

Table 29.2 summarizes the chemical and nutritional composition of raw and processed sweet peppers, and paprika. Water constitutes more than 90% of the *Capsicum* fruit, with fibe (2.2%), glucose (0.85%),

Table 29.2 Chemical and nutritional composition of raw and processed sweet red peppers (SRP), raw sweet green (SGP) and yellow (SYP) peppers, and paprika

Composition (100 grams)	Raw SRP	Canned SRP	Frozen, chopped SRP	Freeze-dried SRP	Paprika spice	Raw SGP	Canned SGP	Frozen SGP	Freeze-dried SGP	Raw SYP
Chemical										
Energy (kcal)	31	18	20	314	289	20	18	20	314	27
Carbohydrates	6.0	3.9	4.5	68.7	55.7	4.6	3.9	4.5	68.7	6.32
- Sugars (g)	4.2	—	3.3	40.8	10.3	2.4	—	—	38.5	0.9
- Dietary fibe (g)	2.1	1.2	1.6	21.3	37.4	1.7	1.2	1.6	21.3	
Fat (g)	0.3	0.3	0.2	3.0	12.9	0.2	0.3	0.21	3.0	0.21
Protein (g)	0.9	0.8	1.1	17.9	14.76	0.9	0.8	1.1	17.9	1.00
Ash (g)	0.47	3.8	0.3	8.4	7.02	0.4	3.8	0.3	8.4	
Water (g)	92.2	91.3	93.9	2.0	9.54	93.9	91.3	93.9	2.0	92.02
Vitamins										
Vitamin C (mg)	127.7	46.5	58.7	1,900	71.1	80.4	46.5	58.7	1,900	183.5
Vitamin A(IU)	3,131	520	2,428	77,261	52,735	370	155	367	5,640	200
Vit. Equiv. (ug)	157	—	121	3,863	2,637	18	8	18	282	10
β-carotene (ug)	1,624	26	380	42,891	27,679	208	—	—	3,177	120
Vitamin B6 (mg)	0.3	0.18	0.14	2.2	4.0	0.2	0.2	0.1	2.2	0.17
Vitamin E	1.58	—	—	—	29.8	0.4	—	—	4.0	—
Mineral (mg)										
Potassium	211	146	91	3,170	2,344	175	146	91	3,170	212
Iron	0.4	0.8	0.6	10.4	23.6	0.3	0.8	0.6	10.4	0.46
Magnesium	12	11	8	188	185	10	11	8	188	12
Calcium	7	41	9	134	177	10	41	9	134	11
Phosphorus	26	20	17	327	345	20	20	17	327	24
Sodium	4	1,369	91	193	34	3	1,369	5	193	2

Source: USDA Nutrient database (http://www.nal.usda.gov/fnic/foodcomp/search/), accessed on December 15, 2008.

starch (0.81%), fructose (0.75%), and pectin (0.73%) making up the other major components (Pruthi 2003a; USDA 2008).

Capsicum peppers have high vitamin C and A contents, comparable to that of citrus fruits and carrots, respectively. They also contain most B vitamins, particularly Vitamin B6. Martinez et al. (2007) reported generally higher fat, ash, and protein in green peppers than in red peppers (*Capsicum annuum L. var annuum cv Arnoia*). Total soluble solid content and titrable acidity significantl increased during ripening in "*Arnoia*" peppers. They found potassium to be the most abundant mineral in red and freshly picked green peppers, and also reported high magnesium and iron levels (Table 29.2).

Ripe fruits of *Capsicum annuum L.* contain mono- and diacylgalactolipids as major lipids; in the endoplasmic reticulum, it is phosphatidylcholine. Linoleic and linolenic are the major polyunsaturated fatty acids in the pericarp, but the seed has very high linoleic content. The aroma and fl vor of fresh *Capsicum* are imparted by its low volatile oil, ranging from 0.1% to 2.6% in paprika (Pérez-Gálvez et al. 1999; Pruthi 2003b).

Antioxidant Constituents of Capsicum Peppers

Levels of dietary antioxidants may be affected by maturity, genotype, and processing (Howard et al. 1994; Maiani et al. 2008).

Vitamin C

Vitamin C has been hypothesized to help with cancer by inhibiting the formation of N-nitroso compounds in the stomach and by stimulation of the immune system (Howard et al. 1994). Red peppers have a very high

vitamin C content, contributing 124–338% of the Recommended Dietary Allowance (RDA) for vitamin C (Andrews 1984; Vanderslice et al. 1990; Howard et al. 2000; Pruthi 2003b; Marin et al. 2004; Materska and Perucka 2005; Martinez et al. 2005). However, since *Capsicums* are utilized in such small quantities as spices in cooking, they have not been regarded as a major source of Vitamin C in the diet. However, with the popularity of Mexican, Asian, Mediterranean, and Middle Eastern cuisines which generously incorporate peppers, it is foreseeable that peppers will also become a popular vegetable source of vitamin C and antioxidants in the diet.

As peppers mature, pH values (6.23 in immature fruits; 5.08 in red ripe peppers) become more favorable for ascorbic acid stability; hence, red ripe chilies contain higher amounts (about 45% higher reported for red pepper cv. *Vergasa*, and 27% higher for cv. *Arnoia*) of ascorbic acid than immature green peppers (Howard et al. 1994; Martinez et al. 2007). Vitamin C values of 107.3 ± 1.84 (green mature) and 154.3 ± 7.56 (red peppers) mg/100 g edible portion have been reported. Interestingly, Vitamin C content of green peppers purchased from the supermarket was up to 30% lower than that in freshly picked green peppers (Martinez et al. 2007).

Pasteurization of processed jalapeño cultivars resulted in a 75% decrease in total ascorbic acid content (Howard et al. 1994). Martinez et al. (2005) reported that ascorbic acid content in pepper "*Fresno de la Vega*" (*Capsicum annuum L.*) changed in response to the preservation procedures assayed, with reductions of 12% and 20–25% during the water blanching and canning process, respectively. Dehydration resulted in an 88% decrease in ascorbic acid content. However, retention during freezing was 60%, which increased to 80% when the product was previously blanched. Freeze-drying did not cause significan losses (Daoud and Luh 1967).

Carotenoid Pigments

Carotenoids play an important role in human health by acting as biological antioxidants, protecting cells and tissues from the damaging effects of free radicals and singlet oxygen (Maiani et al. 2008). The chloroplast pigments (chlorophylls, lutein, and neoxanthin) disappear during pepper ripening, and new carotenoid chromoplast pigments biosynthesized are carotenoid esterified The fatty acids esterifie to the xanthophylls are mainly lauric, myristic, palmitic, oleic, and linoleic, forming mono- or diesters. Lutein and α-carotene are the predominant carotenoids in immature green and green peppers, respectively. Xanthophylls (capsorubin, *cis*-capsanthin, and *cis*-zeaxanthin) appear during the red stage. Esterificatio of xanthophylls with fatty acids is viewed as a process directly linked to the transformation of chloroplast into chromoplast (Hornero-Mendez and Minguez-Mosquera 2000). The total carotenoid pigments (capsanthin, the major pigment; capsorubin; and capsanthin 5,6-epoxide) increased four times during the red stage, with a high provitamin A due to the high concentrations of α-carotene and α-crytoxanthin (Marin et al. 2004). Maiani et al. (2008) reported the major carotenoid content (expressed as μg/100 g fresh weight) of four colors of peppers: (a) lutein: green peppers (92–911 μg), orange (245 μg), red (248–8,506 μg), and yellow peppers (419–638 μg); (b) zeaxanthin: red peppers (593–1,350 μg), orange and yellow peppers not detected, and green peppers (42 μg); (c) β-cryptoxanthin: green peppers (up to 110 μg), orange (3 μg), red (248–447 μg), and yellow peppers (15–41 μg); (d) α-carotene: green peppers (139 μg), orange (72 μg), red (287 μg), and yellow (10–28 μg); and (e) β-carotene: green peppers (2–335 μg), orange (400 μg), red (1,441–2,390 μg), and yellow peppers (42–62 μg). These data confirme earlier finding of Howard et al. (2000) that red ripe chilies

contain high amounts of carotene ("provitamin A", α-carotene, and α-cryptoxanthin), contributing 0.33–336 Retinol Equivalents (RE/100g) of provitamin A activity, while a considerably lower amount is present in yellow and green unripe fruits. Howard et al. (1994) had previously reported provitamin A activity ranging from 27.3 RE/100 g to 501.9 RE/100 g in fresh pepper cultivar (*Capsicum annuum*). Kim et al. (2004) identifie the main carotenoids (mg/100g dry weight) in Korean red pepper (*Capsicum annuum* L.) as capsanthin (101.4–104.8), zeaxanthin (26.2–27.1), β-cryptoxanthin (39.4–40.9), β-carotene (103.1–109.7), and possibly capsorubin in the saponifie extracts. Myristoylpalmitoyl capsanthin was more stable than myristoylcapsanthin during storage, both identifie from the unsaponifie extract with lauroylmyristoyl capsanthin.

Carotenoid pigments are more liposoluble and more stable to photo- and thermoxidative reactions and other processes involving lipoxygenase; hence, there is longer conservation of colors (Pérez-Gálvez et al. 1999; Hornero-Mendez and Minguez-Mosquera 2000). Maiani et al. (2008) reported increase in zeaxanthin in whole and cut red peppers during hot air drying. Freeze-drying preserves the color of red bell peppers (Daoud and Luh 1967). Kim et al. (2004) did not observe significan ($p > 0.05$) difference in carotenoid content when subjecting red peppers to two drying methods, but peppers dried at a higher temperature (80°C, 5 hours) turned darker compared to those dried at 70°C for 6 hours, possibly due to caramelization reactions, not destruction of carotenoids, since red peppers contain appreciable reducing sugars and amino acid.

The major red color pigments in paprika are capsanthin, capsorubin (both comprising 60% of total carotenoids), and cryptocapsin. β-carotene, β-cryptoxanthin, lutein zeaxanthin, violaxanthin, and neoxanthin are the yellow to orange pigments. (Howard et al. 2000; Buckenhuskes 2003; Marin et al. 2004; Maiani et al. 2008). Zeaxanthin decreased in whole pods during hot air drying at temperatures greater than 100°C or during slow drying (Maiani et al. 2008). Paprika powder pigment ranges from 0.1% to 0.8%. Stability against oxidative degradation during storage is improved by a high capsanthin/capsorubin ratio because of the fewer polar groups of capsanthin and available moisture. The extractable paprika color values available in the industry are 85, 100, 120, and 150, expressed as ASTA (American Spice Trade Association). The red pepper pigments of cayenne pepper include xantophyll, carotene, and β-carotene (Govindarajan 1986a; Pruthi 2003b; Buckenhuskes 2003).

Phenolics and Antioxidant Properties

Phenolics are secondary metabolites in plants composed of phenolic acids (phenols with carboxyl group) and polyphenols (includes fl vonoids). A number of studies have demonstrated phenolics and fl vonoids to possess antioxidant, antimutagenic, anticarcinogenic, anti-inflammation and anti-allergy properties, as well as having the ability to modify gene expression (Lee et al. 1995; Marinova et al. 2005; Maiani et al. 2008).

Total Phenolic Content

Red bell peppers have significantl higher total phenolic content than green peppers, and contain a higher level of β-carotene, capsanthin, quercetin, and luteolin than the other colors. Green peppers had undetectable capsanthin and lowest luteolin content; yellow peppers contained the lowest β-carotene (Sun et al. 2007). Table 29.3 summarizes the total phenolic content and total antioxidant capacity of sweet peppers. The yellow peppers exhibited the highest total antioxidant capacity, followed closely by the orange and red peppers, with the green peppers having the lowest value. The same order was observed for the total phenolic content, with green peppers

Table 29.3 Phenolic content and antioxidant capacity of capsicum peppers*

Peppers (Raw)	Moisture	L-ORAC† (umole of TE/g)	H-ORAC† (umol of TE/g)	TAC‡ (umol of TE/g)	TP§ (mg of GAE/g)	Serving size¶ (g)	TAC/serving (umol of TE)**
Green, sweet	94.7	0.14	5.44	5.58	2.71	119	664
Red, sweet	92.2	0.24	8.77	9.01	4.24	119	1072
Orange, sweet	90.2	0.76	9.08	9.84	5.43	186	1830
Yellow	90.1	0.69	9.56	10.24	5.66	186	1905

Source: Wu et al. 2004
ORACFL, lipophilic-oxygen radical absorbance capacity flourescen probe; ORACFH, hydrophilic-oxygen radical absorbance capacity fluorescent TAC=L-ORACFL + H-ORACFL, total antioxidant capacity.
*Data expressed on the "as is" weight basis and presented as mean ± SD for sample numbers >2.
†ORACFL data expressed as micromoles of Trolox equivalents per gram (*í*mol of TE/g).
‡TAC = L-ORACFL + H-ORACFL.
§Total phenolics data expressed as milligrams of gallic acid equivalents per gram (mg of GAE/g).
¶Serving size from USDA National Nutrient Database for Standard Reference (www.nal.usda.gov/fnic/foodcomp, accessed on December 15, 2008).
**Sample number for each food.

having the lowest amount and yellow peppers possessing the highest phenolic content (Wu et al. 2004). Lee et al. (1995) had earlier identifie fl vonoid aglycones, quercetin, and luteolin as the major fl vonoids present in conjugate forms in fresh *Capsicum annuum* cultivars. Total fl vonoid content varied from nondetectable to 800 mg/kg after hydrolysis; Chile, yellow wax, and ancho peppers contained greater fl vonoid content than jalapeño peppers. Marin et al. (2004) characterized and quantifie fi e hydroxycinnamic derivatives and 23 fl vonoids (hydroxycinnamic derivatives, O-glycosides of quercetin, luteolin, and chrysoeriol, and C-glycosyl fl vones) from sweet peppers (*Capsicum annuum L. cv. Vergasa*). Immature green sweet peppers exhibited the highest content of polyphenols (1.99 mg of hydroxycinnamates per 100 g) and very high phenolic content, while a —four- to fi e-fold reduction was observed for the green, immature red, and red ripening stages (0.33–0.45 mg/100 g). The amount of *O*-glycosylfl vones in pepper was higher than that of other fl vonoids for all the maturity stages, but in immature green pepper, it decreased by more than 85% of the content in green fruits, probably due to fruit size increase and to degradation of fl vonoids.

Hertog et al. (1992) reported that red bell pepper contained 13–31 mg luteolin/kg. Among Bulgarian peppers, Marinova et al. (2005) identifie the highest amounts of phenolics in green (246.7 mg GAE/100 g) and red peppers (173.2 mg GAE/100 g).

In the case of hot peppers, Howard et al. (2000) reported increase in total soluble phenolics with maturity. However, Conforti et al. (2007) reported that total soluble phenolic compounds were similar for the firs (small green; 76 mg/g) and second (green; 74 mg/g) stages of ripening, but decreased in the last stage of maturity (43 mg/g) in hot peppers (*C. annuum var. acuminatum*). Materska and Perucka (2005) identifie the main phenolics isolated from hot red pepper as sinapoyl and feruloyl glycosides, and from hot green pepper as quercetin-3-O-L-rhamnoside. Marin et al. (2004) also identifie sinapic and ferulic acids (60% of the dry mass), while luteolin apiosylglucoside and quercetin rhamnoside were less relevant (35%). Earlier, Materska et al. (2003) identifie for the firs time in nature two compounds isolated from hot pepper (*C. annuum L.*): *trans*-p-ferulylalcohol-4-O-(6-(2-methyl-3-hydroxypropionyl) glucopyranoside and luteolin-7-O-(2-apiofuranosyl-4-glucopyranosyl-6-malonyl)- glucopyranoside.

Free-Radical Scavenging Capabilities

All colors of sweet red bell peppers exhibited free-radical scavenging abilities, although green pepper had the lowest activity (Sun et al. 2007).

The highest radical-scavenging activity (129 lg/ml) of hot peppers was demonstrated during the firs stage of maturation (small green), probably due to the higher levels of phenols, sterols, and of phytol, an acyclic diterpene alcohol (Conforti et al. 2007). Quercetin3-O-α-L-rhamnopyranoside from green pepper was identifie as having the highest antiradical activity comparable to quercetin, while capsaicin, dihydrocapsaicin, and *trans*-p-feruloyl-α-D-glucopyranoside were similar (Materska and Perucka 2005).

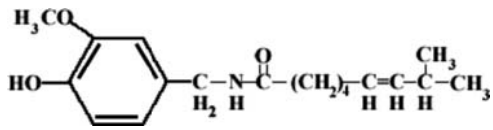
Antioxidant Activity

All four colors of sweet bell peppers demonstrated abilities in preventing cholesterol oxidation during heating, but the green pepper exhibited slightly higher capability in preventing the oxidation of docosahexanoic acid (DHA) (Sun et al. 2007). The highest antioxidant activity in *C. annuum* was found for *trans*-p-sinapoyl-β-D-glucopyranoside, but lower than free sinapic acid (Materska and Perucka 2005). Howard et al. (2000) demonstrated with in vitro models that increasing levels of fl vonoids in combination with constant levels of caffeic and ascorbic acid exhibited an antioxidant activity that was either additive of the two compounds, or competitive in their ability to scavenge peroxyl radicals. Significan increases in antioxidant activity in the presence of ethylenediaminetetraceticacid (EDTA) indicated a prooxidant effect. Earlier, Lee et al. (1995) reported that phenolic compounds correlated well ($r^2 = 0.86$) with antioxidant activity, with luteolin exhibiting highest antioxidant activity, followed by capsaicin and quercetin on equimolar basis.

Conforti et al. (2007) have pointed out that the different composition of lipophilic compounds and amounts of phenols during three stages of ripening of hot peppers modify the antioxidant activity of peppers as radical scavenger, oxidation inhibitor of linoleic acid, and oxidation inhibitor of membrane lipids. Thus, red and green peppers exhibited the highest antioxidant properties with linoleic acid and membrane peroxidation, respectively.

Pungency Principle

The pungency or heat of *Capsicum* peppers is due to a group of phytochemical compounds, capsaicin (8-methyl 6-nonenoyl-vanillylamide), and known collectively as capsaicinoids. The chemical structure of capsaicin is:



The aromatic ring with the phenolic hydroxyl and ether groups, and the composition and chain length of the fatty acid influenc the pungency of red peppers (Fujimoto et al. 1980). The capsaicinoids include: (a) capsaicin [$(CH_3)_2CHCH{=}CH.(CH_2)_4{-}CO{-}R$]; (b) dihydrocapsaicin [$(CH_3)_2CH.(CH_2)_6{-}CO{-}R$]; (c) nordihydrocapsaicin [$(CH_3)_2CH(CH_2)_9{-}CO{-}R$]; (d) homodihydrocapsaicin [$(CH_3)_2CH(CH_2)_9{-}CO{-}R$]; (e) homocapsaicin [$(CH_3)_2CHCH = CH.(CH_2)_5{-}CO{-}R$; (f) nonanoic acid vanillylamide [$(CH_3(CH_2)_7{-}CO{-}R$]; and (g) decanoic acid vanillylamide [$CH_3(CH_2)_8{-}CO{-}R$]. Nornorcapsaicin, norcapsaicin, nornordihydrocapsaicin, and nonivamide also exhibit pungency (Fujinari 1997; Manirakiza et al. 2003; Pruthi 2003b). Different genes control the synthesis of each capsaicinoid, accounting for the different capsaicinoid proportions within the same *Capsicum* species and the variation in the

total capsaicinoid content among different varieties (Manirakiza et al. 2003; Pruthi 2003b). The chemistry and biosynthesis of capsaicinoids are discussed by Ishikawa (2003), Manirakiza et al. (2003), and Ravishankar et al. (2003). The stem end of the pod has most of the glands that produce the capsaicin. The white fles surrounding the seeds (pericarp tissues) contains the capsaicinoids; hence, removing the placenta or midrib is effective at reducing pungency. Red fruits exhibited the major content of capsaicin (40.8%) and dihydrocapsaicin (35.0%). Green fruits showed trace amounts of capsaicin (1.46%), but was absent in small green immature fruits (Table 29.3).

Heat processing of red pepper diminished (18% to 36% loss) capsaicin, probably due to chemical alteration, with pressure cooking causing the maximum loss (Suresh et al. 2007). However, Lee and Howard (1999) earlier reported that capsaicinoid content was stable during processing and storage, also demonstrating that $CaCl_2$ treatment did not affect capsaicinoid retention during pasteurization and storage of canned peppers, which appeared to be related to phytochemical solubility and structural properties.

To determine the heat level (amount of capsaicin) of peppers, the Scoville (after Wilbur Scoville) Organoleptic test is used. The test involves human subjects tasting a chili extract sample diluted in water to lose heat, until it can no longer be detected by the tasters. The Scoville Heat Unit (SHU) is define as the number of parts of sugar-water needed to neutralize the heat of one part chili extract. If cayenne pepper is 30,000 SHU, it means that 30,000 parts of sugar-water are needed to dilute one part of cayenne extract to the last point that hotness can be detected. Capsaicinoid concentration is converted to SHU by multiplying the pepper dry weight concentration (ppm) by the coefficient of heat value for each compound. Pure capsaicin measures 16,000,000 SHU, while sweet bell pepper is 0 SHU. Table 29.1 provides typical SHUs of some *Capsicum* species. General heat levels are consistent for a particular variety or species, with the fruits of *C. chinense* considered the hottest compared to *C. annuum* and *frutescens*. However, the Scoville technique is subjective, affected by the number of samples a taster can handle, and needs extensive panelist training and monitoring of sensitivity to the chemicals responsible for the heat.

If the objective is the determination of the capsaicinoid composition, then Gas Chromatography or High Performance Liquid Chromatography are the preferred analytical methods, but are more costly and require specifi sample preparations (Manirakiza et al. 2003). Pruthi (2003b) summarized the analytical techniques for the determination of capsaicin. With the high correlation between moisture loss and capsaicinoid reduction, Zhou and Goh (2005) suggested that it may be feasible to use moisture loss as indicator for capsaicinoid degradation during industrial-scale production.

Processing

Capsicum peppers for processing are categorized as: (a) Chili peppers: processed for their fl vor; (b) Paprika: processed primarily for color; and (c) Cayenne: processed for pungency. Figure 29.3 shows examples of ethnic pepper products sold in mainstream supermarkets. Table 29.4 describes specialty blends of pepper spices and chili products. Processing methods are briefl described below.

Drying and Dehydration

Sun Drying

Traditional sun drying of peppers is still widely practiced throughout Asia, Africa, and Central and South America, but confine to home growers in the United States. The conventional practice involves spreading the fruits on drying racks, roof tops, or on fla surfaces (concrete, wooden floors or the

Figure 29.3 Diverse ethnic pepper products sold in mainstream supermarkets.

ground as practiced in Asia and Africa). In Central and South America, Hungary, Spain, and southwest United States, farmers take partially dried red peppers and tie them together into bundles to hang on racks, house walls, fences, and even clothes lines. This stringing process, "*ristra*," is a form of storage and decoration. Drying on *paseras* (raised soil beds slanted for rain water to run off) is practiced primarily in Mexico.

In India, sun drying takes 5–15 days for the reduction of moisture content from 70–80% (wet basis or wb) to about 10% (wb), depending upon climatic conditions. The yield of dried chillies produced is about 25–30% of the fresh weight of chillies. Chilies are often light-coated with oil of *mahuwa* (*Madhuca longifolia*) to impart glossiness (Peter et al. 2003). Studies showed that drying time (20–25°C; 34–50% RH) was reduced from 15 days by these treatments: (a) to 12 days by pricking chilies longitudinally; (b) to 7 days with blanching; (c) to 7 days after dipping in 2.5% potassium carbonate solution; and (d) to 6 days with deodorized olive oil (Prakash and Eipeson 2003). In Japan, after partial sun drying, peppers are further dehydrated using a mechanical dryer, then there is fina sun drying before packing. Sun drying process may have potential issues like (a) bruising and splitting, discoloration, loose seeds, and weight loss; (b) inadequate protection from rain and pests; (c) growth of microflor and spoilage with excessive delay in drying; and (d) heterogeneity in size, color, and quality (Pruthi 2003a).

Drying by Smoking

This is a traditional Nahuatl practice for drying jalapeños and other thick-fles peppers. A pit below ground level serves as source

Table 29.4 Chili products and spice specialty blends

Product	Description
Paprika	Ground product from red colored, mild pods used to improve color in tomato ketchup and sauces. Sweet paprika is mostly pericarp with more than half of the seeds removed; hot paprika contains some seeds, placenta, calyces, and stalks.
Cayenne pepper	Ground product from small, ripe chilies. Tart fl vor, slightly smoky, and intensely pungent. Adds zest to frankfurters, bologna, Mexican, and country sausages.
Yellow ground chili	Range from yellow to red and mahogany, used in South America.
Red pepper	Mixture of ground and crushed high-colored bigger-sized red chilies. Adds color and pungency to Mexican style dishes, spaghetti, stews, and soups.
Crushed red pepper	Mixture of crushed high capsaicinoid varieties. "Pepperone rosa" and "pizza pepper" used in Italian and Mexican sausages, meats, spaghetti, pizza.
Chili oil	Bright red seasoning oil made with crushed, dried red chilies added to very hot sunfl wer oil, cooled and strained.
Thin sauces	Fiery liquid made from crushed chilies blended with spices and vinegar; e.g., Tabasco sauce.
Chili sauces	Thick sauces made from raw whole chilies preserved in brine or vinegar. Used as dips and condiments.
Chili jam and *Sambal*	Sambal is a popular dipping sauce in Indonesia and Malaysia made from chili peppers with garlic, onion, shallots, salt, vinegar, and sugar. Chili pastes and thick sauces used in stir-fries and slow-cooked dishes.
Mexican sauce (*Salsa picante*)	Mixture of chopped tomatoes, onions, and chili peppers with spices (e.g., cilantro), garlic, and salt. For dipping toasted tortilla chips.
Pimento or pimiento	Canned sweet, thick-fleshe bright red Capsicum.
Chili powder	Blend of ground chili, cumin, dried oregano, paprika, and garlic powder, used to fl vor Mexican type and southwestern Tex-Mex dishes, e.g., *chile con carne*, hot tamales; used by canners to season eggs, shellfish vegetables, stews, gravies.
Curry powder	Ground roasted dry chili, blend of as many as 30 spices (coriander, cumin, turmeric, etc.), contains only 5–10% chili and/or paprika.
Barbecue seasonings	Basic ingredient is high capsaicinoid chili powder.

Source: Adapted from Norman (2002) and Govindarajan (1986b).

of heat, containing a tunnel leading to an inverted pyramid-shaped compartment on top of which a latticework of bamboo holds the peppers. Air drafts pull the smoke through the tunnel up through the bamboo and over the fruits. Peppers smoked without seeds are called *capones* and command a higher price than *chipotles* containing seeds (Andrews 1984).

Dehydration

In the United States and other developed countries, commercial processors bring harvested peppers in bulk to dry in heated buildings, in tunnel driers, or stainless steel continuous-belt or belt-trough driers. Dehydration offers these advantages: (a) more consistent quality product; (b) less drying time; (c) lower losses; (d) not dependent on weather; and (e) reduced microbial contamination.

Chili peppers

In the United States, *Ancho* (Mexican) and *Anaheim* (California) peppers are dried for spices. Mature pods are harvested, washed, and spread on trays as whole or 1-inch length slices. The drying time at 65°C for a fina moisture content of 7–8% is about 12 hours and 6 hours, for whole and slices, respectively. Chilies dried at 80°C were reported to turn black and had reduced their pungency and glossiness. Some processors use a two-stage drying: drying firs to 12–20% moisture, storage at 0°C, then further drying to 7–8% moisture or less when required for grinding (Luh and Kean 1988; Pruthi 2003a).

Bell peppers

Hand-harvested peppers are washed, inspected, graded, cored, cut, washed, trimmed,

diced, sulfite to a fina sulfur dioxide content of 1,000–2,500 ppm, and dried to a fi nal moisture content of 5% (Somogyi and Luh 1988). Banu et al. (2002) reported that pretreating diced green peppers with osmotic dehydration using salt and sorbitol increased weight loss, solids gain, and tissue Brix, and decreased water activity. Luning et al. (1995) reported that glucose, fructose, ascorbic acid, and citric and oxalic acids decreased significantl after drying bell peppers, while sucrose, malic, fumaric, and *cis*-aconitic acid levels increased. Compounds with fresh odor notes (e.g., 3-hexenal, octanal) decreased or disappeared after drying, while compounds like 4-octen-3-one or 2-heptenal increased or were formed during drying; most are autoxidation products of unsaturated fatty acids. Increased levels of 2-methylpropionic and 2- and 3-methylbutyric acid, 2-methylpropanal, and 2- and 3-methylbutanal were probably due to Strecker degradation.

Pimientos

Peppers are cored, lye or flam peeled, and processed as whole, shoestring strips, or diced. Dicing and drying steps are similar to that for bell peppers, except for the absence of sulfiting Dried pimientos are utilized in potato salads, stew, luncheon meats, and cheese.

Processing of Paprika Spice

The quality of ground paprika is determined by its capsaicin and carotenoid contents, particle size, and water content. Its stability during storage is dependent on drying conditions, where the degradation rate increases as the drying temperature increases (Ramesh et al. 2001).

The traditional predrying and postmaturation practice in Hungary was stringing of harvested peppers. Ripping is the removal of the calyx and placenta (containing septum and seed). The pericarpium is stringed and kept in a heated place until bone dry. Seeds are separated from the placenta and septum and washed until free of capsaicin. Dried seeds are added to the dried, crushed pericarpium in the required amount and milled, resulting in a completely sweet powder. Peppers go through a 4–6 week period of drying, bagging, crushing, and sifting. Large processors buy raw peppers and after a temporary storage, immediately dry them without going through the after-ripping and hand-selection steps (Somogyi et al. 2003).

Carotenoids, especially the yellow (β-carotene, β-cryptoxanthin) pigments, are degraded, decreasing the pro-vitamin during paprika processing (Minguez-Mosquera and Hornero-Mendez 1994). Preprocessing steps for drying spice paprika, like cutting and steam blanching for 3 minutes, facilitated higher retention of Vitamin C, tocopherol, carotenoids, and a higher ASTA value. Blanching the whole fruit or only pericarp had different effects due to the presence of seeds and stems. Higher air velocities and lower relative humidity are recommended for reducing the drying time of spice paprika (Ramesh et al. 2001).

Chili Powder

In spice trade, quality is graded by the particle size and color of chili powder (Table 29.4). Smaller particles aid in fl vor release during cooking, while a bright color connotes freshness. Zhou and Goh (2005) reported that high-speed cutting was more efficien than stone grinding when producing chili powders. However, quality degradation was much faster in the high-speed cutter than in the stone grinder. The difference in the mechanical energy utilization may account for the different degradation reaction rates.

Capsicum or Paprika Oleoresin

Oleoresin of *Capsicum* refers to a solvent-extracted product using solvents (alcohol, ether, ethylene dichloride, acetone, or hexane) which conform to specification of international and national food laws, followed by removal of the solvent by filtration and distillation (Prakash and Eipeson 2003). The color and flavor components of the fresh chili peppers should be recreated upon dilution and utilization as food additive. Commercial *Capsicum* oleoresins include: (a) Oleoresin paprika (*C. annum*) with high color value but little or no pungency, used in meats, dairy products, soups, sauces, and snacks; (b) Oleoresin red pepper (*C. annum*) from moderately pungent *Capsicum* used in canned meats, sausages, smoked pork, spreads, soups, snacks, and drinks for their color and flavor; and (c) Oleoresin *Capsicum* (Bird chilies—*C. frutescens*) or African *Capsicum*, used for its high pungency in foods and beverages (Govindarajan 1986b). The US Essential Oils Association (EOA) provides specification for pungency determined by diluting an alcoholic solution of the oleoresin in 3–5% sugar solution. The strength of dilution agreed to by three panelists gives the SHU. Extraction of the chili pericarp resulted in an oleoresin with 94% of the color and 90% of the capsaicinoids. Color value is determined by measuring the absorption of a 0.01% solution of the oleoresin in acetone at 458 nm (Pruthi 2003b). Oleoresins possess the following advantages over chilies: (a) easily standardized for flavor strength; (b) no speck formation; (c) long shelf life; (d) less bulk; (e) contain natural antioxidants, and (f) free from enzymes. Fujimoto et al. (1980) demonstrated that pungency decreases with increasing fatty acid chain length of synthetic N-vanillylamides (saturated C12 to C22), and that the antioxidant effect of 0.02 mol/kg of synthetic amides on the methyl ester of saffl wer oil was equivalent to that of natural red pepper pungent mixture, with no detectable pungency even for the C12 amide.

Canned Pepper Products

Pimiento

Large, smooth-skinned, deep red pimientos are suitable for canning. They are graded according to diameter: No. 1 (>51 mm), No. 2 (<51 mm), and No. 3 (<45 mm). Peeling can be accomplished by roasting (1 minute heating), oil-heating (204°C for 3–4 minutes), steam-heating (20–25 kg pressure), or lye treatments (boiling in 10% sodium hydroxide followed by 150°C steam-pressures). A coring step removes the core and seeds. Pimientos are flattened packed into cans with or without brine added, cans exhausted (93–100°C/12–15 minutes), sealed, and processed in boiling water (30 minutes) if acidifie to below pH 4.5. The use of acidificatio and calcium chloride resulted in an increase in drained weight and firme product (Powers 1961; Supra et al. 1966; Luh and Kean 1988). Flora and Heaton (1979) reported slight decrease in canned pimiento's pH with increase in processing time. However, there were no changes in pH of acidifie pimientos over a 12-month storage period. Whole pimientos were more sensitive to acid bath variations than diced. The pH in canned pimientos ranged from 4.6–5.3, with average of pH 4.95. The average titrable acidity of red and green pimientos was 0.28% and 0.60%, respectively (Pruthi 2003a).

Jalapeño Rings

Calcium addition to high acid-salt brines has been shown to reduce softening in jalapeño pepper rings due to acid hydrolysis (Howard et al. 1994). Softening occurred at the top of the container, while firmnes retention was observed at the bottom. The combination of

rotary processing and calcium chloride treatment resulted in more uniform heat penetration and texture retention of canned jalapeño rings compared to nonagitated processing (Gu et al. 1999). Calcium improved the texture by maintaining greater levels of insoluble pectic substances and reducing pectin solubilization, resulting in fresh-like, uniform texture throughout the container. $CaCl_2$ treatment of pasteurized yellow banana peppers resulted in a decline of shear force values during processing and storage, but greater firmnes retention (Lee and Howard 1999).

Chili Puree/Paste

Fresh red chilies are blanched (100°C/10 minutes), strained, and wet ground to produce chili puree, which is acidifie with acetic acid ($pH < 4.5$). Sodium benzoate (1,000 ppm) can be added as preservative (Pruthi 2003a).

Fermentation

Fermented Jalapeño

Freshly harvested green Jalapeño peppers (*Capsicum annum cv. Jalapeño*) are washed. However, since washing diminishes natural fermentative ability, *Lactobacillus plantarum* culture is added to help in the fermentation process. Small incisions are made to eliminate gas during fermentation and facilitate brine diffusion to the center of jalapeños completely immersed in 10% brine for 4–6 weeks in closed tanks. Dilution of brine results from the cell fluid hence, daily addition of 1% salt during the firs week, and three times a week for the rest of the immersion time keeps the desired 18–20% brine concentration. When jalapeños turn translucent olive green, lactic acid concentration increases from 0.8% to 1.5%, decreasing pH. Fermented jalapeños are washed to eliminate excess salt, classifie by size, packed in jars, and pasteurized at 71°C/30 minutes (Cabrera 2004).

Pickling

Pickled Jalapeño Peppers

Fermented jalapeños can be pickled by mixing with other vegetables (blanched carrots, onions), spices, salt (3%), packed with vinegar (<3% acetic acid), and processed. One can also start with fresh jalapeño peppers which have been washed, graded, sized (dice, rings, etc.), and packed into cans with blanched vegetables, spices (pepper, cinnamon, marjoram, thyme, clove, laurel), other condiments (onion, garlic fried in vegetable oil), and vinegar. Cans are exhausted, sealed, and processed (93.3°C/10 minutes). For acid pickle, pH 4.3–4.5 is recommended. Cabrera (2004) provides a detailed discussion of the fermentation and pickling processes, as well as quality evaluation of jalapeño peppers.

Chili Pickles

Chili pickles from India are usually packed in oil, brine, or citrus juice. Sorted and graded raw chilies are washed, blanched (90°C, 1 minute), drained (55–65%), packed into cans, and fille with the packing solution. Although processing time varies depending on jar size, sterilization is generally at 85°C (Pruthi 2003a).

Ascorbic acid values in fresh pepper rapidly decreased after pickle processing (firs 3 weeks), but did not significantl ($p < 0.05$) change through storage time (8 weeks). Sugar and chickpea added together in pickled pepper processing resulted in greater ascorbic acid retention (48.2% and 40.9%, for 3 and 8 weeks, respectively) (Yalim and Ozdemir 2003).

Freezing

Bell Peppers

Large, thick-walled peppers with small placenta are ideal for freezing. Hand-harvested peppers are washed, inspected, graded, cored,

halved, washed, steam- or hot-water blanched (2 minutes), and packed as halved or diced frozen bell peppers. They are packed for foodservice or remanufacturing use in frozen mix and canned vegetables (Luh and Lorenzo 1988).

Pimientos

Thick-walled, tough-skinned red sweet peppers are harvested fully mature, cored, and seeded before or after peeling (flame hot oil, or lye). They are frozen whole, as shoestring strips, or diced, and used for remanufacturing into potato salad, stew, luncheon meats, and cheese because of their color and fl vor (Luh and Lorenzo 1988).

Jalapeños

A recommended low-temperature (55°C) long-time blanching of diced jalapeño pepper prior to freezing had no significan effect on product quality, and produced firmnes and color values of 779N and –10.55 (of parameter a*), respectively, in the frozen jalapeño peppers (Quintero-Ramos et al. 1997).

Freeze-Grinding of Spices

Freeze grinding helps in the retention of fla vor and color. The Cryomill process of freeze-grinding spices involves the controlled injection of liquid nitrogen (direct-contact refrigerant) directly into the mill grinding zone. A temperature controller monitors the fl w of liquid through a valve and maintains product temperature. Part of the exhausted stream of cold nitrogen is recirculated to the spice hopper for the precooking of spices. Advantages of the process include: (a) reduction of spice oil oxidation; (b) extremely fin grinding; (c) uniform fl vor dispersion throughout fina product; (d) elimination of specking problems; (e) reduced settling rate in liquid preparations; (f) retention of original fl vor strength and weight; (g) increased stability; (h) lower spice microbial load; (i) increased grinding rates; and (j) lower actual costs with increased fl vor strength (Pruthi 2003a).

Minimal Processing

With the constant consumer demand for convenience products and the emphasis on eating fresh vegetables, there is much potential for fresh-cut, ready-to-eat peppers. Green peppers in modifie atmosphere packaging stored at 8°(±1°C) exhibited a shelf life of 7 days. Beyond this time, the microbial proliferation (total count $>$ 107–108 cfu/g) was over the safety limit for human consumption (Senesi et al. 2000). In a study by Kang and Lee (1997), minimally processed cut green peppers were more sensitive to chilling injury at 5°C compared to intact produce, and exhibited a shorter shelf life of 4 days compared to storage life at 10°C. Increased respiration in response to chilling injury was observed earlier than onset of spoilage due to microbial growth.

Quality Evaluation

The document "United States Standards for Grades of Sweet Peppers for Processing" provides detailed guidelines including varietal characteristics, definitions and grades of peppers (USDA 1977). India's system of grading peppers could be representative of those in other countries: (a) commercial grading at producer's level; (b) grading for internal trade or voluntary grading; and (c) compulsory grading for export. The ASTA and the US Food and Drug Administration provide cleanliness specification and defect action levels, respectively, for spice imports.

Food Safety Challenges

An overview of food safety issues during trading of chili peppers and paprika as a spice is provided below.

Microbiological contamination: Except for gamma irradiation (10 kGy) which is still not accepted by many countries outside the European Community (EC), spices do not undergo a germ-reduction treatment (Pruthi 2003a). A high microbial count is indicative of low sanitary quality and poor hygienic practices during production and handling. In Germany, *Salmonella* should not be detectable in 25 g of spice, and approximate microbial values (cfu/g) should be met: 1.0×10^4 (for *E.coli*, *Bacillus cereus*, and *Clostridia*) and 1.0×10^2 for *Staphylococcus aureus* (Buckenhuskes 2003).

Mycotoxins: The presence of aflatoxi has been reported in both paprika and chili powders. The guideline for molds in spices is approximately 105 cfu/g. EC Regulation restricts aflatoxi content to 5 μg aflatoxi B1 per kg, and 10 μg total aflatoxi per kg food (Buckenhuskes 2003), or a limit of 0.03 ppm for chili (Chakrabarti and Roy 2003).

Adulteration: For both whole chilies and powdered or paste chili, adulteration includes: (a) extraneous matter (calyx pieces, loose tops, dirt, lumps of earth, stones, mold); (b) extraneous coloring and coatings; (c) insect-damaged foods; and (d) harmful substances. Powder or paste chili includes additional adulterants: (a) edible oil for postharvest processing (2% maximum); (b) microscopic structures (aleurone, chloroplasts, cuticle, cuticle grooves, endocarp, endosperm, hairs); (c) detected abstraction or deficien y of normal levels of capsaicin and carotenoids; and (d) fraudulent boosting of nonvolatile ether extracts with mineral oils (Chakrabarti and Roy 2003). An example of adulteration would be the Sudan I (carcinogenic chemical dye) adulterated chili products in France in May 2003.

Contaminants: They include agricultural and biological residues, fungi, rodent hair and excreta, radioactive and radiolytic products, and extraneous color.

Pollutants: They include toxic trace metals and pesticides from agricultural, chemical, and processing operations.

An Individually Quick Frozen (IQF) pepper-processing plant in Turkey reported contamination with Listeria spp. in cube-cut but not in strip peppers. Although *L. monocytogenes* was not identified the isolates contained other Listeria species including *L. innocua*, which could indicate an eventual environment for *L. monocytogenes* (Lee et al. 2007).

Conclusion

As the world gets more exposure to various ethnic, emerging fusion and gourmet cuisines, and with the changing demographics in the Western world, the demand for *Capsicum* peppers will continue to increase. There will be an increased market for the natural *Capsicum* color and color-rich fraction of chili-pericarp oleoresins free from pungency, to take the place of synthetic food colors in the processed food industry.

However, not only will *Capsicum* peppers be regarded as a spice, condiment, and vegetable, but they will continue to be scrutinized for their nutritional and phytochemical properties and medicinal potentials.

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Chapter 30

Peas, Sweet Corn, and Green Beans

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Introduction

Green pea (*Pisum sativum*), sweet corn (*Zea mays* var. *rugosa*), and green beans (*Phaseolus spp.*) are among some of the most common vegetables grown and consumed throughout the world. Green pea is a vegetable crop native of southwest Asia and was among the firs crops cultivated (Oelke et al. 1991). In the United States, the largest acreages of fiel pea are in Washington, Idaho, Oregon, Minnesota, and North Dakota. The commercial cultivation of pea has led to a gradual separation of this vegetable into three types, grown for (1) vegetable use, (2) seed and fodder, and (3) the edible podded types which have evolved most recently (Oelke et al. 1991). Green peas are used as fresh, frozen, or canned, and are also grown to produce dry split or fiel peas.

Sweet corn (*Zea mays* var. *rugosa*) is a corn variety that is different from fiel or grain corn. As the name denotes, it is a variety of corn with higher sugar content, and prepared and consumed as a vegetable more than its counterpart grain corn from which oil is extracted and corn flour/mea is processed. Another major difference is that fiel corn is harvested when the grains are dry, whereas sweet corn is harvested at the "milk stage" and has high water content. Due to high moisture content, the sweet corn has a short shelf life and must be consumed fresh within a few days of harvest or processed into frozen and canned forms, or soups and other products. Although the specifi time when sweet corn originated is not known, it was grown by the American Indians and firs collected by European settlers in the 1770s. Soon after, it became a popular vegetable in southern and central regions of the United States (Schultheis 1998).

Green beans (snap beans) and long beans are commodities of the Fabaceae (*Leguminosae*) family; for this vegetable, both the fles y pod and seeds are consumed. Beans in this category include fresh snap or common beans—string beans, yellow wax beans, green beans (*Phaseolus vulgaris* L.), runner or fla beans (*P. coccineus* L.), and long beans (*Vigna sesquipedalis*). Since green beans are the most commonly consumed bean variety, the topic coverage in this chapter will focus on green beans only. Fresh pod beans are available in major production areas in the United States; however, during winter months they are produced largely in Florida and Mexico (Cantwell 2004). Green beans are commonly referred to as French beans or runner beans in British English. Green beans, as the name depicts, are not completely dry as is the case for other fiel beans. This vegetable is consumed fresh (cooked), or canned or frozen for extended use in off-season and/or convenience.

This chapter will focus on topics related to production, postharvest physiology and storage, processed products, nutritional profiles and any other significan information on peas, sweet corn, and green beans.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

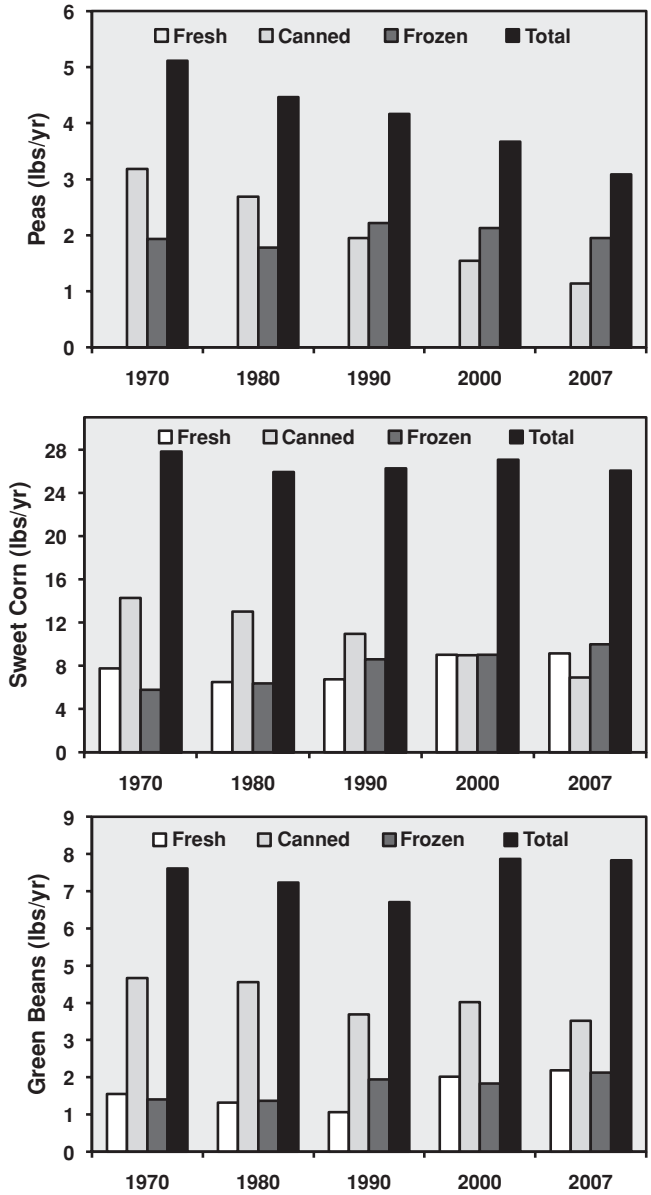

Figure 30.1 Per capita consumption of peas, sweet corn, and green beans in the United States (USDA-ERS 2009).

Consumption Trends

Peas, sweet corn, and green beans are among some of the popularly consumed vegetables all over the world. The US per capita consumption of these three vegetables (USDA-ERS 2009) in fresh, canned, and frozen forms is shown in Figure 30.1. It is to be noted that data on the consumption of fresh peas are not available as they are not consumed in this form. The only pea variety consumed in fresh

cooked form is edible podded peas, which are not the subject of this chapter as that variety is produced on a much smaller scale.

Since 1970, total pea consumption has seen about a 40% drop; this decrease can be attributed almost exclusively to lower consumption of canned peas. The per capita consumption of frozen peas has remained steady through the same period. One possible reason for a significan drop in pea consumption could be a corresponding "disliking" of canned food in general by the consumers, which is evident in similar decrease in consumption of canned green beans and canned sweet corn, with 25% and 51% lower per capita consumption, respectively. In contrast to peas, the total per capita consumption of sweet corn (26.1 lbs/year) and green beans (7.8 lbs/year) has remained fairly steady. For both of these vegetables, any decreases in canned consumption were offset by corresponding similar consumption increases in frozen form. In summary, the only signifi cant decrease in the total consumption among these three vegetables was observed for peas.

Production, Harvest, and Quality Grades

Pea

Peas, a cold-season crop, grow well under cool and moist conditions. Morris and Jobling (2004) described three types of edible peas, from the family *Fabaceae*, also called *Leguminosae*. Among these, the most common type is the garden or green pea, *P. sativum* var. sativum L. This pea is characterized by a tough pod, which is discarded prior to eating. Most often these peas are frozen or processed as canned (Basterrechea and Hicks 1991; Snowden 1991). In the United States, the success of the processed pea industry has resulted in a significan decline in the sale of peas in the podded form, which are still very commonly sold and consumed in India, China, Pakistan, and many other countries. The other two types of peas have soft, edible pods and belong to the subspecies *P. sativum* var. macrocarpon Ser (Suslow and Cantwell 1998).

Pea plants grow best at an optimum temperature range of 13–18°C (55–64°F). Typically, they do not flouris under hot summer conditions and lowland tropical climates; however, they grow well in cooler high-altitude tropical areas (Oelke et al. 1991). Most cultivars reach maturity in about 60 days. Pea cultivars can be divided into two types: low-growing, i.e., close to ground, and vining or climbing cultivars. In the United States, over 300,000 acres of peas are harvested annually, which is more than 9% of the US land devoted to vegetable production (Kee et al. 2004).

It is recommended that for best quality, peas should be harvested before physiological maturity, i.e., before peas deform the hull (Basterrechea and Hicks 1991). As peas approach harvest, their maturity is evaluated with a tenderometer. The tougher, more-starchy peas have a higher tenderometer reading. Tenderometer readings are also taken for grading and payment purposes at harvest (Kee et al. 2004). Pod-stripper combines have become the predominant method of harvesting green peas for processing. Most of the acreage is harvested by processor-owned machines, although grower-owned harvest equipment is still used by many farmers. To accommodate orderly fl w to the processing plant, peas are planted on a schedule coordinated by the processor and frequent harvesting is necessary (Kee et al. 2004; Morris and Jobling 2004). Good-quality peas should be uniformly bright green, fully turgid, and free from defects and mechanical damage. Peas lose sugars and fl vor rapidly after harvest unless they are promptly cooled to 0°C or 32°F (Morris and Jobling 2004).

Pea grades include *US No. 1* and *US Fancy*, which are based primarily on external appearance. Peas should have similar varietal

characteristics; they should not be overmature or excessively small, not be badly misshapen, and should be fresh and free from decay and damage caused by black calyxes, freezing, splitting, hail, dirt, leaves or other foreign mater, mildew or other diseases, insects, or harvester damage (USDA-AMS 1997; Morris and Jobling 2004).

Sweet Corn

Corn, also referred to as maize in many countries (*Zea mays*), was grown in North America before 200 BC. Field corn, characterized by dry/hard grain, is primarily for animal feed and other food/non-food uses, such as ethanol, cooking oil, and defatted germ flou (Schultheis 1998; Siddiq et al. 2009a, 2009b). In contrast, sweet corn is produced for human consumption only as either a fresh or processed product—canned or frozen or as soups. Sweet corn is distinguished from fiel corn by the high sugar content of the kernel. The water content of sweet corn is 8–10 times higher than fiel or dry corn (Brecht 2004).

The main sweet corn varieties are: Sh2 (super-sweet), SUSU (normal sugary), and SESE (sugary enhancer). Sweet corn can also be classifie by its color: white, yellow, or bicolored (Schultheis 1998). The super-sweet corn varieties have fir kernels, are very sweet, and are typically not as "creamy" as the other varieties. Normal sugary corn varieties are creamy and sweet and among the most popular varieties even among gardeners; these varieties do not store well after harvesting and thus should be eaten within few days of harvest. Sugary enhancer varieties are characterized by a smooth and buttery texture. This variety is considered best for fl vor, texture, and ease of growing (Schultheis 1998). Sweet corn harvest maturity is determined by a combination of ear fill silk drying, kernel development, kernel sweetness, and kernel tenderness (Brecht 2004). In addition, the appearance of the juice, or endosperm, is a good indicator of maturity. According to Schultheis (1998), the *milky* stage usually lasts about a week; the husks should hold tightly to the ear/kernels and the silks should be brown and starting to dry, which occurs about 3 weeks after the silks firs appear. Another indicator is that ear and the kernels should produce a little milky flui when pierced, the exception being super sweets varieties which produce a relatively clearer liquid.

The sweet corn grades are *US Fancy*; *US Fancy, Husked*; *US No. 1*; *US No. 1, Husked*; and *US No. 2* (USDA-AMS 1992). These grades are based mainly on maturity, freshness, and cob length, as well as freedom from various injuries and decay. Sweet corn is commonly handled in wire-bound wooden crates and, to a lesser extent, in waxed fibe - board cartons, or returnable plastic containers (Brecht 2004). For retail packages, some of the production is prepackaged in trays with polyvinylchloride (PVC) fil overwrap. The PVC fil acts as a good moisture barrier (Risse and McDonald 1990; Aharoni et al. 1996). For this type of prepackaged sweet corn, the ends of ears are typically trimmed and husks partially removed to expose some kernels.

Green Beans

Green beans are a summer vegetable crop with fairly short growing season. The major production in the United States is located in Wisconsin, western New York, and Oregon. They are also grown along the Atlantic coastal plain and in the Midwest from Arkansas up through Minnesota and Wisconsin, generally the eastern Corn Belt (Taber 2009). Management of successful green or snap bean production involves two phases: (1) scheduled planting to maintain continuous supply through the harvest period, and (2) timely harvesting when beans are at peak quality (Taber 2009).

Green beans are classifie based on their physical characteristics, such as Stringless, Round-podded, Flat-podded, and

French-filet The pods can be of two types: fla or round, when seen in cross-section (Agular et al. 1998). Green bean pod color can be green, golden, purple, red, or streaked. Some prominent varieties within each type are: Stringless—Blue Lake, Bountiful, Contender, Maxibel, Topcrop; Round-podded—Bush Blue Lake 274, Contender, Fortex, Jade, Kentucky Blue, Maxibel, Provider, Topcrop, Venture; Flat-podded—Bush Kentucky Wonder, Gina, Roma II; and French-filet—Nic el, Grenoble, Straight "N Narrow." The plant growth can be characterized as *bush* or *pole*-type. Bush types, which do not need to be trellised, are the dominant type in commercial production. They are short erect plants that can grow to 1–2 feet with fairly well-set pods (Agular et al. 1998).

Green beans are adaptable to a wide variety of soil types but have difficult emerging in crusted soils. They grow well in well-drained soils that have good water-holding capacity, with optimum soil pH of 5.8–7.0 (Andersen 2003). Green bean plants are sensitive to cold and can be damaged by even a slight frost. For this reason, the firs planting of beans should not be made until after the danger of the last killing frost in spring. Therefore, they should be planted in the spring when the soil temperatures reach about 13°C (55°F) and ambient air temperatures are about 16°C (60°F). Successive plantings every 2–3 weeks are normal (Agular et al. 1998; Anon 2007).

Snap beans are harvested at the optimum edible maturity stage when the seeds are about one-third developed. All pod beans should be harvested when the pod is bright green and fles y, and the seeds are small and green. Beyond this stage, excessive seed development reduces quality and the pods become pithy and tough, and lose their bright color (Cantwell 2004). Many bush beans are mechanically harvested; commercial crop is harvested up to fi e times, with each harvest three to fi e days apart. Green beans for the fresh wholesale market are packed in bushel baskets or cardboard cartons.

Grades, based primarily on external appearance, are *US Fancy*, *US No. 1*, and *US No. 2* (Cantwell 2004). Green beans, though not sized for market, should have a reasonable size specifi to the characteristics of each variety. Beans are packed in 25–30 lb (11.4–13.6 kg) crates, and 15 lb or 20 lb (6.8 or 9.1 kg) cartons. For the food service market, presnipped beans are available in 10 lb or 4.5 kg bags (USDA-AMS 1990; Cantwell 2004).

Postharvest Handling and Storage

Postharvest quality of peas, sweet corn, and green beans is important for the consumers. It is a well-known fact that one of the most important vitamins in fresh produce for human nutrition is vitamin C; more than 90% of vitamin C in human diets is supplied by vegetables (Techavuthiporn et al. 2008). According to Lee and Kader (2000), the level of vitamin C in vegetables can be classifie as greater than 95% (e.g., broccoli, Brussels sprouts), 65–70% (e.g., green peas, spinach), and 15–30% (e.g., asparagus, green beans). Most fresh vegetables have a very short shelf life and rapidly lose internal quality, especially vitamin C, because of metabolic activity after harvest. Postharvest handling procedures greatly influenc the rate of vitamin C degradation after harvest. After harvesting, vegetables need to be cooled as quickly as possible to minimize quality deterioration resulting from biochemical changes or respiration. One of the most important factors affecting the postharvest life and quality of horticultural crops is temperature. Quality loss after harvest occurs as a result of physiological and biological processes, the rates of which are influence primarily by the produce temperature. As the maintenance of market quality is of vital importance to the success of the vegetable industry, it is necessary not only to cool the product but to cool it as quickly as possible after harvest (Brosnan and Sun 2001).

Table 30.1 Respiration rates of peas, sweet corn, and green beans at different storage temperatures

	Respiration rate (mg CO_2/kg/hr)		
Temperature (°C/°F)	Peas*	Sweet corn†	Green beans‡
0/32	30–46	30–51	40–80
5/41	55–72	43–83	66–90
10/50	63–108	90–120	110–175
15/59	165–185	142–175	170–374
20/68	220–322	210–311	234–396
25/77	298–327	282–435	—

*Morris and Jobling 2004.
†Brecht 2004.
‡Cantwell 2004.

Respiration

Respiration rates of peas, sweet corn, and green beans are given in Table 30.1. According to Saltveit (2004), green beans fall under *extremely high respiring* and peas and sweet corn under *very high respiring* commodities. A major part of postharvest interventions is dedicated to reducing respiration and other metabolic reactions associated with quality retention by manipulating the external environment. In general, the storage life of vegetables varies inversely with the rate of respiration; this is because respiration supplies compounds that determine the rate of metabolic processes directly related to quality parameters, e.g., firmness sugar content, aroma, and fl vor (Saltveit 2004). Given all these factors, the firs quality-improvement step that can be taken is cooling of vegetables and handling in a safe and sanitary manner (to avoid damage and bruising) and subsequent storage at low temperatures.

PreCooling

Precooling of vegetables can be done by a variety of methods (ASHRAE 1998). Some commonly used methods are hydro-cooling, forced-air cooling, vacuum cooling, and package (contact) icing; a combination of methods can be used to improve efficien y. According to Vigneault et al. (2009), each precooling process can take on different forms depending on the size of the enterprise, the produce to be cooled, the conceptual vision of the designer, and the economic constraints, but the basic principle of these precooling systems remains the same. According to Talbot et al. (1999), the selection of a particular precooling method is determined by several factors, including the rate of cooling required, compatibility of the method with the commodities to be cooled, subsequent storage and shipping conditions, and equipment and operating costs. Table 30.2 lists the recommended precooling methods for peas, sweet corn, and green beans.

Vacuum cooling is a very effective method of cooling vegetables to remove fiel heat. Using this method for 25–30 minutes, raw product temperatures can be cooled down to 6°C,

Table 30.2 Suggested cooling methods for peas, sweet corn, and green beans

	Size of operation	
	Large	Small
Peas	Forced-air Package-icing Vacuum cooling	Forced-air Package-icing
Sweet corn	Hydro-cooling Vacuum cooling Package-icing	Hydro-cooling Forced-air Package-icing
Green beans	Hydro-cooling Forced-air	Forced-air

Source: Adapted from ASHRAE (1998).

4.5°C, and 12°C for peas, sweet corn, and green beans, respectively (Brosnan and Sun 2001). However, vacuum cooling is generally seen as more expensive than other cooling methods (Ryall and Lipton 1979); thus, its use is primarily restricted to products for which vacuum cooling is much faster or more convenient. The expensive equipment required makes vacuum cooling feasible only for large growers or organizations (Brosnan and Sun 2001). Isik and Celik (2006) reported that precooling after packaging can decrease water loss during this process and hence retain quality better; e.g., in the case of green beans, about two-third lower water loss was observed when precooling was done in packages.

Forced-air cooling, hydro-cooling, and vacuum cooling are commonly used methods for peas (Morris and Jobling 2004). Ryall and Lipton (1979) recommended that it is important that the peas are pre-wetted to ensure rapid cooling under vacuum without loss of moisture from the product.

Sweet corn is at about 30°C when harvested and rapid removal of fiel heat is critical to retard deterioration. Maximum quality can be retained by precooling corn to 0°C within few hours of harvest (Brecht 2004). Super-sweet varieties have respiration rates equal to that of traditional sweet corn varieties and lose sugar as rapidly (Olsen et al. 1991); thus, cooling as quickly as possible is critical. Vacuum cooling can adequately cool sweet corn, but it must be wetted firs (and top-iced after cooling) to minimize water loss from husks and kernels. Hydro-cooling of sweet corn is also practiced. After hydro-cooling, top-icing is desirable during transport or holding to continue cooling, remove the heat of respiration, and keep the husks fresh (Brecht 2004).

Cantwell (2004) recommended that snap (or green) beans can be hydro-cooled after harvest. This method is especially beneficia in dry climates where dehydration is a concern and in situations where moisture loss occurs rapidly after cooling (e.g., when beans are packed in wire-bound crates). Forced-air cooling is the preferred method if beans have been packed in cartons. Efficien cooling can be achieved without leaving free moisture on beans; however, water loss does occur. Although hydro-cooling is very rapid, signifi cant postharvest decay can occur if the product remains wet after cooling (Boyette et al. 1994; Sargent et al. 2000).

Storage

Peas can be stored for 1–2 weeks at 0°C (32°F) with 95–98% RH (Suslow and Cantwell 1998; Morris and Jobling 2004). If there is surface moisture on peas, then it is essential that they be stored below 2°C (35.6°F). Most sweet corn varieties are not stored for more than a few days, because of the resulting serious deterioration and loss of tenderness and sweetness (Brecht 2004). The loss of sugar is about four times more at 10°C (50°F) than at 0°C (32°F). Pericarp toughening can be minimized by prompt cooling and by maintaining sweet corn at 0°C (32°F). Under optimum storage conditions, the potential postharvest life of common sweet corn varieties is under 2 weeks (Brecht 2004). The recommended conditions for commercial storage of green beans are 5–7.5°C (41–46°F) with 95–100% RH (Cantwell 2004), with an expected storage life of 8–12 days. Though a fairly good quality can be maintained for a few days at temperatures below 5°C (41°F), the chances of chilling injury are higher at such temperatures. To reduce water loss, the use of waxed cartons and plastic fil liners is recommended. It is to be noted that the perishability and rate of water loss of immature beans are higher than for mature beans (Zong et al. 1992). Maintaining a cold chain is essential in ensuring bean quality as high temperature would cause dehydration and fungal growth on the produce and therefore affect its shelf life (ADC 2001).

The recommended controlled atmosphere (CA) storage conditions are 2–5% O_2 and

3–10% CO_2 for green beans (Cantwell 2004). The main benefi is retention of color and reduced discoloration and decay of damaged beans (Trail et al. 1992; Cano et al. 1997). There is limited research on CA storage of peas, with minimal benefit of this storage technology for peas (Suslow and Cantwell 1998). In sweet corn, reduced O_2 and elevated CO_2 reduce respiration and slow sucrose loss; elevated CO_2 also reduces decay and maintains green husk color (Aharoni et al. 1996; Brecht 2004). The use of CA storage for sweet corn is not very common, except in selected cases when sweet corn is shipped from the United States to Europe or Far East, which can involve transit time of about 2 weeks (Brecht 2004).

Peas are not sensitive to low temperature and should be stored as close to 0°C (32°F) as possible, but without freezing. Similarly, sweet corn is not chilling-sensitive and can be stored as cold as possible without freezing (Brecht 2004; Morris and Jobling 2004). Green beans are chilling-sensitive, with visual symptoms dependent on the storage temperature. At temperatures below 5°C (41°F), the typical symptom of chilling injury is a general opaque discoloration of the entire bean. A less common symptom is pitting on the surface accompanied by an increased water loss. At temperatures of 5–7.5°C (41–46°F), the most common symptom of chilling injury is the appearance of discrete rusty brown spots (Cantwell 2004). The susceptibility to chilling injury in sweet corn is variety-dependent (Watada and Morris 1966).

Proximate and Nutritional Composition

Peas, sweet corn, and green beans, like most vegetables, are a healthy food choice, being low in sugars and fat, and a fairly good source of dietary fibe . Table 30.3 shows proximate composition, and mineral and vitamin content of all these three vegetables. From the energy or calorie point of view, peas and sweet corn are comparable, whereas green beans have a much lower caloric value/100 g (31 kcal versus 81 kcal and 86 kcal from peas and sweet corn, respectively). Peas have more protein (5.42 g/100 g) than sweet corn (3.27 g/100 g) and green beans (1.83 g/100 g).

Potassium, phosphorus, and magnesium are the major minerals present in peas, sweet corn, and green beans. These three vegetables, especially peas and green beans, have very low sodium content, which is helpful to persons on a low-sodium diet. Peas, sweet corn, and green beans are not good sources of iron, zinc, copper, manganese, or selenium. Calcium, with its contents in the range of 2–37 mg/100 g, is another mineral low in all these vegetables.

Except for vitamin C, total folate, and vitamin A, peas, sweet corn, and green beans have very low content of other vitamins, namely thiamin, ribofl vin, niacin, pantothenic acid, and vitamin B-6. Among these three vegetables, peas have the highest content of vitamins. Beta-carotene contents of peas, sweet corn, and green beans are 449 μg/100 g, 47 μg/100 g, and 379 μg/100 g, respectively. Lutein and zeaxanthin (combined) range from 640 μg/100 g in green beans to 2,477 μg/100 g in peas.

Processing and Processed Products

Canning and freezing are the two most commonly used commercial methods of processing for peas, sweet corn, and green beans. Other products, such as purees from peas and green beans, are marketed as baby food or specialty applications.

Canning

Peas

Peas should be harvested at an optimum maturity for best-quality fina product. Harvest maturity, aside from pea size, is measured

Table 30.3 Proximate composition, and mineral and vitamin content of raw peas, sweet corn, and green beans (per 100 g)

	Units	Peas	Sweet corn	Green beans
Proximate				
Water	g	78.86	76.05	90.32
Energy	Kcal	81	86	31
Protein	g	5.42	3.27	1.83
Total lipid (fat)	g	0.4	1.35	0.22
Ash	g	0.87	0.62	0.66
Carbohydrate, by difference	g	14.45	18.7	6.97
Fiber, total dietary	g	5.1	2	2.7
Sugars, total	g	5.67	6.26	3.26
Minerals				
Calcium	mg	25	2	37
Iron	mg	1.47	0.52	1.03
Magnesium	mg	33	37	25
Phosphorus	mg	108	89	38
Potassium	mg	244	270	211
Sodium	mg	5	15	6
Zinc	mg	1.24	0.46	0.24
Copper	mg	0.176	0.054	0.069
Manganese	mg	0.41	0.163	0.216
Selenium	µg	1.8	0.6	0.6
Vitamins				
Vitamin C, total ascorbic acid	mg	40	6.8	12.2
Thiamin	mg	0.266	0.155	0.082
Ribofl vin	mg	0.132	0.055	0.104
Niacin	mg	2.09	1.77	0.734
Pantothenic acid	mg	0.104	0.717	0.225
Vitamin B-6	mg	0.169	0.093	0.141
Folate, total	µg	65	42	33
Choline, total	mg	28.4	23	15.3
Carotene, beta	µg	449	47	379
Vitamin A, IU	IU	765	187	690
Lutein + zeaxanthin	µg	2,477	644	640
Vitamin K (phylloquinone)	µg	24.8	0	14.4

Source: USDA-NAL 2009.

using a tenderometer, which registers the force necessary to shear a sample of the peas. This instrument has been in use for many years; some relatively newer developments are the electronic tenderometer and the texturemeter (Downing 1996).

A typical commercial pea canning process fl wchart is shown in Figure 30.2. After being received at the processing plant, peas are evaluated for quality. Fresh peas from trucks are emptied into multi-ton-capacity hoppers, from where they are conveyed by vacuum to a platform where they are cleaned by screen. Heavy-duty air blower removes fiel debris, pods, leaves, and stems. Peas are then conveyed into the plant to a second wash system that screens out dirt and rocks not originally caught. From this second screening, peas are flume to froth flotatio washers, which forces extraneous matter to the surface. After this wash, peas are hydro-pumped to graders that separate them into different sizes.

After cleaning, washing, and grading, peas are blanched to inactivate enzymes. The reel, auger, or belt-type hot water blanchers are commonly used for this process; two of these blanchers are shown in Figure 30.3. It is important to keep water temperatures above 170°F (77°C) at all times during the blanching

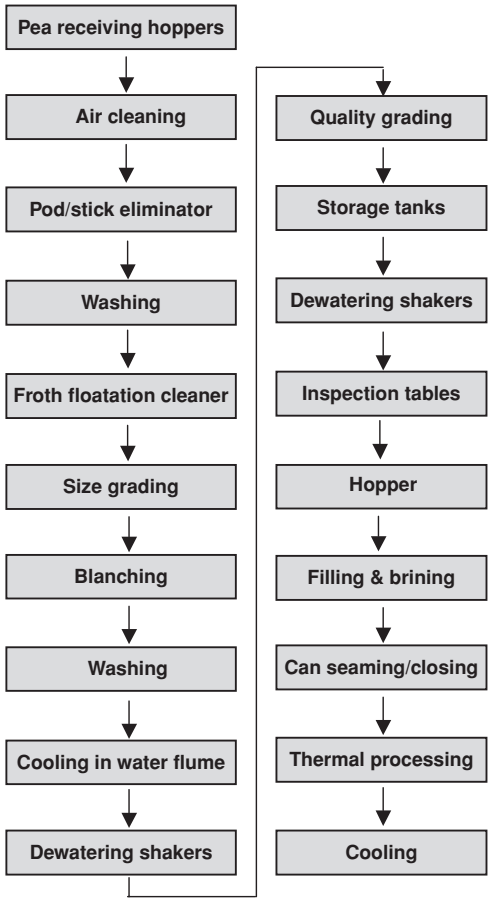

Figure 30.2 Flowchart of peas" canning process. (Adapted from Downing (1996).)

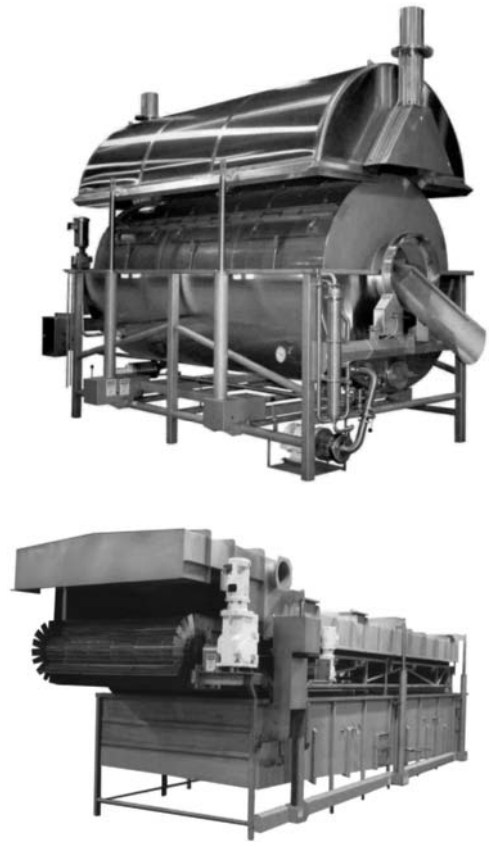

Figure 30.3 Continuous vegetable blanchers: rotary type, top; belt type, bottom. (Courtesy: Hughes Co, Inc., Columbus, Wisconsin, USA.)

operation. Steam blanching instead of hot water has been advocated to reduce the amount of soluble constituents that are removed (Downing 1996). The effectiveness of blanching process must be monitored closely. Many enzymes have been suggested as indicators of sufficien heat treatment for determining the adequacy of the blanching process; however, among various enzymes, peroxidase has been the most widely used indicator-enzyme for this purpose (Hemeda and Klein 1991; Akyol et al. 2006; Aguero et al. 2008). The peroxidase is known to be one of the most heat-stable enzymes in vegetables and its inactivation is indicative of proper blanching (Halpin and Lee 1987).

Blanched peas are hydro-pumped to a quality grader platform where they are separated based on maturity. In the dewatering unit of the quality grader, peas pass through a salt solution. Peas' higher weight and starch content, which are marks of maturity and lower quality, force the "second" or "extra" standard peas to sink, while those of better quality float After quality separation, peas are fille into cans, followed by addition of salt and sugar brine. There is a wide variation in the amount of sugar and salt used in the brine, but about 15 lbs (6.8 kg) of salt and 25 lbs (11.4 kg) of sugar per 100 gallons (378 liters) of water can be taken as an estimate for brine composition. After fillin the cans with required

minimum weight of peas and appropriate amount of brine (to leave average headspace), cans are exhausted to remove any gases. Exhausting is not necessary for small cans if the brine being added is at boiling temperatures. However, No. 10 cans should always be exhausted. After exhaustion, cans are sealed using high-volume automatic seamers. A closing temperature of 140°F (60°C) is usually sufficien to prevent buckling of cans processed at or above 240°F (116°C).

Thermal processing or retorting is done in still retorts, or more commonly in continuous retorts (cooker-coolers). Processing time is dependent on the process temperature, can size, and initial temperature of the cans. Table 30.4 shows the process time-temperature combinations based on these factors; these figure are for use in a still retort and given here as a general guide. After retorting, the cans must be immediately cooled to 95–105°F (35–41°C) by immersion in or a spray of cold water; this is necessary to minimize the danger of spoilage from the growth of thermophilic bacteria. After cooling, cans are dried, labeled, and cased for warehousing and shipment.

Sweet Corn and Green Beans

Many of the unit operations for canning of sweet corn and green beans are typical of most vegetables. Therefore, only pertinent information related to sweet corn and green beans is discussed.

Sweet corn may be canned as whole kernel or in a cream style. Whole kernel-style corn is usually packed from younger (less mature) ears than cream style. Only tender, freshly harvested corn in the milk stage should be selected for canning. The corn ears should be husked and the ears trimmed; Figures 30.4 and 30.5 show a corn husker and cutter or kernel remover, respectively. All traces of silk should be removed prior to washing the ears. Silking is performed as a separate operation by running the corn through a special machine, which rolls the ear rapidly between a pair of rollers and, at the same time, brushes it with fibe brushes as the ear advances. Sprays of water are introduced at the same time which wash away the silk and clean the ears. Corn coming from the washer on the way to the cutter is inspected on a moving belt. The imperfectly formed ears unfi for canning are

Table 30.4 Process times and temperatures for canning peas in still retort

Can size	Minimum fil weight oz. (g)	Minimum initial temperature* °F (°C)	Minutes at retort temperature of: 240°F (116°C)	245°F (118°C)	250°F (121°C)
211 × 304	5.9 (167)	70 (21)	31	20	13
		140 (60)	28	18	12
211 × 304	6.4 (181)	70 (21)	34	22	16
		140 (60)	30	20	13
303 × 406	11.0 (312)	70 (21)	39	27	20
		140 (60)	35	24	17
303 × 406	11.5 (326)	70 (21)	44	31	23
		140 (60)	38	26	19
303 × 406	13.5 (72)	70 (21)	65	52	43
		140 (60)	56	43	35
603 × 700	72.0 (2,041)	70 (21)	57	39	28
		140 (60)	48	31	21
603 × 700	76.0 (2,155)	70 (21)	66	45	32
		140 (60)	52	34	23

Source: Downing 1996.
*Minimum initial temperature is the average temperature of the contents of the coldest can in the retort at the time steam is turned on.

Figure 30.4 Sweet corn husker. (Courtesy: Hughes Co, Inc., Columbus, Wisconsin, USA.)

separated. The whole grain cutter makes a single cut, the depth of which is adjusted to the depth of the kernel in the corn being cut. This cut is deep enough to take most of the kernel without cutting into the cob (Downing 1996). The next step is blanching by which the whole kernel corn can be blanched either on the cob or after removal from the cob. The blanched corn is washed and fille into cans with brine and exhausted prior to sealing. Depending on the can size and the initial temperature, sealed cans are thermally processed at or above 240°F (116°C) for variable length of time. For example, for a 303 × 406 can (12-oz fil weight) at an initial temperature of 140°F (60°C), the processing time is 46, 31, and 22 minutes at 240°F (116°C), 245°F (118°C), and 250°F (121°C), respectively (Downing 1996). Immediately after retorting, the cans are cooled down to below 105°F (41°C).

The canning process for green beans is similar to that for sweet corn. The difference is that green beans are canned after cutting into the desired sizes. After arrival at the processing plant, the beans are washed and conveyed to size graders. This can be a revolving cylinder with slots of various diameters through which the beans fall onto conveyers. They are then taken to a snipping machine which cuts them into the desired size. Green beans washer and snipper are shown in Figure 30.6. This process also removes the tips and stems of the pods. Green beans of smaller sizes can be canned as whole beans. Those of longer dimensions are cut crosswise and canned as pieces. Figure 30.7 shows commercial cutting equipment that can be used for green

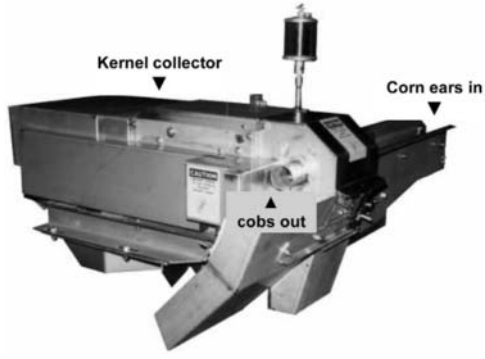

Figure 30.5 Sweet corn kernel separator/cutter. (Courtesy: Hughes Co, Inc., Columbus, Wisconsin, USA.)

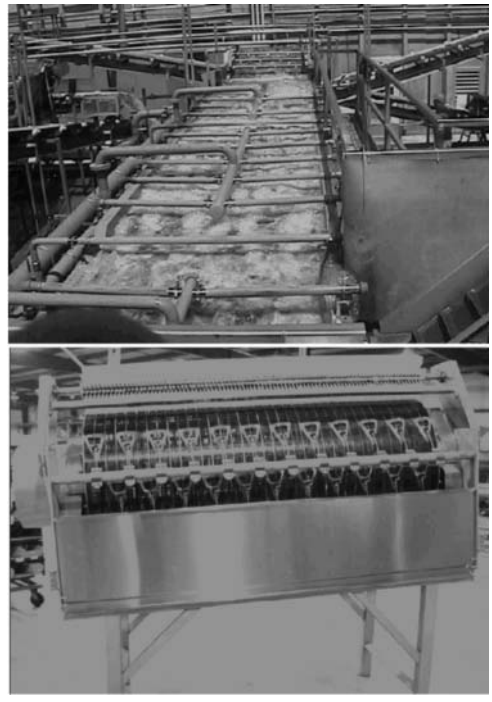

Figure 30.6 Green beans washing line (top) and stem snipper (bottom). (Courtesy: Lyco Manufacturing, Inc., Columbus, Wisconsin, USA.)

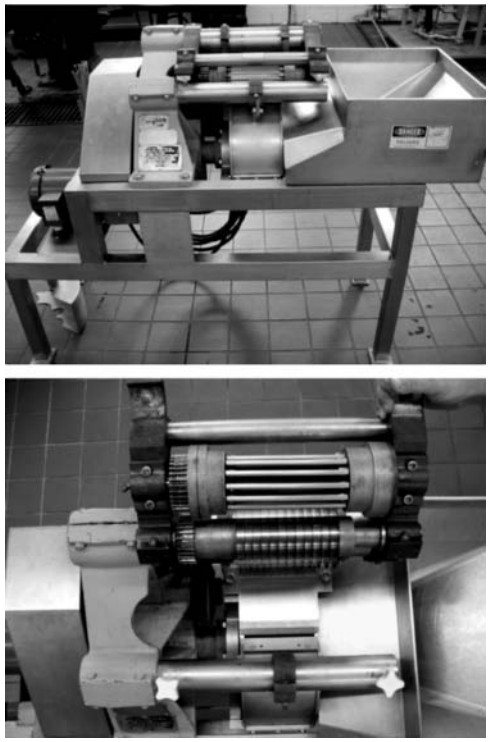

Figure 30.7 Cutting equipment (with safety guards removed) used for green bean cuts (top), a view of the blades of the equipment (bottom).

beans. Beans to be canned as French style are cut after being blanched. If beans were cut in this manner before being blanched, an objectionable amount of small cut pieces and dislodged bean seeds from the slit pods would accumulate in the blancher. Beans are most commonly blanched in continuous reel-type blanchers, such as those used for peas. The optimum blanching temperature to prevent sloughing of the skins is 170–180°F (77–82°C) for 3–5 minutes depending on the bean size (Downing 1996). Blanched beans are washed, graded, and fille into cans with brine and exhausted prior to sealing. At an initial temperature of 140°F (60°C) for a 303 × 406 can with 12-oz fil weight, the processing time is 36, 30, and 26 minutes at 240°F (116°C), 245°F (118°C), and 250°F (121°C), respectively (Downing 1996). Processed cans are cooled down to below 105°F (41°C) before labeling and casing.

Freezing

Many of the steps involved in the freezing of peas, sweet corn, and green beans prior to blanching (cleaning, washing, grading, cutting, and preparations) are the same as for the canning processing. The rest of the freezing process for each vegetable is briefl discussed here.

Peas must be frozen as soon as possible after the harvest. This is important because the quality starts to deteriorate soon after harvesting. The processors use variable blanching times; 1–2 minutes in 170°F (77°C) hot water is typical. The residual activity of peroxidase enzyme is used as an indicator of the effica y of the blanching process. Blanching at optimum conditions helps retain quality parameters such as ascorbic acid and chlorophyll pigments in a frozen storage up to 12 months (Gokmen et al. 2005). Blanched peas are cooled down rapidly in cold water flumes The grading procedure (floatation used is similar to that used for canning peas. Peas may be prepacked and frozen in cartons or they may be frozen as IQF (individually quick frozen) for packaging or bulk storage. Fluidized-bed technique is commonly used and has been very successful for freezing peas. In the fluidized-be IQF process, the freezing rates are so rapid that peas are brought down to an internal temperature of −18°F (0°C) in about 4 minutes (Dietrich et al. 1977).

For freezing processing, sweet corn is usually harvested while it is still young and tender, and kernels are at full "milk" stage. Freezing is an economical method of preserving sweet corn in its natural state. To maintain its optimum quality, the crop must be processed fairly quickly (within a few hours after harvesting). Several researchers have reported that frozen corn maintains high quality after being frozen within a few hours of harvesting

(Makhlouf et al. 1995; Li and Sun 2002; Jen 2009). This applies both to whole kernels and corn on the cob. Corn on the cob is a particularly difficul vegetable to freeze (Jen 2009). Prior to freezing, it is necessary to deactivate the enzymes by blanching. If the enzymes are not deactivated, they have the potential to break down the cell structure and produce oxidation reactions, off fl vors, and a loss in texture and nutrients. The blanching of whole kernel corn can be done either before they are removed from the cob or both before and after removal from the cob. Barrett et al. (2000) suggested that it is better to check blanching efficien y by testing for residual lipoxygenase activity than that of peroxidase, though the latter is used in the industry at present. These researchers reported that short blanch treatments targeting lipoxygenase inactivation positively affected color and texture of sweet corn. Whole kernels and corn on the cob should be frozen quickly once blanched and cleaned to ensure quality. They can then be packaged in plastic pouches made from low-density polyethylene, nylon, or in paperboard cartons lined with crystalline polypropylene. For whole kernel corn, IQF is the method of choice for freezing.

The process for freezing green beans is similar to that for peas and sweet corn. After blanching, green beans are frozen using IQF process. Although frozen storage is well known for its excellence in preserving vegetable quality, significan color and chlorophyll losses in green vegetables occur during storage. Color loss during frozen storage is attributed to the fading of the vivid green color of chlorophyll to an olive brown, characteristic of pheophytin (Schwartz and Von Elbe 1983; Heaton et al. 1996; Martins and Silva 2003); this phenomenon is known as pheophytization. Because pheophytization reaction rates are generally higher than other chlorophyll degradation pathways, it is considered an important mechanism of chlorophyll destruction during food processing (Martins and Silva 2004).

Other Processed Products

Purees

Peas and green beans are pureed and, most commonly, processed as baby food in glass jars. Pea puree is one of the natural ingredients used in baby food formulations. Blanching of puree is as important as the sterilization process to enhance the quality of baby foods. Enzyme inactivation and color improvement are the major objectives in blanching of purees. Long blanching time during water blanching of vegetables has adverse effects on the quality and yield of the product (Icier et al. 2006). Degradation of chlorophyll in processed puree is of concern (Shin and Bhowmik 1995; Canjura et al. 1999). Ryan-Stoneham and Tong (2000) studied the chlorophyll degradation of pea puree and reported that by adjusting (increasing) the pH of the puree, the loss of color can be minimized.

Fresh-Cut Products

Only sweet corn is marketed in fresh-cut form on a limited scale. Brecht (2004) reported that fresh-cut sweet corn kernels are extremely perishable due to their respiration rate being very high compared to that of intact ears. Therefore, temperature control, i.e., storage at low temperature, is extremely critical if the kernels are to have acceptable shelf life. Some of the problems encountered during handling include off fl vors, microbial survival or growth, and discoloration if the temperature is not maintained close to 0°C (32°F). Browning is another problem when the kernels are cooked; this browning is greater in kernels from more mature ears and is correlated with temperature, storage duration, and extent of physical damage (Brecht 2004).

Dehydrated Products

Peas, except for fiel peas, are grown for drying. Some early research has been reported on dehydrated green beans (Eheart and Sholes

1945; Schroeder 1962). Schroeder (1962), who patented a process for dehydration of vegetables, dehydrated green beans that had been cut into uniform size prior to dehydration; the dehydrated green beans had a moisture content of 2.41%. Bergman (1976) patented a process for producing blended vegetable products that included dehydrated green beans.

Effect of Processing on Nutrients

Processing of peas, sweet corn, and green peas affects their nutrient composition. Since canning and freezing preservation are the only two predominant commercial processes, this section covers the effects of these two processes on nutritional profil of processed peas, sweet corn, and green beans. With respect to minerals and vitamins, only those with significan contents are included in Tables 30.5–30.7.

Peas

The proximate composition and the nutrient profil of canned and frozen peas, in comparison to raw peas, are shown in Table 30.5. Both the canning and freezing processing have minimal effect on moisture content, caloric value, and protein, fat, carbohydrate, and dietary fibe contents. Canning process, in general, results in the significan loss of mineral content, most likely due to leaching or as a result of multiple washings prior to canning; freezing had minimal such effect on minerals. Canning also has a similar detrimental effect on most vitamins, whereas freezing has minimal effect on vitamins. Canned peas show a 60% loss of vitamin C; similarly, canning also results in a 68% and 49% loss in beta-carotenes and vitamin A, respectively.

Sweet Corn

The proximate composition and the nutrient profil of canned and frozen sweet corn, in

Table 30.5 Effect of processing on the nutritional composition of peas (per 100 g)

	Units	Raw	Canned*	Frozen
Proximate				
Water	g	78.86	81.7	79.98
Energy	kcal	81	69	77
Protein	g	5.42	4.42	5.22
Total lipid (fat)	g	0.4	0.35	0.4
Ash	g	0.87	0.97	0.78
Carbohydrate, by difference	g	14.45	12.58	13.62
Fiber, total dietary	g	5.1	4.1	4.5
Minerals				
Calcium	mg	25	20	22
Magnesium	mg	33	17	26
Phosphorus	mg	108	67	82
Potassium	mg	244	173	153
Sodium	mg	5	2	4
Vitamins				
Vitamin C, total ascorbic acid	mg	40	9.6	18
Folate, total	µg	65	44	53
Carotene, beta	µg	449	320	1,225
Vitamin A, IU	IU	765	533	2,058
Lutein + zeaxanthin	µg	2,477	1,350	2,352
Vitamin K (phylloquinone)	µg	24.8	21.4	27.9

Source: USDA-NAL 2009.
*No salt added, drained solids.

Table 30.6 Effect of processing on the nutritional composition of sweet corn (per 100 g)

			Canned		
	Units	Raw	Cream style*	Whole kernel†	Frozen
Proximate					
Water	g	76.05	78.73	76.71	75
Energy	kcal	86	72	81	88
Protein	g	3.27	1.74	2.64	3.02
Total lipid (fat)	g	1.35	0.42	0.93	0.78
Ash	g	0.62	0.98	0.92	0.48
Carbohydrate, by difference	g	18.7	18.13	18.8	20.71
Fiber, total dietary	g	2	1.2	1.9	2.1
Sugars, total	g	6.26	3.23	3.04	2.5
Minerals					
Calcium	mg	2	3	5	4
Magnesium	mg	37	17	15	18
Phosphorus	mg	89	51	48	70
Potassium	mg	270	134	135	213
Sodium	mg	15	3	298	3
Vitamins					
Vitamin C, total ascorbic acid	mg	6.8	4.6	0.7	6.4
Folate, total	µg	42	45	43	36
Carotene, beta	µg	47	30	22	49
Vitamin A, IU	IU	187	74	45	195
Lutein + zeaxanthin	µg	644	949	176	672

Source: USDA-NAL 2009.
*No salt added.
†Added salt, drained solids.

comparison to raw sweet corn, are shown in Table 30.6. Similar to peas, canning and freezing have minimal effect on moisture content, caloric value, and protein, fat, carbohydrate, and dietary fibe contents of sweet corn. Generally, canning process results in significan minerals loss, whereas freezing had no such effect. Canning also has a similar detrimental effect on most vitamins, whereas freezing has minimal such effect. Canning results in a 32% loss of vitamin C, whereas these losses are 35% for beta-carotene and 60% for vitamin A.

Green Beans

The proximate composition and the nutrient profil of canned and frozen green beans, in comparison to raw green beans, are shown in Table 30.7. As in the case of peas and green beans, canning and freezing have similar effects on nutrient changes in green beans. Vitamin C loss was 75% in canned green beans, while these losses were not as severe for beta-carotene and vitamin A, which were 29% and 30%, respectively.

Summary

Peas, sweet corn, and green beans are healthy and nutrient-rich vegetables. The shelf life of these vegetables, which is very short, can be significantl extended by canning and freezing. Each of these techniques can be used commercially and by domestic approaches. If done properly and the containers used are hermetically sealed, both approaches could produce safe and nutritious processed food with extended shelf life. Retorted corn, peas, and green beans could be packaged in metal cans, glass jars, or plastic containers. Because of the heat of the retort, if plastic containers are used, the material of choice for sealing them

Table 30.7 Effect of processing on the nutritional composition of green beans (per 100 g)

	Units	Raw	Canned*	Frozen
Proximate				
Water	g	90.32	93.3	89.93
Energy	kcal	31	20	39
Protein	g	1.83	1.15	1.79
Total lipid (fat)	g	0.22	0.1	0.21
Ash	g	0.66	0.95	0.53
Carbohydrate, by difference	g	6.97	4.5	7.54
Fiber, total dietary	g	2.7	1.9	2.6
Minerals				
Calcium	mg	37	26	42
Magnesium	mg	25	13	22
Phosphorus	mg	38	19	32
Potassium	mg	211	109	186
Sodium	mg	6	2	3
Vitamins				
Vitamin C, total ascorbic acid	mg	12.2	4.8	12.9
Folate, total	μg	33	32	15
Carotene, beta	μg	379	121	292
Vitamin A, IU	IU	690	353	547
Lutein + zeaxanthin	μg	640	441	663
Vitamin K (phylloquinone)	μg	14.4	38.8	44.8

Source: USDA-NAL 2009.
*No salt added, drained solids.

must be polypropylene. For extended shelf life in these plastic containers, high-barrier multilayer structures are used. Most of them tend to have aluminum foil within the structure as a barrier against moisture and oxygen. Frozen corn, peas, and green beans have been graining increasing acceptance by consumers in recent times. This is so because freezing results in less nutrient and sensory losses of the product when compared with canned vegetables.

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Chapter 31

Garlic and Onion: Production, Biochemistry, and Processing

Wieslaw Wiczkowski

Introduction

The *allium* is a large and an important genus of about 750 species belonging to the family of Alliaceae, which are widely distributed in nature (Fritsch and Friesen 2002). Onion (*Allium cepa*, Photograph 31.1) and garlic (*Allium sativum*, Photograph 31.2) are the two most important members cultivated from ancient times. These plants, which originated in Central Asia, have spread throughout the world due to trade and colonization (Hanelt 1990). Although existing in ancient Greece, India, and China, the firs mention of the practical application of these plants was in the Egyptian papyrus in 1550 BC (Block 1985). The bulbs of these plants are consumed as raw vegetables and as ingredients in food preparations. They have been also used for several health problems including heart, intestinal, and lung disorders as well as headaches and fever. The extracts of these plants have been used as an antiseptic (Farbman et al. 1993; Rivlin 2001).

The firs known scientifi research with allium was performed in the nineteenth century by Louis Pasteur who demonstrated the antibacterial properties of garlic. During the firs and second World Wars, allium extract was employed as a gangrene-preventive agent. Since then an intensive research on various aspects of onion and garlic has followed. This chapter reviews the production, nutritional and bioactive properties, biochemistry, and processing aspects of garlic and onion.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Production

Onion and garlic have large impact on the total production of vegetables due to their good storage properties and endurance during transport, and as a result they are traded more widely in comparison to other vegetables.

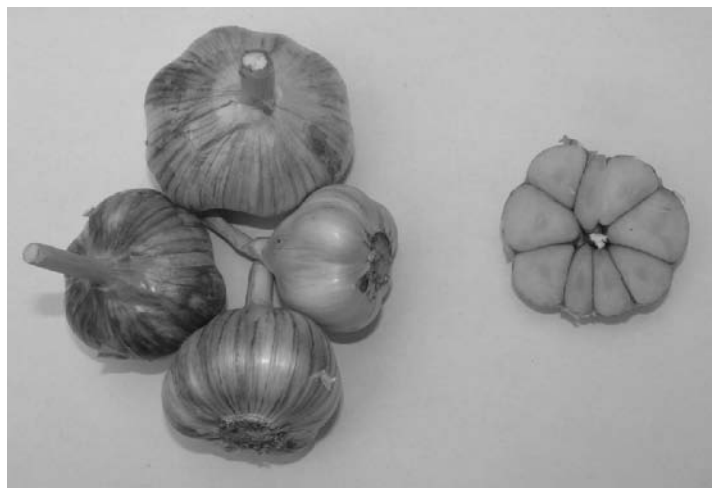
The common onion, although a biennial plant, is usually cultivated as an annual. In the firs year of growth, it produces a large edible underground storage bulb which consists of a swollen stem and several fles y leaves or scales (Photograph 31.1, Figure 31.1). The formation of the bulb is genetically controlled by a day-length response. After vernalization by winter cold, in spring this plant produces several tubular fl wer stalks with an umbel of hundred fl wers and each of these fl wers has the potential for generating up to six seeds. Onions can be grouped by color (yellow/brown, red, white), shape, dry matter content, and pungency. This vegetable can be also classifie on the basis of taste, from mild and sweet to very pungent.

Onion is the second most widely cultivated vegetable and is currently cultivated in more than 170 countries in the world. The production of this vegetable in 2007 was around 68 million tons (FAO 2009). Based on the average production from 2000 to 2007, the

Photograph 31.1 Bulbs of onion.

world's top producer of onion was China, contributing to 32% of the total production, followed by India (12%), the United States (5%), Turkey (4%), and Pakistan (3%). Onion production can be divided into three product areas: fresh bulbs for market, dehydrated onions as ingredient for food processing, and onions for essential oil production.

Garlic is a perennial plant, which can be cultivated as a biennial or an annual. This



Photograph 31.2 Bulbs of garlic.

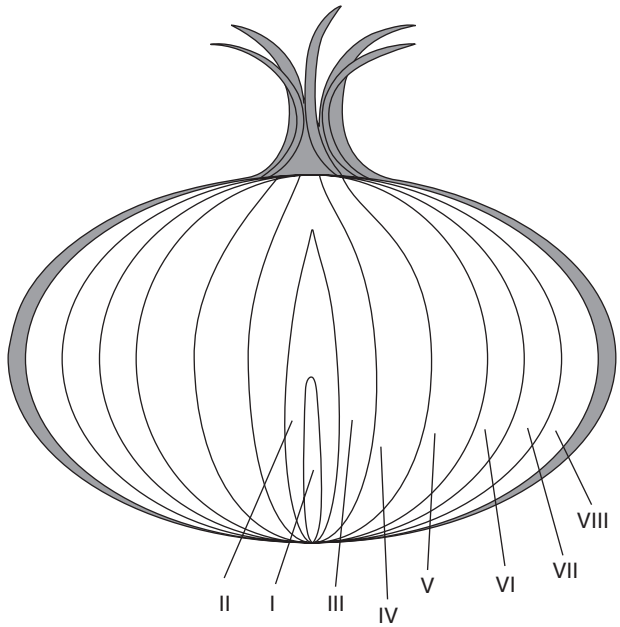


Figure 31.1 The diagram of onion fleshy scales arrangement in bulb. – I to VIII are the consecutive onion fleshy scales.

vegetable produces edible underground bulbs which consist of several storage cloves (Photograph 31.2). Garlic forms fl wer stalk with ostensible umbel of fl wers. Generally, this plant does not produce seeds. Garlic can be divided into two subspecies: hard-neck garlic and soft-neck garlic. The latter type is commonly used due to ease of cultivation and as it can be stored for longer period. This type of garlic has white papery skin and an abundance of cloves, often forming several layers around the central core. In comparison to soft-neck garlic, the hard-neck garlic has fewer, larger cloves. The hard-neck garlic may be purple, purple striped, or white. Moreover, this type of garlic has less outer bulb wrappers in comparison to the soft-neck.

The annual world production of garlic is over 15 million tons per year on a total surface area of 1 million hectare. Similar to onion production, world garlic output is still increasing. The leading garlic producer is China, accounting for 77% of world output, followed by India (4%), South Korea (2%), the Russian Federation (1.6%), and the United States (1.4%) (FAO 2009). Garlic production can be classifie into several groups: garlic for fresh market, dehydrated garlic as ingredient for food processing, and garlic for food supplement output (dehydrated powder, essential oil, oil macerate, powder, and aged garlic extract).

Consumption

Onion and garlic are commonly consumed vegetables and they can be found in a number of prescriptions in different traditions and cultures. The average annual per capita onion consumption in the world is approximately 7 kg. Among all countries, Libya has the highest average per capita onion consumption of 30 kg. In case of garlic, the highest consumption is noted in China and Korea. In Europe the highest consumption is in Spain and Turkey (approximately 1.5 kg per person per year). The average annual garlic consumption

in the United States is approximately 1.2 kg per person (FAO 2009).

Onion and garlic are of important culinary value because of their characteristic fl vor. These vegetables have also been recognized as important sources of valuable phytonutrients. Both are consumed as fresh and as additives (powdered spice) to many food products. There are many possible preparations of these plants. The bulbs can be boiled, baked, or fried. They are also preserved in the form of pickles. Usually onions with yellow/brown skin are used in domestic cooking, although red skin onions are favored in some parts of the world. The use of sweet onion with mild pungency is growing in popularity for direct consumption.

Nutrition and Bioactive Constituents

Cardiovascular diseases and various cancers are the main risk factors leading to deaths in industrialized countries. Epidemiological studies have shown that diets rich in fruits and vegetables are associated with diminished risk of diseases such as cardiovascular diseases, cancers, neurodegenerative diseases, diabetes, obesity, hypercholesterolemia, and disturbances of gastrointestinal tract (Reddy et al. 1993; Suzui et al. 1997; Lampe 1999; Moskaug et al. 2004; Wenzel et al. 2004; Prakash et al. 2007). Moreover, it has been shown that consumption of fruits and vegetables may slow the processes of aging. These preventive actions could be connected to the naturally occurring phytochemicals in fruits and vegetables (Hollman 2001). This has encouraged many health organizations and scientists around the world to recommend increased intake of fruits and vegetables to improve our health and lower risks of certain chronic diseases.

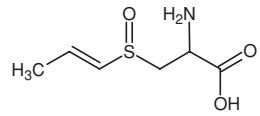
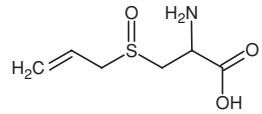
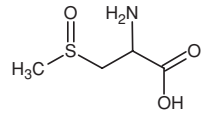
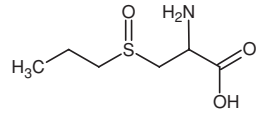
Onion and garlic consumption may be recommended not only for their unique fl vor and odor but also for health benefit (Corzo-Martinez et al. 2007). Studies have indicated that these vegetables are rich sources of health-promoting phytochemicals (Herrmann 1976; Hertog et al. 1992; Crozier et al. 1997; Griffith et al. 2002; Slimestad et al. 2007). Among them, organosulfur (Lanzotti 2006) and phenolic compounds (Wach et al. 2007) as well as carbohydrates (Jaime et al. 2001, 1998) are the main groups. Many studies have demonstrated various biological activities of these compounds (Banerjee and Maulik 2002; Benkeblia 2004; Manach et al. 2004; Rose et al. 2005; Corzo-Martinez et al. 2007; Singh et al. 2008). Although the exact mechanisms of their preventive effects are not fully known, it is suggested that organosulfur compounds and polyphenols can modulate the activity of several metabolizing enzymes, stimulate immune function, protect cells of liver, and act as antioxidants.

The whole bulbs of these plants are a good source of the (+)-*S*-alk(en)yl-L-cysteine sulfoxides and γ-glutamyl peptide which together cover over 70% of the total sulfur in these vegetables (Lawson 1996). There are four main nonvolatile and odorless alk(en)yl cysteine sulfoxides present in onion and garlic. These are *S*-allyl cysteine sulfuroxide (alliin), *S*-*trans*-prop-1-enyl cysteine sulfoxide (isoalliin), *S*-methyl cysteine sulfoxide (methiin), and *S*-propyl cysteine sulfoxide (propiin) (Table 31.1).

In garlic, the main fl vor precursor is alliin and its concentration is reported to be about 10 mg/g fresh weight (Lawson 1998; Yoo and Pike 1998). Methiin and isoalliin appear in lower concentrations while propiin is present in trace amounts.

In case of onion, the predominant fl vor precursor is isoalliin which covers more than 80% of the total amount of alk(en)yl cysteine sulfoxides. Similar to garlic, in onion methiin appears in lower concentrations while alliin and propiin are present in trace amounts (Jones et al. 2004). Generally, concentration of sulfur compounds in garlic is four-fold higher in comparison to onion (Yoo and Pike 1998).

Table 31.1 The main alk(en)yl cysteine sulfoxides present in onion and garlic

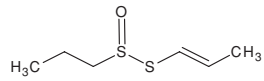
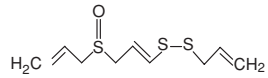
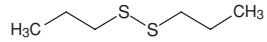
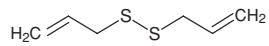
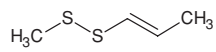
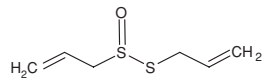
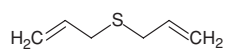
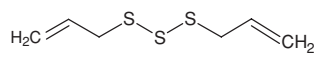
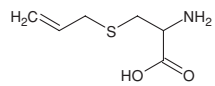
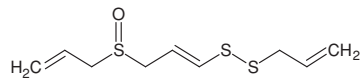
Name	Chemical structure	Characteristic plants
Isoalliin		Onion
Alliin		Garlic
Methiin		Onion, garlic
Propiin		Onion, garlic

During tissue destruction the alk(en)yl-L-cysteine sulfoxides are degraded by alliinase enzymes. This leads to the formation of new compounds such as alkyl alkanethiosulfinate which have an influenc on the characteristic odor and fl vor of alliums. These ingredients may be decomposed to other organosulfur compounds including propyl 1-propenyl thiosulfinate 1-propanethial-*S*-oxide, allicin, dipropyl disulfide diallyl sulfide diallyl disulfide diallyl trisulfide methyl propenyl disulfide and ajoene (Table 31.2). Simultaneously, γ-glutamyl cysteine are also converted to different organosulfur compounds including S-allyl cysteine and S-allyl mercaptocysteine (Block 1985).

Flavonoids are the second important group of allium compounds present in large amounts in onion; however, they are almost absent in garlic. Extracts of onion contain ferulic, gallic, and protocatechuic acids (Ly et al. 2005; Prakash et al. 2007). In four onion varieties (including red, violet, white, and green onions) the content of gallic and protocatechuic acids decreased from outer dry to fles y inner layers. There was more ferulic acid in the inner layers than outer layers of red, violet, and white onions.

Two representative groups of fl vonoids are found in onions. First, the anthocyanins responsible for red and purple color; second, the fl vonols that give the pigment for yellow/brown skin of onions. At least 25 fl vonols have been found in onion (Griffith et al. 2002; Slimestad et al. 2007). Among them, quercetin (3,3′,4′,5,7–pentahydroxy fl vone) is the major one. It covers more than 80% of the total content of fl vonoids in onion (Tsushida and Suzuki 1995; Rhodes and Price 1996; Price et al. 1997; Price and Rhodes 1997; Wiczkowski et al. 2003; Bonaccorsi et al. 2005; Galdon et al. 2008). Within the types of onions, the highest level of quercetin has been reported in fles y scales of yellow/brown onion (170–1,200 mg/kg fresh weight) and in red onion (190–1,900 mg/kg fresh weight), while lower levels of quercetin were found in white onion (50–650 mg/kg fresh weight) (Tsushida and Suzuki 1996; Crozier et al. 1997; Price et al. 1997; Price and Rhodes 1997; Lugasi and Hovari 2000) (Table 31.3). In case of quercetin profile onion

Table 31.2 The characteristic organosulfur compounds generated in processed onion and garlic

Name	Chemical structure	Characteristic plants
Propyl 1-propenyl thiosulfinat		Onion
1-propanethial-*S*-oxide		Onion
Dipropyl disulfid		Onion
Diallyl disulfid		Onion, garlic
Methyl propenyl disulfid		Onion
Allicin		Garlic
Diallyl sulfid		Garlic
Diallyl trisulfid		Garlic
S-allyl cysteine		Garlic
Ajoene		Garlic

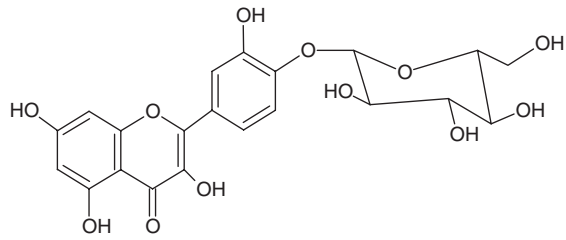
fles contains quercetin almost exclusively in the form of glycosides which constitute 99.3% of total quercetin. The quercetin-4′-glucosides and quercetin-3,4′-diglucoside are two main derivatives of quercetin (Figure 31.2). Minor quercetin compounds quercetin-3-glucosides, quercetin-7,4′-glucoside, quercetin-3,7,4′-triglucoside have been reported. With regard to quercetin aglycone, in the edible part of onion, this form of quercetin is reported to about 0.7% (Wiczkowski et al. 2003; Galdon et al. 2008). Over 50% of total quercetin in onion is concentrated in the two outer layers (Figure 31.1) (Patil and Pike 1995; Wiczkowski et al. 2003; Lee et al. 2008). Apart from quercetin, derivatives of kaempferol and isorhamnetin have been identifie in onion; however, these constituents are present in low concentrations (Herrmann 1976, 1988; Bilyk and Sapers 1985; Hertog et al. 1992; Park and Lee 1996; Sellappan and Akoh 2002; Bonaccorsi et al. 2005; Muminowa et al. 2006; Galdon et al. 2008).

High concentration of quercetin has been found in dry onion skin. This part of onion contains fi e-fold higher concentration of quercetin in comparison to the fles y scales (Patil and Pike 1995). Further, dry onion skin has a different configuratio of quercetin derivatives compared to fles y scales where as much as 53% of total quercetin is present in free form (Wiczkowski et al. 2003). This high amount of quercetin in the outer layers of onion bulbs is probably a consequence of exposure to sunlight (Hirota et al. 1998; Harborne and Williams 2000; Aherne and O'Brien 2002; Higashio et al. 2005; Lee et al. 2008). It is postulated that prevalence of the quercetin aglycone in the dry onion skin is

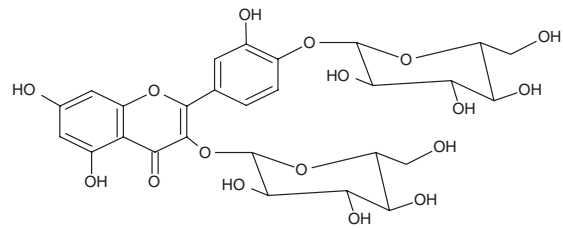
Table 31.3 Content of flavonoids in different types of onions (mg/kg fresh weigh)

Type of onion	Q4′Glu	Q3,4′Glu	Q3Glu	IR4′Glu	Q	Cy3(6″Mal)Glu	Cy3(6″Mal 3″Glu)Glu	Cy3Glu	References
Yellow/brown	100–1,300	50–655	6–9.3	1.7–29	1.5–4	x	x	x	Bonaccorsi et al. 2005
Red	233–924	290–1,025	17–37	41–59	0.1–9	10–130	4–55	3.5–45	Lachman et al. 2003; Lee et al. 2008; Lombard et al. 2005; Price and Rhode 1997; Price et al. 1997; Tsushida and Suzuki 1996; Slimestad et al. 2007
White	20–37	29–50	x	x	0.1–3	x	x	x	Wiczkowski et al. 2003

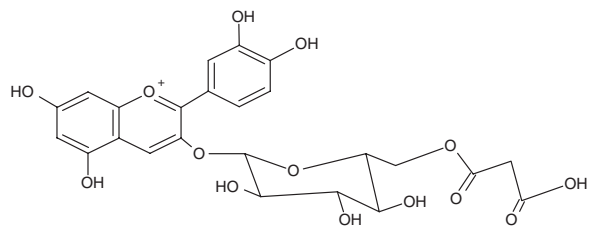
Q4′Glu, quercetin-4′glucoside; Q3,4′Glu, quercetin-3,4′-glucoside; Q3Glu, quercetin-3-glucoside; IR4′Glu, isorhamnetin-4′-glucoside; Q, quercetin; Cy3(6″Mal)Glu, cyanidin-3-(6″-malonyl)-glucoside; Cy3(6″Mal3″Glu)Glu, cyanidin-3-(6″-malonyl-3″-glucosyl)-glucoside; Cy3Glu, cyanidin -3-glucoside



Quercetin-4′-O-β-glucoside



Quercetin-3,4′-O-bis-β-glucoside



Cyanidin-3-O-β-(6′′-malonyl)-glucoside

Figure 31.2 The main flavonoids in onion.

probably connected with its protective function against UV-B, where it acts like a filte protecting the inner vegetative parts of onion (Hirota et al. 1998; Wiczkowski et al. 2003).

More than 20 derivatives of anthocyanins have been identifie in red onions (Slimestad et al. 2007). Cyanidin glucosides and acylated glucosides of cyanidin are the main anthocyanins of red onion. However, low concentration of peonidin, delphinidin, and petunidin derivatives has also been reported (Flueki 1971; Fossen et al. 1996; Donner et al. 1997; Wu and Prior 2005). Among them, cyanidin-3-(6″-malonyl)-glucoside (Figure 31.2), cyanidin-3-(6″-malonyl-3″-glucosyl)-glucoside, cyanidin-3-(3″-glucosyl)-glucoside, and cyanidin-3-glucoside are present in the highest concentration (Terahara et al. 1994; Ferreres et al. 1996; Fossen et al. 1996; Donner et al. 1997; Masuzaki et al. 2006). Moreover, cyanidin-3-(6″-malonyl)-glucoside represents more than 50% of the total anthocyanins content in different cultivates of red onion (Fossen et al. 1996). Generally, 20–250 mg of anthocyanins per kilogram of fresh weight of red onions have

been reported (Ferreres et al. 1996; Fossen et al. 1996; Rhodes and Price 1996; Slimestad et al. 2007) (Table 31.3). Anthocyanins cover about 10% of the total fl vonoid content of the red onions (Rhodes and Price 1996).

The beneficia health properties of fl vonoids seem to be related to the antioxidant activity of these compounds (Murota and Terao 2003). In vitro investigations have demonstrated that the antioxidant properties of fl vonoids are linked to their ability for scavenging free radicals, chelating metals, and inhibiting the activity of oxidases (Afanasev et al. 1989; Bors et al. 1990; Chen et al. 1990; Terao et al. 1994; Ioku et al. 1995; Terao and Piskula 1998). Flavonoids possess the ability to block the oxidative activity of systems with transition metal ions (Cu^{+}/Cu^{2+}, Fe^{2+}/Fe^{3+}) that play an essential role in the formation of reactive oxygen species during Fenton's reaction.

The antioxidant properties of fl vonoids result from their chemical structure: 3′,4′-o-dihydroxyl (catechol) system in the B ring, reciprocal configuratio of the double bond C2-C3 and the 4-carbonyl group of the C ring, and configuratio of the 3-hydroxyl group and the double bond C2-C3 of the C ring with the 5-hydroxyl group of the A ring (Bors et al. 1990; Manach et al. 1996; Cos et al. 1998; Terao and Piskula 1998; Rice-Evans 2000). All the mentioned structural conditions may be found in quercetin molecules which are abundant in onion, and in the in vitro systems efficientl scavenge hydroxyl radical (OH), superoxide radical (LOO), superoxide anion radical (O_2^{-}), singlet oxygen ($^1O_2$), and nitrogen oxide (NO).

Biochemistry of Main Compounds

Water is the predominant constituent of fresh onion (80–95%) and garlic (60–70%). Carbohydrates constitute about 65% and 80% of dry weights of onion and garlic, respectively. These vegetables also contain protein, lipids, calcium, potassium, magnesium, iron, silicon, amino acids, fibe , several vitamins, saponins, sulfur compounds, and polyphenols (Fenwick and Hanley 1985; Block et al. 1996).

The unique fl vor of onion and garlic is generated by chemical transformation of relatively stable, volatile, odorless sulfur compounds, S-alk(en)yl cysteine sulfoxides. These compounds have their origin in plant sulfur metabolism. The sulfate is utilized as the main source of sulfur for the biosynthesis of the amino acid cysteine and glutathione (Hasse et al. 2004). The sulfate is firs modifie to the 5-adenylsulfate, which is used by 5-adenylsulfate reductase to form sulfit prior to its conversion to sulfid by the sulfid reductase. After this process, cysteine is formed from the reaction of sulfid with *O*-acetylserine. Next, cysteine is rapidly directed into several metabolic pathways involved in protein synthesis as well as in others plant secondary metabolic pathways.

To date, two mechanisms of alk(en)yl-cysteine sulfoxide biosynthesis have been proposed (Lawson 1996) (Figure 31.3). According to the firs pathway, the biosynthesis of fl vor precursors, alk(en)yl-cysteine sulfoxide in onion and garlic proceeds via *S*-alk(en)ylation of the cysteine residue of glutathione, transpeptidation (to lose the glycyl group) followed by oxidation to cysteine sulfoxide, and removal of the glutamyl group to yield alk(en)yl-cysteine sulfoxides. The second pathway for biosynthesis of alk(en)yl-cysteine sulfoxide envisages direct alk(en)ylation of cysteine or thioalk(en)ylation of *O*-acetyl serine followed by oxidation to a sulfoxide (Block 1992; Jones et al. 2004; Rose et al. 2005).

Block (1992) suggested that sulfur compounds in onion and garlic are: (a) formed at room temperature after cutting, maceration, or homogenization of these plants; (b) degradation products generated from thiosulfinate at room temperature; and (c) oil ingredients

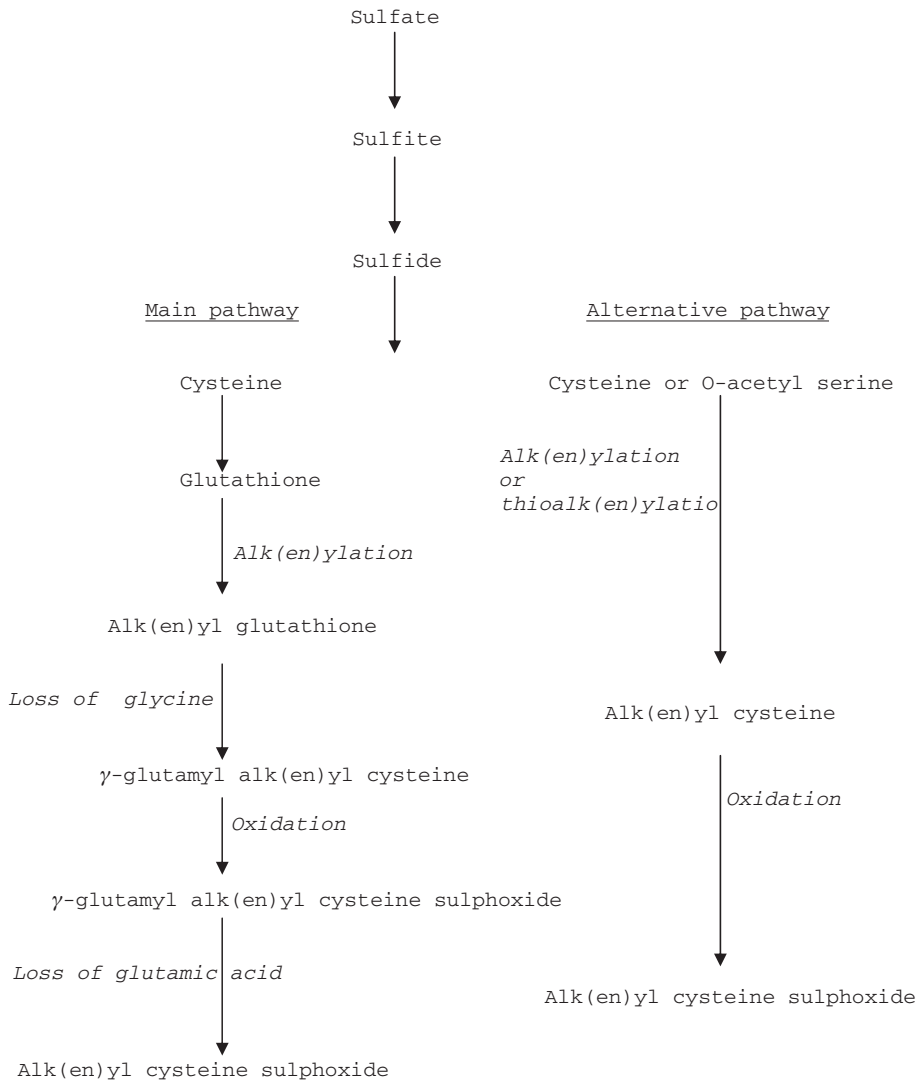


Figure 31.3 Biosynthesis of alk(en)yl cysteine sulfoxides.

created by vigorous preparation (e.g., steam distillation).

The enzyme alliinase (alliin alkyl-sulphe nate-lyase, EC 4.4.1.4) or lachrymatory-factor synthase play an important role in the production of the fl vor and odor of garlic and onion. In the intact tissues of these vegetables, alliinase and alk(en)yl cysteine sulfoxides are stored in separate cellular parts. In whole onion and garlic, alliinase is located in their vacuoles while the alk(en)yl-cysteine sulfoxides are positioned in the cytoplasm (Lancaster and Collin 1981). Upon tissue damage, the vacuole and cytoplasmic contents are mixed, promoting the enzymatic hydrolysis of the alk(en)yl-cysteine sulfoxides. As a result of this process, pyruvate, ammonia, and thiosulfinat or propanethial-*S*-oxide are generated (Block 1992; Imai et al. 2002). The concentration of generated

pyruvic acid is often used as a measurement of fl vor/pungency (Yoo and Pike 2001), although pyruvic acid itself does not contribute to the aroma. It has been widely used as an assay of volatile sulfur aroma because of its high correlation with aroma and its ease of determination (Randle and Bussard 1993).

The kinetics of alk(en)yl-cysteine sulfoxides hydrolysis and reactivity of sulfenic acids, the initial compounds of cleavage, determine the types of generated thiosulfinate (Rose et al. 2005). These chemicals can be divided into two groups: symmetrical thiosulfinate that originate from the combination of two sulfenic acid molecules sharing the same alk(en)yl group, and asymmetrical thiosulfi nates that are formed by combination of two different sulfenic acid molecules. In addition, Shen et al. (2002) reported that thiosulfinate can react with sulfenic acid, producing another species of thiosulfinates Moreover, the propanethial-*S*-oxide which is formed from isoalliin (the main alk(en)yl-cysteine sulfoxide in onion) causes the characteristic effect of lacrimation while cutting onions (Brodnitz and Pascale 1971). In conclusion, the thiosulfinate derived from the condensation of sulfenic acid together with pyruvate, ammonia, and propanethial-*S*-oxide constitute firs category of sulfur compounds generated in onion and garlic.

Furthermore, the thiosulfinate undergo others reactions including degradation or decomposition, resulting in a number of fl vor sulfur compounds. The mono-, di-, and trisulfide as second group of compounds are generated in onion and garlic. The occurrence of dipropyl disulfide methyl propyl disulfide 1-propenyl, propyl disulfide methyl 1-propenyl disulfide 1-propanethiol, dipropyl trisulfide and methyl propyl trisulfid as main sulfur compounds in chopped onion and garlic was found (Kallio and Salorinne 1990) (Table 31.2). Many of these compounds are formed during the thermal decomposition of thiosulfinat intermediates. Moreover, the reports of Jarvenpaa et al. (1998) indicated that chemical composition of onion and garlic volatiles changes dramatically with time. Also, the pH, temperature, samples preparation, and storage have influenc on reactivity and decomposition of thiosulfinate

The third group of sulfur substances is generated through steam distillation. During this process, essential oil is produced. Thiosulfide and disulfide formed during allium bulb cutting are thermally unstable; therefore, when the tissues of onion and garlic are heated to about 100°C, these compounds form polysulfid (Rose et al. 2005). Finally, the 1,2-epithiopropane, methyl allyl sulfide diallyl sulfide diallyl disulfide diallyl trisulfide and tetrahydro-2,5-dimethylthiophene are ingredients of distilled oil produced from onion and garlic (Yu et al. 1989; Rose et al. 2005) (Table 31.2).

The polyphenols are secondary metabolites in certain plants having diverse biological functions (Iwashina 2000; Winkel-Shirley 2001a, 2001b). Flavonoids are one of main groups of polyphenols widely distributed in the plant kingdom, including allium vegetables (Herrmann 1976, 1988). The structure of fl vonoids is based on a 2-phenyl-benzo-a-pyrone skeleton formed by two phenyl rings linked with a heterocyclic pyrone ring. The structure of diphenylpropene (fl van) may be distinguished in all fl vonoids. It is generated during condensation of three molecules of malonylo-CoA with 4-coumaroylo-CoA (Aoki et al. 2000; Aherne and O'Brien 2002) (Figure 31.4). The A ring is formed from three malonylo residues made during a metabolic pathway of glucose. The B ring is generated from 4-coumaroylo-CoA produced by the shikimic acid pathway from phenylalanine. During specifi synthesis, chalkone is formed. Next, under the influenc of chalkone isomerase, it is transformed into fl vanone. These compounds remain in equilibrium and constitute major substrates for a number of fl vonoids. Further transformations—hydroxylation, dehydrogenation, and reduction, mediated by

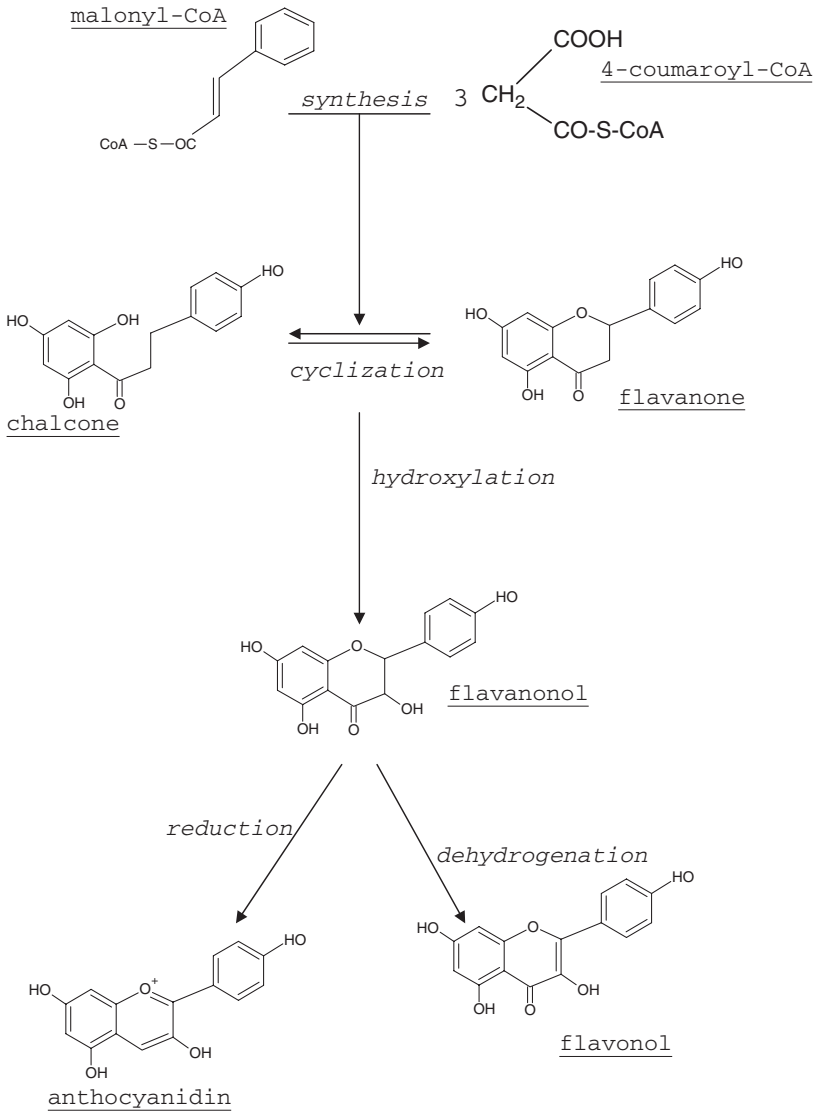


Figure 31.4 Biosynthesis of onion flavonoids.

specifi enzymes (hydroxylases, dehydrogenases, reductases)—result in the formation of representatives of the particular fl vonoid classes of onion.

Processing and Major Processed Products

Onion and garlic are used for direct consumption, cooking, food service, and food processing. These vegetables are also used by the pharmaceutical industry for dietary supplement production. Several factors can affect the quality of raw material and products, including cultivation, agro-technical and weather conditions during maturation, harvest, curing, skin integrity, storage, and processing. The cultivars of onion and garlic are characterized by different potential for direct consumption and food processing and

storage. The application of fertilizers has an influenc on onion and garlic storage. Generally, storage life of these vegetables is reduced by a high level of nitrogen fertilizers (Batal et al. 1994). Although fl vor potential of these plants is genetically determined, the use of sulfur as a fertilizer may help in the development of pungent fl vors (Randle 1997). Sulfur also affects the quality of onion bulbs (Lancaster et al. 2001). Pungency of garlic and onion is also affected by cultivars, temperature during the growing season, form of nitrogen, and the plant maturity at harvest (Randle 1992, 1997; Randle and Bussard 1993; Randle et al. 1994; Hamilto et al. 1997; Kopsell and Randle 1997; Horbowicz 1998; Kopsell et al. 1999). The conditions of growth and harvest can also influenc fl vonoid content (Horbowicz 1999; Mogren et al. 2006)

Postharvest quality of garlic and onion bulbs is affected by the fiel temperature. In general, hot dry weather at the end of the season speeds up leaf drying and allows harvesting of bulbs with improved storability. Maintenance of skin integrity, firmness color, and fl vors of onions and garlic is important during curing and for storage. Respiration, resumption of growth, pathological breakdown, and physiological damage are the biological factors involved in lowering the quality of these vegetables. The pungency and fla vor can be affected by the type of storage (Uddin and MacTavish 2003). Therefore, careful handling and the choice of a suitable storage method for the cultivar type are vital to ensure that the product retains its quality until utilized (Batal et al. 1994; Adam et al. 2000). Under refrigerated and controlled atmosphere storage, onions can be stored for up to 9 months (Smittle 1988). Fresh garlic can be stored for up to 3 months from the time of harvest in standard warehouse, up to 6 months in cold storage, and up to a year in a controlled atmosphere facility.

The degree of changes in concentration and composition of phytochemicals of onion and garlic during processing depends on processing methods (Breene 1994). Peeling, cutting or chopping, boiling, baking, and frying are common to domestic preparations of onion and garlic. These treatments make essential changes in concentration of their native compounds and structure. As described before, during these treatments the sulfur compounds are degraded and decomposed to new constituents responsible for the characteristic fl vor and aroma of these plants. Next, heat processes have led to formation of subsequent groups of sulfur compounds which are relatively tolerant to high temperature. Shen et al. (2002) showed that the half life of sulfur compounds at 80°C and pH 4.5 was 0.8–10 hours, depending on the type of these substances. During tissue destruction and thermal treatment, aglycones of polyphenols are released from their conjugated form, improving bioavailability of these compounds (Manach et al. 2004; Manach et al. 2005; Williamson and Manach 2005).

Home processing of onion and garlic can lead to decrease in quality of these vegetables through undesirable discoloration. In the case of onion, pink or red color is generated, whereas garlic products may turn green, blue-green, blue (Kubec et al. 2004, 2007; Toivonen and Brummell 2008). The role of isoalliin in color changes of these vegetables is suggested (Shannon et al. 1967; Lukes 1986; Kubec et al. 2004).

In the United States frozen onions constitute around 10% of all onions consumed (Griffith et al. 2002).

The major processes used for the formation of onion and garlic products are: drying, distillation, maceration in oil, hydro-alcoholic short extraction, and hydro-alcoholic long maceration (Staba et al. 2001). The hot air drying, in which onion and garlic are exposed to a blast of hot air (vertical bin dryer, fluidize bed dryer, and tunnel dryer), and freeze-drying, in which frozen bulbs of these vegetables are placed in a vacuum chamber to remove the water, can be used. Drying system and conditions significantl influenc the quality of the fina products. Generally, freeze-drying produces high-quality products

by retaining active phytochemicals. However, this type of food preservation is expensive.

Different kinds of dried onions and garlic are commercially available, including minced, chopped, powdered, granulated, sliced, fla ed, and toasted (Lee et al. 2008). Dried garlic and onions are widely used in the food industry in manufactured soups, ketchups, sauces, dressings, mayonnaises, sausages, meat products, potato chips, and crackers. They can also be added to pre-prepared foods.

Although blanching is a common operation used in vegetable processing, often this step is omitted in the processing of garlic and onion because it affects the characteristic allium fl vor. The fl vor, odor, and color are influence by drying temperature and time as well as storage (Pezzutti and Crapiste 1997; Adam et al. 2000). Nonenzymatic browning can occur during the drying process. The browning is affected by the temperature of drying and the moisture of the product. In vegetable drying, the choice of temperature to use is often a compromise between effi ciency of process, energy cost, and product quality. It was shown that drying temperature above 65°C significantl decreased the quality of dried onion by changing its color (Adam et al. 2000). To reduce the heat energy required during drying, onion varieties with higher dry matter content can be used (Griffith et al. 2002).

Studies have shown that fl vonols and anthocyanins are relatively stable during cooking and storage as compared to sulfur compounds. However, onion stored for 24 weeks at 4°C lost about 30% of the native quercetin content (Price et al. 1997). Generally, some processing treatments of the plant material may reduce fl vonoids by 50%. The major treatments affecting fl vonoids include peeling, cutting, and shredding (Peterson and Dwyer 1998; Aherne and O'Brien 2002). During peeling, red onions lost approximately 20% of the initial quercetin-4′-glucoside and as much as 70% of the anthocyanins (Gennaro et al. 2002). Up to 40% loss of quercetin due to mechanical peeling of onion has been reported (Ewald et al. 1999). The quercetin-3,4′-glucoside was rapidly degraded in macerated onion tissues with a 50% loss after 5 hours resulting in the production of quercetin monoglycoside and aglycone (Price and Rhodes 1997). This phenomenon can be explained by the activity of onion glucosides which are released during tissues damage (Tsushida and Suzuki 1996). The transformation and also degradation of quercetin compounds are observed during onion roasting at 180°C (Rohn et al. 2007). Of all processes involved in food preparation, cooking is reported to be responsible for most of the losses of polyphenols (Faller and Fialho 2009; Gorinstein et al. 2009). Decrease in fl vonoids content is caused by boiling water which leaches these compounds from plant matrix (Hirota et al. 1998). The total decrease in fl vonoid content of a product may reach 75%, although approximately 30–40% of these lost compounds may pass to liquid (Nemeth et al. 2003). A similar phenomenon was observed during microwave cooking of onion in water when 60% losses were linked to leaching of compounds (Crozier et al. 1997). On the contrary, microwave heating without added water resulted in increase in total content of quercetin, probably due to better extractability (Ioku et al. 2001; Patil 2004). Onion sautéed for 5 minutes and baked for 15 minutes at above 150°C resulted in increase in quercetin glucosides concentration by 25% and 7%, respectively, as compared to raw onion (Lombard et al. 2005). The lowest losses (∼20%) have been reported to occur during frying of onions (Aherne and O'Brien 2002). The total fl vonoid content of onion did not change during frying with oil and butter for 40 minutes (Ioku et al. 2001).

Onion and garlic products that contain the safe, effective, stable, and odorless components are valuable as dietary supplements. Various powder pills and oil pills of onion and garlic are commonly available. Among

them, one of the most popular garlic preparations in the market is the aged garlic extract. It is obtained by storage at room temperature of sliced garlic soaked in a water/ethanol mixture for longer than 10 months (Amagase 2006). Other popular supplements, essential oil extracts are manufactured by steam distillation and have been considered as natural preservatives or food additives.

Conclusion

As reviewed here, onion and garlic possess unique fl vor and phytochemical properties, and have a special place in our diet. Further developments in chemistry, extraction, and processing methods can yield new onion and garlic products with specifi composition and health-promoting properties.

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Chapter 32

Edible Mushrooms: Production, Processing, and Quality

Ramasamy Ravi and Muhammad Siddiq

Introduction

The word "mushroom" is derived from the Gallo-Roman *mussiro* which evolved to *mussereroun* in Middle English (Flippone 2009). All mushrooms are placed in a division called "Eumycota," meaning "The True Fungi." The mushrooms are not plants, as they lack chlorophyll; however, researchers typically classify them as plants under the vegetable category. Mushrooms are a unique food because they can convert inedible plant wastes into palatable food with characteristic texture and fl vor. The production and utilization of edible mushrooms can be an important area to increase consumption of nutritive foods.

Mushrooms are healthy vegetables, low in calories and fat. The protein content of mushroom is relatively higher than most vegetables, and the amino acid profil of the mushroom protein is comparable to the animal proteins (Danell and Eaker 1992). Mushrooms are also a good source of vitamin C, B vitamins, and minerals. They are the only non–animal-based food containing vitamin D, and thus a natural source of vitamin D for vegetarians (Mattila et al. 2000). Manzi and Pizzoferrato (2000) reported that most edible fungi are rich in nonstarch polysaccharides, and β-glucans that are a good source of soluble and insoluble dietary fibe for humans. Many varieties of edible mushrooms are available throughout the year. The dried mushrooms are intensely concentrated in fl vor and can be used as a seasoning item. This chapter discusses production, postharvest storage, processing, and nutritional aspects of edible mushrooms.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Mushroom Production and Consumption Trends

The production figure for leading countries are given in Table 32.1. China (46.3%) and the United States (10.5%) account for more than one-half of the world production. The world production of mushrooms over the last few decades has shown a phenomenal growth. From 1980 to 2000, world production more than doubled from 1,103,804 metric tons (MT) to 2,588,568 MT. During the current decade, up to 2008 (the year for which latest data are available), world production of mushrooms has increased by another 25%, reaching 3,475,116 MT (FAOSTAT 2009). Of the top ten species cultivated worldwide, the following six made up about 92% of the total share: *Agaricus bisporus*, *Lentinus edodes*, *Pleurotus* spp., *Auricularia auricula*, *Flammulina velutipes*, and *Volvariella volvaceae* (Chang 1999).

While the white button mushroom (*Agaricus bisporus*) still retains the highest overall world production, its relative contribution is decreasing due to the dramatic increased production of other species, *Lentinus* and

Table 32.1 Major mushroom producing countries of the world*

Country	Production (metric tons)†			
	1980	1990	2000	2008
China	271,159	363,645	808,231	1,608,219
United States	213,200	324,315	383,830	363,560
The Netherlands	60,000	147,000	265,000	240,000
Poland	26,000	104,000	100,000	180,000
France	152,224	195,700	203,811	150,450
Spain	33,314	74,479	63,254	140,000
Italy	41,500	79,381	72,492	100,000
Canada	29,264	52,240	80,241	86,946
Ireland	6,000	37,000	59,800	75,000
Japan	79,900	79,100	67,224	67,000
Indonesia	300	7,500	28,000	61,349
Germany	47,373	50,200	62,000	50,000
World Total‡	*1,103,804*	*1,773,663*	*2,588,568*	*3,475,116*

Source: FAOSTAT 2009.
*Countries ranked by 2008 figures
†Includes truffles
‡Including all other countries.

Pleurotus in particular. In 1981, *Agaricus* production represented 72% of world production but by 1997 this had dropped to 32%. Overall, the world production of mushrooms is increasingly being dominated by species that are both edible and have medicinal properties.

The per capita consumption of mushrooms in the United States grew over threefold, from 1.26 pounds in 1970 to about 4 pounds in 2007 (Figure 32.1); a major portion of this growth has resulted from a significan increase in the consumption of fresh mushrooms, from about 0.26 pounds to

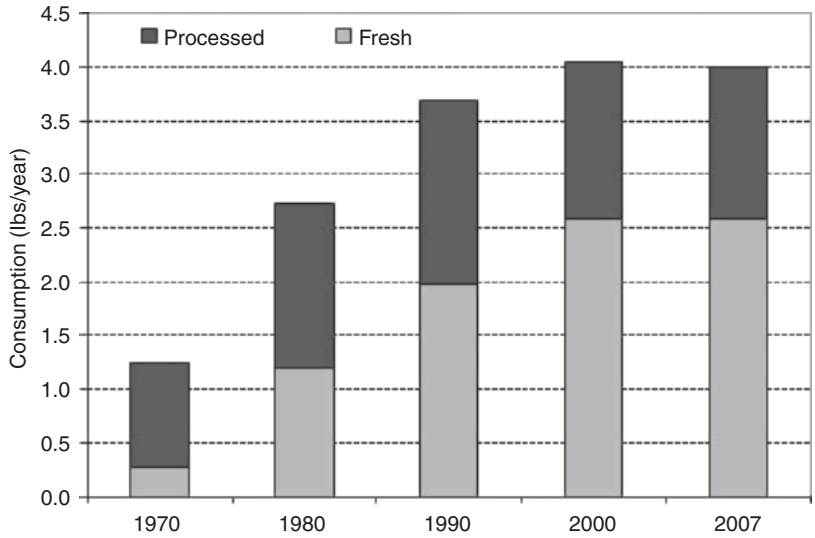

Figure 32.1 Growth in the consumption of mushrooms in the United States. (Adapted from USDA-ERS (2009).)

Table 32.2 Some common mushrooms varieties with their scientific names

Common name	Scientifi name
White or button	*Agaricus bisporus*
Shiitake	*Lentinula edodes*
Oyster	*Pleurotus ostreatus*
Chanterelles	*Chanterelles cibarius*
	Chanterelles subalbidus
	Chanterelles formosus
Porcini	*Boletus edulis*
Enoki	*Flammulina callistosporioides*
	Flammulina elastica
	Flammulina fennae
Morel	*Morchella esculenta*

over 3 pounds in the same time period. The amount of processed mushrooms consumed has stayed fairly unchanged during the last three decades (USDA-ERS 2009).

Mushroom Varieties

Mushrooms can grow under various ecological conditions from desert to forest. Mushrooms belong to the fungi family subdivision of *Basidiomycotina*, of the class *Hymenomycetes*. They comprise a large heterogeneous group with wide variations in their color, shape, size, texture, and fl vor. There are over 38,000 mushroom varieties. Some are edible and some are highly toxic. Some common mushrooms and their scientifi names are given in Table 32.2. Figure 32.2 shows images of selected edible mushrooms. Among the cultivated mushrooms, *Agaricus bisporus* is the most important species. They are divided into several groups depending on the structure of their fruiting bodies and various other macro- and microscopic characteristics. Some popular mushroom varieties are described below (Anon 2009; TMC 2009).

Agaricus (White or Button)

Mildly fl vored white mushrooms are delicious when eaten raw but even more fla vorful when cooked. This is the most common prepackaged variety available in fresh, canned, or frozen forms in supermarkets.

Shiitake

Shiitake mushrooms were originally cultivated on natural oak logs and only grown in Japan. These mushrooms are large, black-brown, and have a rich earthy fl vor. This mushroom is enjoyed in stir-fried form, in soups, or even as a meat substitute. Dried shiitakes have more intense fl vor and are sometimes preferable to fresh.

Oyster or Pleurotus

Oyster mushrooms grow in clusters and their color varies from off-white to brown. They taste like oyster slightly but have a chewy

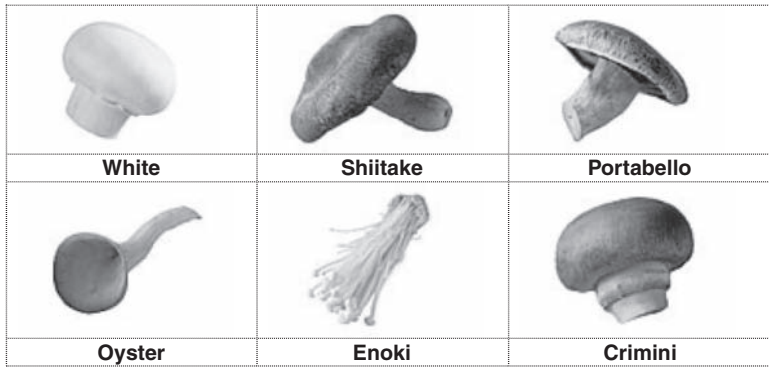

Figure 32.2 Some common types of mushrooms.

texture, which is more suitable for making cooked dishes.

Chanterelles

They are trumpet-shaped and are highly regarded mushrooms favored for their gold to yellow color, and are also rich in fl vor, ranging from apricot to earthier tasting. These mushrooms are available in dried or canned forms.

Porcini

This category of mushrooms varies in size and is grown in parts of East Asia and Europe. Porcini mushrooms are popular and valued for their meaty texture and fl vor.

Enoki

Enoki mushrooms originated from Japan. They are sprout-like with small caps, have thin and long stems, are white in color, and have a light fruity taste. These mushrooms are excellent when served raw, in soups, or salads.

Morel

These conical-shaped, honey-combed surface fungi are small, with dark brown hues. This variety is better for stuffin and is highly suitable for making sauces and stews. They are most expensive because of their unique intense earthly fl vor. This is the most commonly found variety in the wild, although these are now grown commercially.

Crimini

Crimini or, as they are commonly referred to, "Italian brown mushrooms" have a dark cap that can range in color from light tan to rich or dark brown. A big, round, fles y cap and a short stalk characterize crimini mushrooms. As compared to *Agaricus*, crimini mushrooms have a more intense fl vor.

Generally, all edible mushrooms are firm moisture-free (not dry), have unblemished caps, and are free from any mold growths. Commercial mushrooms available in airtight plastic bags tend to retain moisture, which can sometimes accelerate the spoilage. Properly stored mushrooms typically have a shelf life of 5–10 days, depending on the variety and the method of postharvest storage. Mushrooms are versatile and may be eaten raw or cooked whole, sliced, or chopped. The stems of certain varieties like shiitake and portabella can be used as a fl voring agent.

Poisonous Mushrooms

The poisonous species are relatively smaller in number, and among those only fewer are found deadly. There are no general rules or guidelines available for differentiating edible mushroom from poisonous species of mushrooms. Identificatio of mushroom at generic level is inadequate, since even within a given genus (e.g., *Lepiota*) some species are edible while others are highly poisonous. Several species of *Amanita* produce poisonous compound *amatoxin*, which is not destroyed by cooking/boiling or during processing. The following species are highly poisonous: *Amanita phalloides*, *A. pantherina*, *Amanita muscaria*, *Inocybe patiouillardii*, *Cortinarius speciosissimus*, *Cortinarius orellanus*, *Ntoloma sinuatum*, *Lepiota morgani*, and *Agaricus xanthodermus*. Reports of mushroom poison may also be due to secondary infection by bacteria and mold.

GAPs, Harvesting Quality, and Grades

The Mushroom Good Agricultural Practices (MGAP) program provides a set of standards and procedures that mushroom growers can use to maximize their production in an effi cient manner (AMI 2009). The MGAP standards are consistent with current food safety

guidelines for the fresh produce industry described in the Food and Drug Administration (FDA 2008) document, *Guidance for Industry Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables*. The MGAP has the following six principles for producing, handling, and marketing mushrooms: (1) Prevention of food safety hazards is favored over reliance on corrective actions after a problem has occurred; (2) Mushrooms can become contaminated at any point between rinsing and shipping; (3) The use of animal products in substrate, casing, or supplement preparation should be managed carefully to minimize the potential for microbial contamination of mushrooms; (4) Worker hygiene and fiel sanitation practices play a critical role in minimizing the potential for microbial contamination of mushrooms; and (6) Water has the potential to be a source of contamination during mushroom growing and subsequent handling.

Harvesting criteria for commercially grown mushrooms is based on maturity indices and not on cap size. Optimum maturity is reached when the caps are well rounded and full or at least the partial veil is completely intact. Other considerations are freedom from open veils, disease, spots, insect injury, and decay. Thus, a uniform, well-rounded cap with smooth glossy surface and fully intact veil are indicators of high quality. The cap color should be white or dark brown (for non-white varieties) and the stipe or "stem" should have a small length-to-thickness ratio but still sufficien enough to permit some trimming without cutting caps (Adamiski 2004).

In order to remove fiel heat and slow down respiration, mushrooms should be cooled to 2–4°C immediately after harvest. Two commonly used methods of cooling are hydro-cooling and forced-air cooling. Trimming mushrooms is a common practice before packaging for the fresh market. Mushrooms are packed in trays or cartons with a perforated polyethylene fil over-wrap (Suslow and Cantwell 1998; Adamiski 2004).

For fresh mushrooms, the US grades are *US No. 1* and *US No. 2* (USDA-AMS 1997). The *US No. 1* consists of fresh mushrooms of similar varietal characteristics which are mature, at least fairly well-shaped, well-trimmed, free from open veils, disease, spots, insect injury, and decay, and from damage by any cause. For *US No. 2*, the requirements are the same as *US No. 1*, except for greater tolerances for open veils and defects. The size of mushrooms is specifie in terms of diameter, and unless otherwise specified must meet the requirements of one of the following size classifications Small to medium—up to 1–5/8 inches (4.13 cm) diameter; and large—over 1–5/8 inches (4.13 cm) in diameter. Other considerations in determining grades are optimum maturity, uniform shape, trim quality, and overall cleanliness.

Postharvest Physiology and Storage

It is recommended to store mushrooms at low temperatures not only to maintain sensory quality but also to reduce continued development of mushrooms that can occur even after harvesting. If not stored properly, upward bending of caps and opening of the veil can occur. Being very delicate, mushrooms tend to bruise easily and can develop brown discoloration easily. During extended storage at elevated temperatures, bacterial blotch by *Pseudomonas* spp. can become a potential problem. Unlike many other vegetables, mushrooms generally are not susceptible to chilling injury (Suslow and Cantwell 1998; Adamiski 2004).

Mushrooms are a high-respiring commodity; respiration rate at 0°C is 28–44 mg CO_2 /kg.hr, which can reach as high as 240–288 mg CO_2 /kg.hr at 15–20°C. Mushrooms keep good quality for 7–9 days if held at 0–1°C with 95% relative humidity (RH). The shelf life shortens to 3–5 days at storage temperature of 2°C; elevated storage temperature accelerates surface browning, stipe

elongation, and veil opening. High RH is essential to prevent desiccation and loss of glossiness. Moisture loss in mushrooms has been correlated with stipe blackening and veil opening. There has been little success in extending shelf life using chemical treatments (Umiecka 1986; Adamiski 2004). Effects of storage temperature on the microbiological and sensory properties of minimally processed shiitake mushrooms were investigated by Castro et al. (2008). The shelf life of minimally processed shiitake mushrooms was 10 days at 7°C, but approximately 3 days at 15°C.

The use of controlled atmosphere (CA) storage under 3–21% O_2 and 5–15% CO_2 conditions can deliver a moderate benefi in extending shelf life. Storage under low O_2 and high CO_2 inhibits cap opening and internal tissue browning, but can cause yellowing of the cap surface. At O_2 levels of <1%, conditions become favorable for the growth of *Clostridium botulinum*. Additionally, the development of off-odor and off-fl vor, as well as cap opening and stipe elongation can occur. Due to these reasons, CA is not commonly recommended for mushrooms (Saltveit 1997; Adamiski 2004).

Antmann et al. (2008) used modifie atmosphere packaging of shiitake mushrooms, which were packaged under air in two macroperforated packages and under two gas mixtures (15% and 25% O_2) in polyethylene packages, and stored at 5°C for 18 days. The shelf life of mushrooms packaged in macroperforated packages was limited by the deterioration of sensory attributes, particularly by changes in the color and uniformity of their gills. They reported that mushrooms could be stored up to 10 days with a weight loss of lower than 2%. Their results showed that during the firs 6 days of storage, all the evaluated packaging conditions were useful for reducing mushroom deterioration rate.

Villaescusa and Gil (2003) compared the quality of *Pleurotus ostreatus* mushrooms during cold storage under various temperatures and modifie atmospheres in low-density polyethylene (LDPE) and polyvinyl chloride (PVC) or macro- and microperforated polypropylenes (MPP1) packaging. Their results showed that at the end of a 7-day storage, the respiration rates were similar for all the assayed temperatures (Figure 32.3). However, quality dropped sharply and the mushrooms were deemed not marketable beyond 7 days' storage.

Proximate Composition and Nutritional Quality

Proximate composition of selected mushroom varieties along with their energy values is given in Table 32.3. The moisture content of freshly harvested mushroom is about around 90%.

Bano and Rajarathnam (1982) have given nutritional values of three edible mushrooms (*Agaricus bisporus*, *Pleurotus flabel latus*, *Volvariella dysplasia*). The ash, protein, fat, crude fibe , and carbohydrates values (%, wet-weight basis) were in the range of 0.97–1.26, 2.78–3.94, 0.19–8.65, 0.09–1.67, and 5.51–6.28, respectively. The dry matter of mushrooms is usually in the range of 60–140 g per kg. The dry matter proportion increases during mushroom cooking due to water loss. The dried mushrooms are known for their hygroscopicity (Kalac 2009).

Mushrooms are a good source of proteins; their proteins contain adequate quantities of most of the essential amino acids and amides, which are comparable to that of egg proteins. The high concentrations of lysine in mushroom protein make them an ideal food to supplement the cereal-based diets which can be deficien in lysine (Sohi 1990).

Generally, the total lipid content of mushrooms varies from 2% to 6% on dry-weight basis. Within fatty acid composition, polyunsaturated linoleic acid, monounsaturated oleic acid, and saturated palmitic acid are predominant (Kalac 2009). Hanus et al. (2008) examined 15 species of wild edible mushrooms belonging to the genus *Boletus* (*phylum*

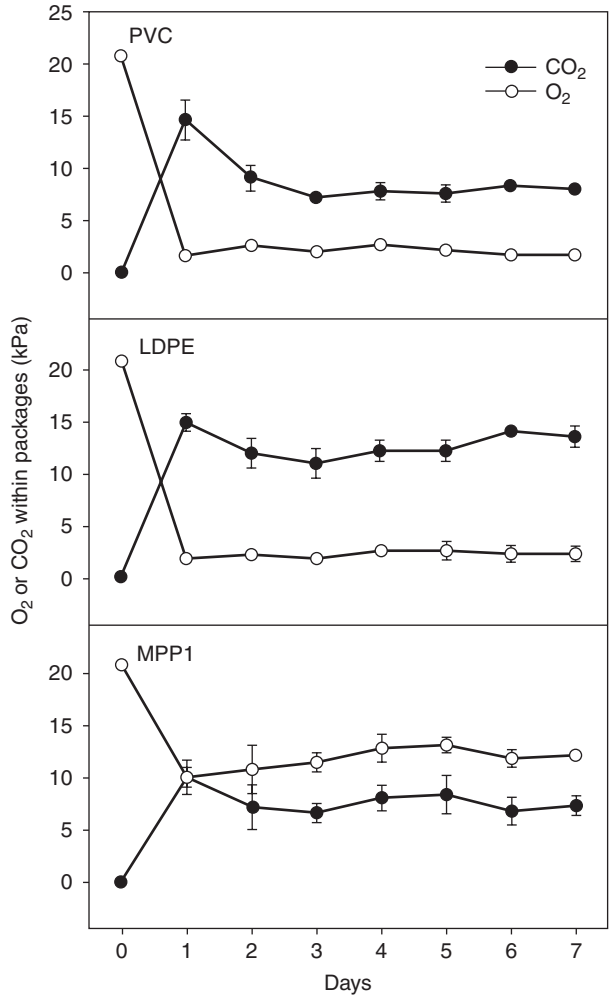

Figure 32.3 Changes in O_2 and CO_2 concentrations of *Pleurotus* mushrooms at 4°C during 7-day storage in low-density polyethylene (LDPE) and polyvinyl chloride (PVC) or macro- and microperforated polypropylenes (MPP1) packaging. (From Villaescusa and Gil (2003).)

Table 32.3 Proximate composition and energy value of selected mushroom varieties, raw (per 100 g)

	White	Oyster	Enoki	Portabella	Crimini	Shiitake
Water, g	92.45	89.18	88.34	92.82	92.12	89.74
Energy, kcal	22.00	33.00	37.00	22.00	22.00	34.00
Protein, g	3.09	3.31	2.66	2.11	2.50	2.24
Total lipid (fat), g	0.34	0.41	0.29	0.35	0.10	0.49
Carbohydrate*, g	3.26	6.09	7.81	3.87	4.30	6.79
Total dietary fibe , g	1.00	2.30	2.70	1.30	0.60	2.50
Ash, g	0.85	1.01	0.91	0.85	0.98	0.73

Source: USDA National Nutrient Database (http://www.nal.usda.gov).
*By difference.

Basidiomycota) and found that the most abundant fatty acids were oleic acid (15–42%), linoleic acid (38–58%), and palmitic acid (7–17%).

Mushrooms are good source of fibe , vitamins, and minerals. The most nutritious mushrooms are almost equal in nutritional quality to meat and milk. Fook et al. (2008) analyzed fi e species (*Hygrophorus* sp., *Pleurotus* sp., *Hygrocybe* sp., *Schizophyllum commune*, and *Polyporus tenuiculus*) of edible wild mushrooms for their proximate composition, vitamins (retinol, alpha-tocopherol, gamma-tocopherol, thiamin, ribofl vin, and ascorbic acid) and mineral contents (Fe, Zn, Co, Ca, Mg, K, and Na), antioxidant activity, and total phenols. The study concluded that edible wild mushrooms may represent an excellent source of micronutrients and antioxidant compounds.

Functional Properties of Mushrooms

The low-calorie and cholesterol-free mushrooms diets also display certain medicinal properties. Those diets are effective against hyperlipemia, hypertension, diabetics, and tumors. Even though mushroom cultivation spans many centuries, it is only over the last 50 years or so that there have been major expansions in basic research and practical knowledge leading to understanding of the health-promoting and disease-preventing activities of mushrooms (Chang and Miles 1989). Leifa et al. (2006) reviewed the advances in mushroom research over the last decade; the aspects covered included: genetics and breeding of mushrooms, active compounds of mushrooms (antitumor polysaccharides or peptidoglycans, other antitumor compounds, antibacterial compounds, antiviral compounds, and cytostatic compounds), and mushrooms and/or mushroom extracts as dietary supplements. A brief description of the salient functional properties of mushrooms is given below:

1. Antioxidant activity: Min et al. (2008) conducted a study to determine the content of phenolic compounds and the antioxidative activity of fi e edible and fi e medicinal mushrooms commonly cultivated in Korea. A total of 28 phenolic compounds were detected in the mushrooms studied. The average total concentration of phenolic compounds was 326 μg/g, the average being 174 μg/g in edible mushrooms and 477 μg/g in medicinal mushrooms. The average total fl vonoids concentration was 22 μg/g and 76 μg/g in edible and medicinal mushrooms, respectively. Significan positive correlations were observed between phenolic compounds detected and antioxidative potential.

   Shu et al. (2009) studied the antioxidant properties of three mushrooms (*Clitocybe maxima*, *Pleurotus ferulae*, and *Pleurotus ostreatus*). Their results indicated that these mushrooms exhibited antioxidant properties. Eun et al. (2008) studied the nutritional components and anticancer properties of *Hypsizigus marmoreus* mushrooms and demonstrated that water is a more efficien solvent than ethanol for extracting nutritional and functional components from this mushroom variety. Zhuo et al. (2008) reported that oyster mushrooms might possess stronger antioxidative activities than straw mushrooms.
2. Hypocholesterolaemic effect: Cardiovascular disease is one of the most common causes of death and a high level of blood cholesterol is considered a risk factor in this respect. A study was conducted to quantify the amount of the cholesterol-reducing agent eritadenine in shiitake mushrooms, in search of a potential natural medicine against blood cholesterol (Enman et al. 2007). Their results indicated that the shiitake mushroom strains are a potential source of therapeutic amounts of eritadenine. Fukada et al. (2006) studied the effect of eritadenine, a hypocholesterolaemic factor isolated

from the edible mushroom *Lentinus edodes*, on plasma homocysteine concentration. The results of this study confirme that eritadenine can effectively counteract the hyperhomocysteinaemic effect. The dietary fibe from the edible fungus *Tremella fuciformis* is shown to have beneficia effects on serum lipid and cholesterol levels (Hsing et al. 2002).

3. Antimicrobial activity: Barros et al. (2007) investigated the antimicrobial activities of phenolic extracts of Portuguese wild edible mushroom species (Lactarius deliciosus, Sarcodon imbricatus, and Tricholoma portentosum) against pathogens. Antifungal activity against Candida albicans and Cryptococcus neoformans varied with mushroom species. Imtiaj and Lee (2007) screened Korean wild mushrooms for antibacterial and antifungal activities. This study indicates that culture filtrate of *Cordyceps sobolifera*, *Oudemansiella mucida*, *Stereum ostrea*, and *Polyporus Cinnabarinus* were the most effective against both bacteria and fungi.

Suyue et al. (2007) isolated bioactive lectin from fruiting bodies of the wild mushroom *Boletus edulis*, and characterized its haemagglutinative, antiviral, and immunomodulatory activities. The lectin showed specifi binding to both melibiose and xylose, and was purifie using ion-exchange, affinit , and gel filtratio chromatography.

Processed Products

Due to high moisture content, freshly harvested mushrooms are a highly perishable commodity. The rapid metabolism and susceptibility to enzymatic browning play a critical role in their spoilage. Canning, drying, and freezing are some of the main methods of mushroom preservation. Retaining the desirable sensory attributes is one of the key issues and a challenge while processing mushrooms.

Among some of the newer processing technologies, ohmic heating has been investigated for mushroom processing (Tulsiyan et al. 2008); mushrooms showed an electrical conductivity of 0.2–1.4, which was comparable to bean sprouts. Master et al. (2000) studied the possibility of using high isostatic pressure treatment as an alternative to conventional blanching of mushrooms. They demonstrated that pressure treatment has the same net effect as conventional blanching on the polyphenol oxidase activity. Both processes cause irreversible enzyme inactivation. The product yield and color were comparable to the heat-blanched products. The pressures needed to achieve enzyme inactivation also resulted in a slightly firme product.

Fresh-cut Mushrooms

Fresh-cut, or minimally processed, produce is one of the fastest growing segments of the food industry in the United States. The overall support for the sales of fresh-cut produce is the perfect match of what consumers want for their time-pressed, health-conscious, and safe food needs (Rowles et al. 2001). Mushrooms fi very well in the fresh-cut segment of the food industry and have been one of the earliest produce items marketed in this form at the retail as well as food-service level.

Quality of fresh-cut products depends on the following factors: visual appearance (freshness, color, defects, and decay), texture (crispiness, turgidity, f rmness, and tissue integrity), fl vor (taste and aroma), nutritive value (vitamins, minerals, and dietary fiber) and safety, i.e., absence of chemical residues and microbial contamination (Piagentini et al. 2002). From consumers' perspective, color or appearance of fresh-cut produce is one of the most important attributes among those described earlier. If the color of a fresh-cut product is not attractive or of acceptable quality, the consumer is less likely to purchase it regardless of its excellent texture, fl vor, taste, or other quality attributes (Siddiq 2005).

Sensory and shelf-life quality of minimally processed mushrooms is limited to a few days, typically 5–10 days, because of enzymatic browning. The degradation of color in mushrooms, like other fresh-cut produce, is due to the action of two enzymes—polyphenol oxidase (PPO) and peroxidase, with the former being the chief culprit. In addition to visible color changes, enzymatic activity also impairs other sensory properties, which limit marketability of the product (Vamos-Vigyazo 1981). Inactivation of PPO in mushrooms by heat or the application of antioxidants or chemical inhibitors is critical to control enzymatic browning and extend the shelf life of mushrooms for commercial use (Zhang and Flurkey 1997; Devece et al. 1999). Mushrooms are a good source of both oxidative enzymes and phenolics. Current conventional techniques to avoid browning include autoclaved and blanching methods. These conventional processes are inherently linked to important weight and nutritional quality losses in the product (Lopez et al. 1999), pointing to the need for alternative industrial blanching techniques.

Fresh-cut mushroom slices should be stored at 34–38°F (1–3°C). Roy et al. (1996) reported that post-cut excessive moisture loss is responsible for the onset of wrinkling and brown surface patches. Simon et al. (2005) evaluated the quality of sliced mushrooms under modifie atmospheres (MA) and reported that MA with 2.5% CO_2 and 10–20% O_2 reduced microbial counts and improved the appearance when compared with an air atmosphere. An MA regime of 15% CO_2 and $<0.1\%$ O_2 inhibited mushroom development and toughening, and reduced microbial growth. Although these atmospheres had no effect on color, they did allow the development of off odors and anaerobic spores were detected.

Extensive research has been done on find ing effective antibrowning treatments for mushrooms. Brennan et al. (1999) studied the effect of sodium metabisulfit on color and shelf life of mushroom slices. Whole, white, closed cap mushrooms were soaked in 0%, 0.1%, 0.2%, or 0.4% sodium metabisulfit for 30 seconds or 10 minutes before cutting and it was reported that whiteness decreased with time and concluded that treatment with sulfit did not bleach mushroom slices or improve their keeping quality. Effects of storage temperature on the microbiological and sensory properties of minimally processed shiitake mushrooms were investigated by Castro et al. (2008); the shelf life of minimally processed shiitake mushrooms was 10 days at 7°C, but <5 days at 10°C, and just 3 days at 15°C.

The effect of active and passive modifie atmosphere packaging (MAP) was studied on the microbiological quality and sensory properties of *Lentinula edodes* (shiitake) mushrooms by Parentelli et al. (2007). Mushrooms were packaged in perforated polypropylene (PP) film (control) or in LDPE or PP bags fille with normal air (passive MAP) or 5% $O_2 + 2.5\%$ CO_2 (active MAP) and analyzed for weight loss, respiration, and sensory properties during storage for 20 days at 5°C. Both active and passive MAP resulted in signifi cantly greater sensory deterioration than control samples, which was attributed to physiological damage caused by increased higher concentration of CO_2 in MAP samples.

Cliffe and O'Beirne (2008) investigated the effects of different washing treatments, combined with MAP, on the quality and storage life of sliced white mushrooms and found that the most effective treatment was with 3% H_2O_2 for 1 minute prior to slicing, followed by a spray application of 4% sodium d-isoascorbate monohydrate or 1% H_2O_2. The treated mushrooms were shown to maintain quality with enhanced shelf life at 4°C.

Canned Mushrooms

About 38% of fresh mushrooms are used for processing in canned form. The major processors are China, the Netherlands,

France, and Spain. According to Codex Alimentarius (CAC 2009), the main exporters of canned mushrooms in the world (with their share in percentage), are China (41.8%), the Netherlands (22.7%), Spain (7.1%) and France (5.8%). The main importers are Germany (19.6%) and the United States (16.6%).

A typical mushroom canning operation fl wchart is shown in Figure 32.4. The most commonly used mushroom variety for canning is white mushroom. After the second step in this fl wchart, mushrooms can be subjected to other preservation methods (drying or freezing). Canned mushrooms, as define in the definition and standards of identity for canned vegetables (21 CFR 51.990; USDA-AMS 1962) "mean the product prepared from the sound, succulent, fresh mushroom by proper trimming, washing, and sorting and is packed with the addition of water in hermetically sealed containers and sufficientl processed by heat to assure preservation of the product. Salt, or monosodium glutamate, or both may be added in a quantity sufficien to season the product. Ascorbic acid (vitamin C) may be added in a quantity not to exceed 37.5 milligrams for each ounce of drained weight of mushrooms." Styles of canned mushrooms as per USDA standards include: (a) whole, (b) buttons, (c) sliced whole, (d) random sliced whole, (e) sliced buttons, and (f) stems and pieces.

Canned mushrooms are graded on a scale of 100 points based on the following factors/attributes: color—30 points, uniformity of size and shape—20 points, absence of defects—30 points, and character—20 points. Based on the scoring scale, grades of canned mushroom are assigned as: (a) US Grade "A" or US Fancy (total score not less than 90), (b) US Grade "B" or US Extra Standard (total score not less than 80), and (c) Substandard (not meeting the requirements of US Grade "B").

A canned vegetable-mushroom mix was developed. Main ingredients of the product were grass pea (*Lathyrus sativus*) seeds and lentils (*Lens culinaris*), which were mixed with fruiting bodies of white button mushrooms (*Agaricus bisporus*) and oyster mushrooms (Pleurotus ostreatus). The canned product thus prepared exhibited positive sensory properties and was rated between 4.1 and 4.8 on a 5-point hedonic scale.

Dried Mushrooms

Drying is one of the oldest methods of preserving food to extend its shelf life. A number of mushroom varieties are available commercially in the dried form. Shiitake mushrooms are the most commonly available variety in the market. Dried mushrooms are convenient to the consumers because they can be used in a variety of home recipes.

Preparation steps for raw mushrooms include sorting, cleaning, washing, cutting/slicing (if not dried in the whole form), and a dip in an antibrowning solution. Thus prepared product is spread on metal drying trays with perforations and dried in commercial dehydrators that are commonly used for other vegetables. The maintenance of an optimum dryer temperature is critical as higher temperatures can not only result in the loss of heat-labile nutrients but can also impart a dark-brown color to the finishe products.

The process temperature during drying of mushrooms is of significan importance. Abhijit and Gupta (2003) studied the effect of temperature during air drying on the drying kinetics, rehydration behavior, and shrinkage of button mushroom quarters, osmosed in brine at a solution to sample ratio of 6 and a temperature of 40°C prior to air drying in a single layer. Rehydration and sensory attributes indicated that drying osmosed mushrooms at 65°C could yield a highly acceptable product, particularly for soup preparation.

Riaz et al. (1991) studied the blanching effect on the coarsely sliced (5 mm thick) oyster mushrooms (*Pleurotus ostreatus*) and suggested that blanching for a prolonged time caused a substantial loss of nutrients.

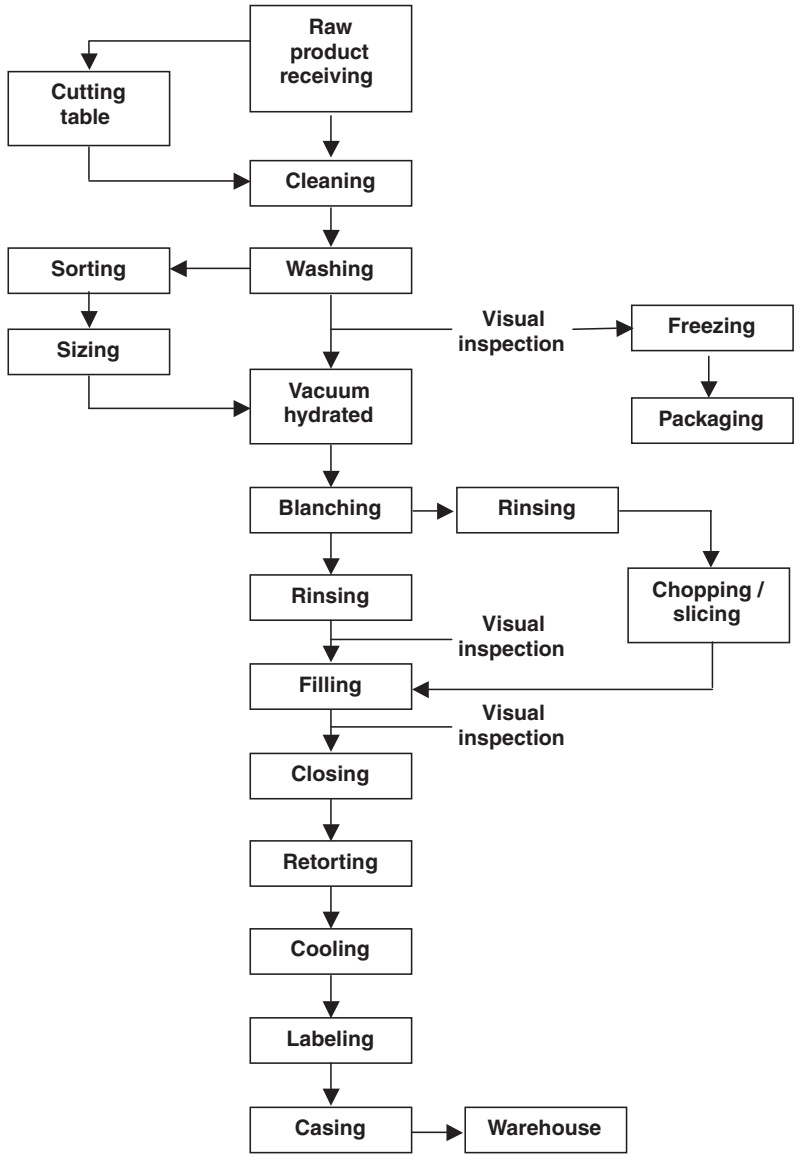

Figure 32.4 Flowchart of mushroom canning process. (Adapted from Downing (1996).)

Dehydrated blanched mushrooms were found to be superior to dehydrated unblanched mushrooms in nutritional and sensory characteristics. Rehydration ratio was better in dried mushrooms prepared without blanching. Storage caused some deterioration in quality, but dehydrated mushrooms were found to be acceptable even after a storage period of 6 months.

Giri and Prasad (2006) studied the effect of microwave-vacuum drying of button or white mushrooms at two power levels—150 W and 250 W, and two at pressures—10 kPa and 20 kPa. The mushrooms thus dried were

compared with those processed in convective hot air drying at 60°C. In both microwave-vacuum and air-drying methods, the shrinkage (volumetric and diametric) of mushrooms showed a linear behavior with moisture content. Microwave-vacuum drying produced less shrinkage than air drying. Experimental data showed that the effect of the system pressure on shrinkage and density was more significan than the power level during microwave-vacuum drying. In another study, Giri and Prasad (2007) dried the button mushrooms using microwave-vacuum approach up to the moisture content of around 6% (db). The effects of microwave power level (115–285 W), system pressure (6.5–23.5 kPa), and slice thickness (6–14 mm) on drying efficien y and some quality attributes (color, texture, rehydration ratio, and sensory properties) of dehydrated mushrooms were analyzed by means of response surface methodology. System pressure strongly affected color, hardness, rehydration ratio, and sensory properties of dehydrated mushrooms. A lower pressure during drying resulted in better-quality products.

In developing countries, solar drying of mushrooms is a common method to save energy costs. However, the quality of the solar-dried mushrooms is not as consistent as a commercially dried product.

Freezing Mushrooms

Freezing processing is another convenient method to preserve mushrooms. However, as compared to other processed mushroom products, i.e., canned and fresh-cut sliced, freezing preservation of mushrooms is done on a relatively small scale. With respect to freezing mushrooms, most of the initial preparation steps—cleaning, washing, cutting, grading/sorting, blanching—are similar to those used for canning.

The most important quality attributes that need to be preserved while freezing mushrooms are color, texture, and aroma. Enzymatic browning is a serious quality concern in mushrooms; blanching and/or pretreatment with antibrowning agents are the commonly used methods to overcome discoloration caused by polyphenol oxidase, the chief enzyme implicated in color quality loss. However, Czapski and Szudyga (2000) reported that blanching is harmful to the characteristic structure of mushrooms. The blanching process can even reduce the initial mushroom whiteness. Another negative effect was that blanched frozen mushrooms showed a notable toughness after thawing and cooking. In an earlier study, Czapski and Bakowski (1995) demonstrated that stabilization of color in frozen mushrooms can be obtained by inhibiting undesired discoloration after dipping fresh mushrooms in sodium metabisulfit solutions. In the United States, sulfit compounds are generally recognized as safe (GRAS) when used in accordance with good manufacturing practice except that they are not allowed to be used on fruits and vegetables intended to be sold/served raw or fresh (FDA 1996).

Jaworska and Bernas (2009) investigated the effect of soaking and blanching on the quality of frozen *Boletus edulis*. Based on the results of the sensory evaluation, a maximum storage period of 4 months was set for the frozen product obtained from unblanched mushrooms. Soaking, blanching, and freezing resulted in the appearance of colors, such as yellow, honey, and pink-violet. As a result of freezing, decreases in the contents of thiamine, ribofl vin, and vitamin C were noted. Blanching in water, as a method of preprocessing, was sufficien for maintaining acceptable sensory quality.

Other Processed Mushroom Products

A number of convenience foods have been prepared from mushrooms; this section describes several such foods.

Table 32.4 Selected commercially available ready-to-eat or condensed soups and pasta sauces

Soups: Ready-to-eat (RTE) or Condensed (C)	Pasta sauces—Italian-type
Creamy portobello mushroom (RTE)	Chunky garden mushroom & green pepper
Cream of mushroom (C)	Chunky garden mushroom supreme
25% less sodium cream of mushroom (C)	Pasta, fresh mushroom
98% fat-free cream of mushroom (C)	Mushroom and garlic
Chicken barley with mushrooms (C)	Mushroom and parmesan
Cream of mushroom with roasted garlic (C)	Organic mushroom
Slow roasted beef with mushrooms (RTE)	Zesty mushroom
Golden mushroom (C)	
Beefy mushroom (C)	

Source: USDA Nutrient Database.

Soup and Sauces

The most widely available and consumed mushroom convenience foods are ready-to-eat or condensed soups and pasta sauces; some of these products are listed in Table 32.4. The quality characteristics of mushroom soups and similar products have been investigated by many researchers (Sudhir et al. 2003; Randhawa and Ranote 2004; Kremer et al. 2005). Mushroom-whey soup powder was prepared by cooking mushrooms with concentrated cheese whey followed by blending (Sudhir et al. 2003). The soup powder reconstituted well when boiled in water for 2 minutes. The reconstituted soup was considered acceptable, with an overall acceptability score of 7.1 on a 9-point hedonic scale. Kremer et al. (2005) worked on the perception of texture and fl vor and their interaction effects in eight white cream soups; the soup samples were prepared with or without potato starch and with or without mushroom fl vor. Randhawa and Ranote (2004) prepared mushroom soup powder from *Pleurotus florid* and *Pleurotus sajor-caju* and studied the physicochemical changes, acceptability, and shelf life of the product. Their results indicated that the product from pretreated *P. florid* was superior, shelf stable, and most acceptable on the basis of the quality attributes tested.

Noodles

Devina et al. (2008) developed a process for preparation of noodles containing white button mushrooms. Noodles with good sensory and functional properties could be prepared using 20 g mushroom meal, 38 g wheat flou , 20 g potato meal, 0.2 g baking powder, and 2 ml edible oil. The resulting noodles were found to have good nutritional quality. Salama (2007) prepared pasta products with oyster mushroom mycelia power and found that replacement of 5%, 10%, or 15% of semolina with mushroom powder resulted in pasta with acceptable cooking properties and best sensory scores for color, fl vor, mouthfeel, elasticity, and overall acceptability.

Mushroom Papad and Mathri

Kumar et al. (2006) developed a popular deep-fried Indian snack food called *mathri*. Traditionally, it is prepared from refine wheat flou . In this study, *mathri* was prepared from white mushroom powder and refine wheat flou in an attempt to improve quality of the product and add variety to traditional Indian snacks. Formulation of the mushroom *mathri* was optimized by response surface methodology, which was as follows: mushroom powder, 9 g; refine wheat flou , 91 g; baking powder, 0.5 g; and hydrogenated vegetable oil, 20 g. Moisture content of mushroom *mathri* was 3–5% as compared with 3.9% in flou -only *mathri*. It is suggested that moisture content of mushroom mathri should be <4.1% for safe storage. Tyagi and Nath (2005) prepared *papad*s with dried mushroom (*Pleurotus florid*) powder up to 40% level. Incorporation of up to 25% mushroom powder in black gram *papad*s or up to 10% in green gram (mung beans) or black gram-green gram

*papad*s gave highly acceptable products. The mushroom powder addition in *papad*s also reduced the fat absorption index and expansion during frying.

Mushroom Cookie, Cake, and Bread

Chomdao et al. (2005) developed a mushroom cookie formulation based on four dried mushroom types (Jew's black ear, Hungarian, straw, and Puethan mushroom powders) and studied the sensory properties of the cookies. Cookies prepared with Jew's black ear mushroom powder were considered to have the best properties. Other ingredients in the cookie formulation were: flou , margarine, red sugar, bean milk, white sesame seeds, oats, baking soda, cream butter milk fl voring, brown colorant, and salt. Nutrient composition, water activity (aw), color, fracture strength, microbiological quality, and acceptability of the Jew's black ear mushroom cookies prepared using an optimized formulation were determined. Eissa et al. (2007) used flour from oyster mushrooms (*Pleurotus sajor-caju*) as a partial replacement for wheat flou in the production of biscuits with a view to increase the nutritional quality of these bakery products.

Chang and Ki (2004) prepared sponge cake containing powdered mushroom (*Pleurotus eryngii*). Batters prepared with added mushroom powder showed higher specifi gravity and viscosity. Addition of mushroom powder decreased the cake height and volume. Sensory analysis indicated that overall acceptability of sponge cakes containing 3% or 5% mushroom powder was higher than the control cakes.

Breads were prepared (Ga et al. 2003) with 1–4% mushroom powder added to wheat flou , using the straight dough procedure. Rough and coarse crumb texture with dark color was observed in bread containing mushroom powder. Sensory analysis revealed that bread with acceptable quality could be obtained by addition of 1% oak mushroom powder.

Effect of Processing on Quality

Nutritional and Antioxidant Quality

Processing affects the nutritional quality of mushroom products to a varying degree and is process-dependent. The data shown in Table 32.5 illustrate some of these effects in the canned, dried, and soup forms of mushrooms. It is to be noted that this data is for selected products and is given as a general comparison; some variations are expected if the mushrooms are from a different variety or a different climatic or growing region. Since all mushroom varieties are high in water content, drying brings about most dramatic changes—manyfold increases in energy values and especially mineral content; whereas, as a result of processing, vitamin contents do not show a clear pattern. Somewhat reduced hydration capacity is another issue that influence the quality of reconstituted mushrooms.

Murcia et al. (2002) studied the effect of canning and freezing on the antioxidant capacity (measured as Trolox equivalent) of fi e mushroom varieties (Table 32.6). Freezing process had the least negative effect on the antioxidant capacity, ranging from 3.8% to 26.0% for different varieties. Canning mushrooms resulted in a significan loss of antioxidant capacity, from 23.4% to as high as 70.7%.

Sensory Quality

Jianhua et al. (2005) studied the sensory characteristics of dehydrated oyster mushrooms from eight different substrates. The sensory properties (rubbery, sweet pea, and bitter) and chemical content were found to be significantl affected by the substrates used for cultivating oyster mushrooms. Ares et al. (2006) evaluated the influenc of passive MAP on the sensory characteristics and shelf life of shiitake mushrooms. Descriptive analysis showed that mushrooms stored under MAP had a higher deterioration rate than

Table 32.5 Nutritional profile of selected raw and processed mushrooms (per 100 g)

	White mushroom				Shiitake mushroom	
Composition	Raw	Canned, drained	Stir-fried	Soup, cream of mushroom*	Raw	Dried
Proximate						
Water, g	92.45	91.08	91.10	90.3	89.74	9.50
Energy, kcal	22.00	25.00	26.00	53.00	34.00	296.00
Protein, g	3.09	1.87	3.58	1.0	2.24	9.58
Total lipid (fat), g	0.34	0.29	0.33	3.7	0.49	0.99
Carbohydrate, g	3.26	5.09	4.04	4.53	6.79	75.37
Total dietary fibe , g	1.0	2.40	1.80	0.2	2.50	11.50
Minerals						
Calcium, mg	3	11	4	19	2	11
Magnesium, mg	9	15	11	2	20	132
Phosphorus, mg	86	66	105	20	112	294
Potassium, mg	318	129	396	41	304	1,534
Sodium, mg	5	425	12	20	9	13
Vitamins						
Vitamin C, mg	2.1	0	0	0.4	0.4	3.5
Niacin, mg	3.6	1.6	3.9	0.3	3.9	14.1
Pantothenic Acid, mg	1.5	0.8	1.5	—†	1.5	21.9
Folate, total, mcg	16.0	12	20	8	—	163
Choline, total, mg	17.3	20.4	21.9	5.8	—	—
Vitamin D, IU	7.0	8	8	0	20	172

Source: USDA National Nutrient Database, 2009 (http://www.nal.usda.gov).
*Canned, low sodium, ready-to-eat.
†No data.

the control samples. Mushrooms stored under atmospheric air during the entire storage time showed a lower rejection rate and a longer shelf life than those stored under passive MAP. Further, their results showed that high CO_2 concentrations (higher than 9%) accelerated mushroom deterioration, indicating that shiitake mushrooms are more sensitive than other mushroom species.

In a study by de Pinho et al. (2008), volatile and semivolatile components of 11 wild edible mushrooms were determined by headspace solid-phase micro-extraction (HS-SPME) and by liquid extraction combined with gas chromatography-mass spectrometry (GC-MS). Fifty volatiles and nonvolatile components were formally identifie and 13 others were tentatively identified A correlation between sensory descriptors and volatiles was observed by applying multivariate analysis to the sensorial and chemical data. This study concluded that the presence and

Table 32.6 Effect of processing on the antioxidant capacity of selected mushroom varieties

	Antioxidant activity (μmol Trolox equivalent)		
Mushroom variety	Raw	Frozen (% loss)	Canned (% loss)
Lepista	3.19	2.36 (26.0)	2.01 (37.0)
Lentinus	9.05	7.59 (16.1)	6.93 (23.4)
Agrocybe	10.39	9.99 (3.8)	3.04 (70.7)
Cantharellus	11.41	10.92 (4.3)	4.88 (57.2)
Hydnum	1.56	1.25 (19.9)	0.46 (70.5)

Source: Murcia et al. (2002).

contents of these compounds contributed considerably to the sensory characteristics of the analyzed species.

Conclusion

Mushrooms are a versatile food product with numerous species consumed worldwide as a delicacy. Though mushrooms grow in the wild, the ones available in the marketplace are commercially grown on mushroom farms. Edible mushrooms are used extensively in cooking, in many cuisines (notably Chinese, European, and Japanese). Mushrooms are commonly thought to have little nutritional value, but many species, besides being rich in protein, are also high in fibe and vitamins such as thiamine, ribofl vin, niacin, biotin, and ascorbic acid. Information about physicochemical and nutritional quality of several mushroom species is still somewhat limited. A huge scope and many opportunities exist in mushroom research, particularly in the fiel of nutraceutical benefit of mushrooms as they possess health-promoting and disease-preventing properties. Despite many health benefit associated with them, the mushroom industry has not got enough momentum. In the developing countries, mushroom growing and farm-level processing using indigenous methods can improve small farmers' profitability.

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Chapter 33

Table Olives and Olive Oil: Production, Processing, Composition, and Nutritional Qualities

Kostas Kiritsakis, Apostolos Kiritsakis, Elena Manousaki-Karacosta, and Fivos Genigeorgis

Introduction

Olive tree is of great significanc to Mediterranean people (Trichopoulou and Vasilopoulou 2000; Bendini et al. 2007) and is widely mentioned in classical and biblical literatures. The olive branch symbolizes peace. Table olives and olive oil are good sources of health-promoting constituents, such as monounsaturated oleic acid, phenolic compounds, vitamins, proteins, etc. (Tsimidou 1998; Kiritsakis 2007). Olives are eaten as appetizer, in salads, sandwiches, and casseroles. They are also popular as a pizza topping. Olive oil has a good taste and aroma and is considered a functional food (Kiritsakis 2007), because of its specifi saponifiabl and unsaponifiabl composition. This chapter provides an overview of the production, quality, nutrition, and processing aspects of table olives and olive oil.

Background

The olive tree grew wild in the Middle East and its fruits were used since prehistoric times. Along with vineyard, olive trees were one of the firs to be cultivated from Central Persia and Mesopotamia to Egypt and Greece. It is believed that the Greeks, and more specifically the Cretan Minoans, were the firs in the cultivation of the olive tree and the systematic cultivation might have started in the island of Crete. Cultivation of the olive tree was quickly spread to the mainland of Greece and olive oil became an important product for the economy of the Mycenaean civilization.

In the sixth century BC, Solon, the great Athenian legislator, enforced laws protecting the olive tree. Ancient philosophers, historians, and physicians such as Hippocrates, the father of medicine, referred to the therapeutical properties of the olive oil. A number of events demonstrate the link between olive tree and social activities in ancient Greece. The tradition of awarding an olive branch or wreath (kotinos) to the winners at the ancient Olympic games is well known.

Olive Tree

The scientifi name of the olive tree is *Olea europaea*. The origin of the word *Olea* is Greek. The olive tree (*O. europaea*) belongs to the family Oleaceae, which includes approximately 30 species. It is the only species of the Oleaceae family producing edible fruits. The main characteristic of the olive tree is its ability to live many (over 500) years and maintain its productivity. Figure 33.1 shows

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Figure 33.1 One of the oldest olive trees in the world, in west Crete (Vouves, municipality Kolymparioy, Chania).

one of the oldest olive trees in the world, still producing olive fruit.

Olive Cultivars

There are more than 700 olive tree cultivars in the world. Large size fruit is preferred for the table olive processing. Other desired characteristics are high fles to stone ratio, low oil content, high sugar content, unblemished fin skin appearance, and solid fles that can be easily separated from the stone. Oil-producing olives, on the contrary, should have higher oil content and produce oil of good aroma and taste. However, most of the table cultivars may also be used for oil production.

Special Greek table olive cultivars are *Kalamon*, *Chalkidikis*, *Conservolia* (*Amphisis*), *Mastoidis* (*Tsounati*), and *Throumbolia*. Cultivars found in other parts of the world are *Manzanillo*, *Sevillano*, *Mission*, and *Ascolano*. *Koroneiki* is a special olive oil cultivar, which produces olive oil with exceptional aroma and taste characteristics.

Composition of Olives

Like cherry and peach, the olive fruit is a *drupe*, oval in shape, consisting of two main parts, the pericarp and the endocarp. The pericarp is composed of the epicarp or skin and the mesocarp or pulp. The endocarp, also called pit or kernel, contains the seed (Figure 33.2). The pericarp contains 96–98% oil; the remaining 2–4% oil is in the endocarp.

Growth and maturation of the olive fruit is a long and slow process lasting 5 months or more. Its composition varies according to cultivar, environmental conditions, and degree of ripeness. The oil is formed in the pulp cells when fruit is sufficientl developed and kernel hardened. The main constituents of the fresh ripe olive fruit are water, oil, sugar, protein, pectin, organic acids, phenols, tannins, oleuropein, anthocyanins as well as inorganic and other components. Citric, oxalic, fumaric, tartaric, lactic, and acetic acids have been reported in the pulp (Fedeli 1977).

Water

Water is one of the main constituents of the olive fruit and accounts for up to about 70% of its weight. Water serves as a solvent for the organic acids, tannins, oleuropein, and other water-soluble constituents of the fruit.

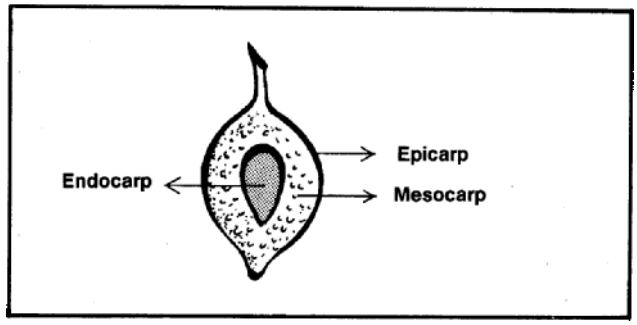

Figure 33.2 Parts of olive fruit.

Oil

The oil is dispersed within the fruit cells forming drops which grow in size and eventually may fil the entire cell (Figure 33.3). Olive oil drops vary in diameter.

Maximum oil yield is obtained at optimum maturity stage of the fruit, which is when the color of olives is typically purple black. At this point, the olive fruit contains maximum quantity of good quality oil. In addition, phenols and volatile aroma constituents are at optimum concentration.

The biosynthesis of olive oil involves the following processes (Hess 1975):

1. Fatty acids are synthesized by successive additions of malonyl-CoA to a primer molecule of acetyl-CoA. Since the three-carbon malonyl residue is decarboxylated after each addition, the progressive lengthening of the fatty acid chain by two carbon atoms is understandable. A multienzyme system catalyzes the condensation, reduction, and dehydration reactions, which are necessary for the completion of the fatty acid synthesis.
2. Glycerol phosphate is formed from the dihydroxy acetone phosphate of the glycolytic pathway.
3. Fatty acids, as CoA derivatives, are then transferred to the free hydroxy groups of the glycerol phosphate and finall dephosphorylation and completion of the esterifi cation of glycerol follows.

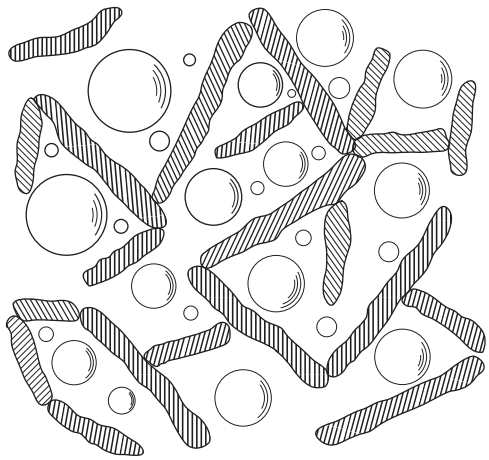

Figure 33.3 Olive drops in the fruit cells. Adapted from Moreno-Martinez (1975)

Sugars

The main sugars in the pulp are glucose and fructose. However, sucrose, mannose, and galactose have also been found in certain cultivars (Fedeli 1977). Glucose and fructose in smaller quantities are also found in the kernel of the fruit. Figure 33.4 shows the change in the sugar content of six table cultivars through time.

A decrease in sugar content of olive fruit with maturation is related to an increase in oil content.

Proteins

Olive fruit mesocarp contains 1.5–3.0% protein. All the amino acids present in other plant

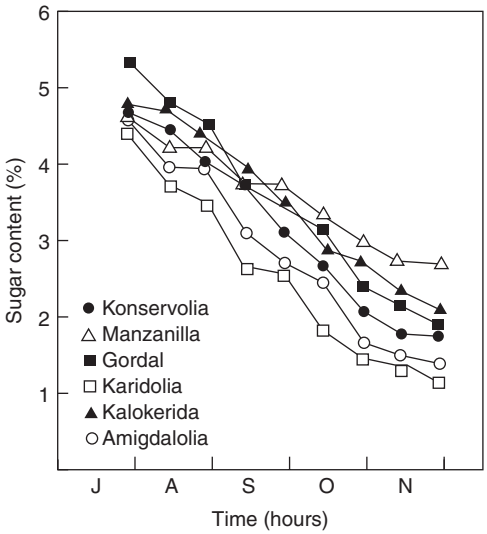

Figure 33.4 Changes in the sugar content in six cultivars with time. Adapted from Kiritsakis (2007).

proteins have been found in olive fruit. Arginine, aspartic, and glutamic acids constitute approximately 40% of the free amino acids.

Anthocyanins

Anthocyanins are glycosides of anthocyanidins, the latter being polyhydroxy derivatives of a basic structure, 2-phenyl-benzopyrylium or fl vylium. Anthocyanins and specificall the glycosides of cyanidin and peonidin are responsible for the purple and blue color of ripe olives (Timberlake and Bridle 1982). Initially, the color of olives is green, turning purple to bluish later and becoming black in overripe olives. The green color is due to chlorophylls, the purple and blue colors are due to anthocyanins, and the black color is formed by the oxidation of some phenolic compounds including oleuropein.

Vitamins

Olives are rich in vitamins E (α-tocopherol) and vitamin A, and contain small amounts of vitamins C and K. The vitamin E can help with oxidative stress due to pollution, cigarette smoke, etc. These environmental toxins expose our body to free radicals or unstable forms of oxygen.

Polyphenols

The polyphenols in olive oil are natural antioxidants, which have been shown to have a host of beneficia effects from healing sunburn to lowering cholesterol, blood pressure, and risk of coronary disease. Polyphenols donate electrons to the free radicals and stabilize them. This prevents the damaging of our cells. Polyphenol content can be affected by olive cultivar, collection time, and processing method. Polyphenol concentrations increase with fruit growth until the olives begin to turn purple. Hydroxytyrosol and tyrosol are some of the many phenol compounds found in olives that contribute to bitter taste and resistance to oxidation.

Oleuropein

Oleuropein is a phenolic glycoside typical to olives (Cruess 1958). It is responsible for the bitter taste of immature olives, which contain approximately 2% (of the fruit weight) of oleuropein (Fedeli 1977). Oleuropein is also known for its antioxidant and pharmaceutical properties. As the fruit reaches maturity, the oleuropein content diminishes so that ripe olives are not as bitter as the unripe olives. The structures of oleuropein and oleuroside are shown in Figure 33.5.

Oleuropein content of olive fruit can reach up to 14% of the dry matter in young fruits. Small fruit cultivars are characterized by high oleuropein content whereas large fruit cultivars usually contain small amounts of oleuropein. Oleuropein is water-soluble and diffuses into the aqueous phase during the processing of the olive fruit. Oleuropein is hydrolyzed by alkali, acids, and the enzyme glucosidase. Marsilio et al. (1996) studied the hydrolysis of olive oleuropein by *Lactobacillus plantarum* strains. It was found that the

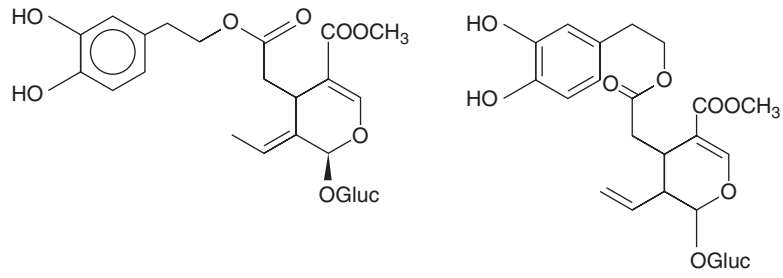

Figure 33.5 Structure of oleuropein and oleuroside.

bacterial strains initially hydrolyze the oleuropein with β-glucosidase to release the aglycon. The oleuropein derivatives as identifie by mass spectroscopy (MS) ion scanning are shown in Figure 33.6.

Other Olive Constituents

The olive pulp contains steroids, cerebrosides, sulfolipids, organic acids, and minerals. Organic acids are either free or in the form of salts. Certain minerals such as iron, calcium, potassium, phosphorus, manganese, magnesium, and copper are found in the pulp of olives.

Production and Consumption of Olives and Olive Oil

The world production of olives and virgin olive oil in 2007 was 17.3 million metric tons (MMT) and 3.0 MMT, respectively (FAO 2009). Top olive producing countries in 2007 were Spain (6.2 MMT), Italy (3.48 MMT), Greece (2.4 MMT), Tunisia (0.9 MMT), and Morocco (0.65 MMT). The top virgin olive

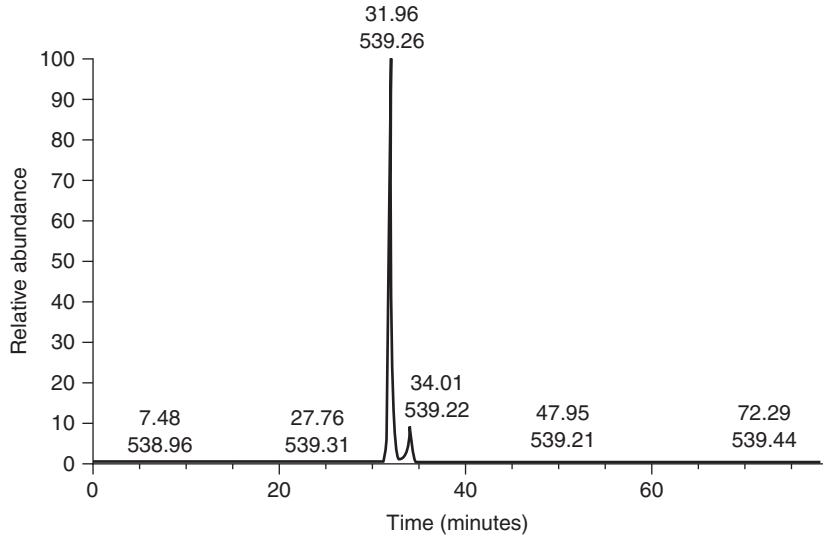

Figure 33.6 Oleuropein derivatives identified during MS ion scanning (oleuropein, retention time 31.96 and oleuroside, retention time 34.01) Adapted from Kiritsakis et al. (2009)

oil producing countries in 2007 were Spain (1.21 MMT), Italy (0.57 MMT), Greece (0.33 MMT), Tunisia (0.2 MMT), and Turkey (0.17 MMT).

According to the Food and Agriculture Organization (FAO) data on consumption, the estimated per capita consumption of olives in 2003 was highest in Greece (32.9 g/day), followed by Albania (16.6 g/day), Cyprus, and Turkey (11.0 g/day), Spain (8.2 g/day), and Italy (5.0 g/day). The per capita consumption of olive oil in 2003 was also highest in Greece (41.0 g/day), followed by Italy (35.6 g/day), Spain (30.1 g/day), Portugal (13.7 g/day), and Jordan (8.2 g/day).

Table Olives

The terms table, eatable, or edible olives are used for specially treated or processed healthy olives harvested at maturity. Table olives are available in different qualities, shapes, colors, forms, fl vors, and tastes.

Cultivars

There are a number of olive cultivars around the world that can be processed and used as table olives. In Greece four main cultivars used as table olives are as follows:

Kalamon: This is also called "king of olives." It is the most liked and highly prized Greek table olive. It is also one of the best-known olives in the world. Kalamon olives are shiny, purple-black in color, and tight-skinned with a characteristic "almond" shape (Figure 33.7).

Konservolia: This is the most widely used cultivar of table olives in Greece. The fruit is processed at different maturity stages as green, reddish, and black olives. It is also known by different local names like Amfissis Artas, Voliotiki, etc.

Halkidikis: This cultivar is grown mostly in the northern Greece in a region called Halkidiki. The Halkidikis olives are predominantly green, oval in shape, and have a characteristic tip in one end.

Throumbolia: This is commonly known as Throumba. It is mostly grown in the Greek island of Thasos and in Crete. Olives are left to ripen on the tree until they begin to wrinkle, soften, and eventually loosen their bitterness.

Figure 33.7 Kalamon olives at the harvesting stage. Adapted from Kiritsakis (2007).

A large number of olive cultivars are also grown in other olive-producing countries (Fernandez et al. 1997; Kailis and Harris 2007). Some of these well-known cultivars are as follows:

Manzanilla: Ranked as the world's number one table olive, Manzanilla is a Spanish cultivar introduced in California in 1875. Manzanilla is mostly processed as black-ripe and green-ripe olives.

Sevillano: Sevillano olives, also called "queen of olives" are very large, green, brine-cured olives, with low oil content. Sevillano is mostly used for the production of canned ripe olives or Spanish-style olives.

Ascolano: Large-fruited cultivar with a soft texture and low oil content but with limited demand as a table olive.

Mission: Mission is a unique cultivar introduced in California by the Mission padres. It is a dual-purpose cultivar with good fruit size and high oil content.

Harvesting

The proper way of harvesting table olives is by hand. The time to harvest is determined by desired fruit characteristics such as sugar content, color and size, hardness of the pulp, appearance of skin, and the method of processing. Green table olives (Spanish style) are harvested early, while for black table olives (Greek style), harvest begins in the second half of winter depending on the weather conditions.

Processing

Officiall , most of the different styles of table olives produced internationally by several processing methods and techniques are Spanish-style green olives, American-style black olives, Greek-style black olives, Kalamon-style Greek olives.

Spanish-Style Green Olives

Olives are harvested green, taken to the factory, and size graded. The olives are then put in large tanks containing sodium hydroxide (NaOH) solution (1.5–2.5%), which facilitates removal of the oleuropein which is responsible for olive's bitter taste. Olive fruits remain in the NaOH solution for 4–15 hours depending on the cultivar, size, and maturity of fruits. The NaOH solution must not reach the pit, because a small amount of oleuropein is desirable to give a characteristic taste to the olives. The olives are then washed with water to remove NaOH. Subsequently, the olives are placed into containers and covered with 10% (10 Be) brine (sodium chloride) solution. Olives remain in the brine until ready for consumption. In order to avoid the presence of air, the containers must be fille up to the top with brine solution. The containers are periodically checked and brine is replenished, if necessary. Under these conditions, fermentation of sugars occurs. For a good fermentation, lack of air, high sugar content, and presence of lactobacteria are needed.

American-Style Black Olives

The olives are normally purple and hand-harvested. This style of table olives was initially produced in California and the method has spread to Algeria, Spain, Greece, and other countries. The black color is obtained by oxidation of polyphenols of the olives with air, in the presence of NaOH solution.

Greek-Style Black Olives

Greek-style olives are harvested ripe. After washing, fruits are put into barrels containing brine. Initially, the brine solution has a concentration of about 6%, but salt is gradually added to increase the concentration to 8%. In winter, due to the low temperatures, fermentation practically stops, but as temperatures

rise in spring, fermentation resumes. The fully fermented olives have little bitter taste; they are packed and marketed as Natural Greek-style black olives.

Kalamon-Style Greek Olives

For this particular style of table olives, the Greek cultivar Kalamon is used. Olives of this unique Greek cultivar have specifi characteristics, such as very cohesive pulp, small pit, and a bright black color. Kalamon or Kalamata olives are considered a special product. Although many people have tried to imitate this style of olives by using other cultivars, no one has succeeded in producing olives of quality and characteristics similar to those of Kalamata olives. For this special product, the olives are harvested when fully ripe (but not overripe), and have cohesive texture and satisfactory color. Olives are transferred to the factory in perforated crates. If not processed immediately, they are kept in large tanks immersed in water for 2–3 months. If the fruits are to be processed immediately, they are selected and classifie according to size. Then, they are slotted lengthwise twice and placed in tanks covered with water, which is changed every day for 7 days to facilitate removal of water-soluble oleuropein. Containers of different sizes are fille with the olives and a mixture of brine and vinegar is added. The brine used is about 9 Be and the proportion of brine to vinegar is 3/1. Finally, a layer of good quality olive oil is added to the top of the containers.

Several traditional-style table olives are produced in olive-producing countries, having characteristics not described here.

Spoilage

There are a number of types of spoilage of green table olives (Spanish-style):

Shrinkage

This is a serious spoilage of the olives that can either be reversible or not. The shrinkage may happen due to following reasons:

1. *Low temperature*: Exposure of the olives to low temperatures for short periods of time causes a mild shrinkage, but the olives will regain their original form later. However, when the exposure is continuous and extended, the shrinkage is permanent. In this case, the olives should not be used since they will decompose when immersed in alkaline solution or brine.
2. *Prolonged drought*: In this case, the shrinkage is usually reversible and the olives return to their normal condition.
3. *Brine with high concentration*: The olives can absorb only a limited amount of salt when they are immersed into the brine solution. When the salt percentage of the brine is too high, it can cause shrinkage in olives. The shrivelled olives are considered a low-quality product and they may not return to their original forms even if they are immersed in water.

Blisters and Skin Scratch

This type of spoilage of the green olives is caused during alkali treatment. If the temperature of the lye solution is higher than 21°C, scratches and blisters on the skin may appear.

Texture Softening

This is a serious spoilage that can lead to an unacceptable product. The reasons causing this spoilage are as follows:

1. *Hot or very thick alkali solution*: This spoilage takes place during the process of removing the bitterness from the olive fruit.

2. *High temperature*: Canned olives exposed to high thermal processing may be damaged.

Gas Spoilage (Fish Eye)

This spoilage is caused by microorganisms producing CO_2 or a mixture of CO_2 and H_2. Enterobacteriaceae such as *Escherichia* and *Enterobacter* are responsible for this spoilage. The extent of the spoilage depends on:

1. The number of e*nterobacterials* present in brine;
2. The temperature during the firs stages of fermentation; and
3. The salt content of the brine.

Butyric Fermentation

Butyric fermentation generally appears soon after the green olives have been immersed in brine. This spoilage is caused by the proliferation of the anaerobic bacterium *Clostridium butyricum*. The odor of the spoiled olives is like unpleasant rancid butter. In general, butyric fermentation appears when the salt concentration is low and the temperature in the fermentation area is high.

Zapatera

The spoilage that causes bad odor is known as *Zapatera* or *Zapateria*; this spoilage downgrades the olive's taste, also giving out an unpleasant odor while decreasing its cohesion and texture. It is associated with low acidity in brine (pH $>$ 4.2). *Zapatera* spoilage is caused by propionic acid bacteria (*Propionibacterium* spp. and *Clostridium* spp.). The best ways to prevent this spoilage are:

1. To control the pH of the brine to 3.6–3.8;
2. To increase salt content in brine (above 8.5%); and
3. To maintain high hygienic conditions during the fermentation and storage.

Propionic Fermentation

As fermentation proceeds, there may be an increase in volatile acetic and propionic acids. The formation of propionic acid in brine is affected by:

1. pH
2. Salt content
3. Temperature

The formation of propionic acid is favored by relatively high temperature. When free acidity, pH, and salt content are appropriate, the formation of propionic acid is considerably decreased.

Soft Texture

This spoilage of the texture is caused by the action of pectinolytic enzymes and fungi.

Marks/Spots

Occasionally off-white spots appear on the skin of green olives at the end of the processing period. It was believed that these were groups of yeast cells. The microbiological examination though proved that they are groups of cells of *L. plantarum*. These spots are harmless for human consumption but they degrade the appearance of the fina product.

Olive Oil

Processing of Oil Olives

To obtain oil of good quality, olives must be collected at the optimum maturity stage (change of the color from green-yellow to black-purple) and processed immediately after harvest (Kiritsakis 1998). The typical processing steps in olive oil processing

are weighing, washing, crushing, malaxation (mixing), separating, and centrifuging the oil.

After washing, the olive fruit is transferred to the crushing unit. The purpose of crushing is to facilitate the release of the oil from the vacuoles. After the olive fruit is crushed, the resulting olive paste is mixed in the malaxator. Malaxation entails stirring the olive mash slowly and constantly for about 30 minutes. The purpose of this procedure is to maximize the release of oil from the vacuoles.

The temperature of the malaxator should be low (not higher than 27°C), in order to prevent destruction of volatile constituents of the oil.

Separation of Oil from Olive Paste

The main constituents of olive paste are olive oil, small pieces of kernel (pit), cellular debris of crushed olives, and water. Pressure or centrifugation is applied for the separation of oil from the other constituents.

The pressure process is the oldest and is widely used to obtain olive oil. The resulting olive paste, i.e., after crushing and malaxation, is placed in oil diaphragms. Upon applying pressure, a liquid phase made up of oil and water is obtained from the olive paste, which is passed through a vertical centrifuge to separate oil from water.

Centrifugation process is a relatively new process for separating the oil from the olive paste and is based on the difference in density between the olive paste constituents (olive oil, water, and insoluble solids). Separation is accomplished through a horizontal centrifuge (decanter). The speed at which two immiscible liquids are separated when they are subjected to centrifugal force is governed by the Stoke's law expressed as follows:

$$V = \frac{D^2}{18} \times \frac{(d_2 - d_1)\omega^2 r}{\eta}$$

where V = speed of separation, D = diameter of the drops of liquid with the higher, density, d_1 = density of the lighter liquid, d_2 = density of the heavier liquid, ω = angular speed, r = distance from the rotating arms, η = viscosity of the liquid with the lower density.

Horizontal centrifuge (decanter) consists of a cylindrical-conical bowl. Inside the centrifuge, there is a hollow, similarly shaped component with helical blades. If water is added for the centrifugation, the temperature of the added water must not be higher than 27°C so as to avoid destruction of the fl vor components of the oil.

Final Centrifugation of Olive Oil

A fina centrifugation of the oil through a vertical centrifuge is needed regardless of the process followed (pressure or centrifugation) for its separation from the other constituents of the fruit.

Two-phase centrifugal-type olive oil mills

When a three-phase centrifugal-type olive oil mill is used for the separation of the oil from the olive paste, water needs to be added to the decanter, which results in large amounts of wastewater. However, the difficult in recycling the wastewater and the demand for better oil quality resulted in the modificatio of the three-phase decanter. Thus, new centrifuges (decanters) that do not necessitate use of water to separate the oily paste into two-phase (oil and oily pomace) have been developed. The two-phase decanters are, thus, ecological systems because of little polluting effluen streams generated.

Oil obtained by the two-phase decanter showed higher oxidative stability as a result of higher amount of phenolic content (Table 33.1), lower turbidity and pigmentations, steroid hydrocarbons, waxes, and alcohols as compared to oil from the three-phase system (Di Giovacchino et al. 1994; Di Giovacchino 1996).

One of the latest two-phase Italian olive processing lines, made by the Pieralisi Company, is shown in Figure 33.8.

Table 33.1 Quality characteristics of olive oils obtained by two and three-phase decanters

Quality characteristics	Two-phase	Three-phase
Acidity (%)	0.35	0.34
Peroxide value (meq/kg)	3.8	4.3
Total polyphenols (mg/L as gallic acid)	333	220
o-diphenols (mg/L as caffeic acid)	342	165
Rancimat stability (induction time) in hours)	15.3	11.6
Chlorophyll pigments (ppm)	6.3	6.6
K_{232}	1.548	1.438
K_{270}	0.105	0.091

Adapted from Di Giovacchino (1996).

Composition of Olive Oil

Olive oil is composed of triacylglycerols and contains small quantities of free fatty acids (FFA), glycerol, phosphatides, pigments, fla vor compounds, sterols, unidentifie resinous substances, and other constituents. Olive oil constituents can be divided into two categories, the *saponifiabl fraction* (FFA, triacylglycerols, phoshpatides) and the *unsaponifiabl fraction* (hydrocarbon, fatty alcohols, etc.). The unsaponifiabl constituents of virgin olive oil account for 0.5–1.5% of the oil, while in olive pomace oil, these constituents are about 2.5%. Some of the nonglycerol constituents (unsaponifiabl matter) contribute to the oxidative resistance and to the fl vor quality of olive oil.

The Fatty Acids of Olive Oil

The major fatty acids present as triacylglycerols in olive oil are oleic (C18:1), linoleic (C18:2), palmitic (C16:0), and stearic acid (C18:0). The fatty acid composition of olive oil can vary depending on the cultivar, fruit quality, as well as genetic and environmental factors (Amellotti et al. 1973; Kiritsakis and Markakis 1987). However, the olive oil contains more oleic acid (55–83%) than other fatty acids.

Table 33.2 shows the fatty acid composition of olive oil.

The Triacylglycerols of Olive Oil

Most of the fatty acids of olive oil are present as triacylglycerols (triglycerides). When diacylglycerols are present, olive oil is of low quality. Fedeli (1977) reported the major triacylglycerols as POO (18.4%), SOO (5.1%), POL (5.9%), OOO (43.5%), OOL (6.8%),

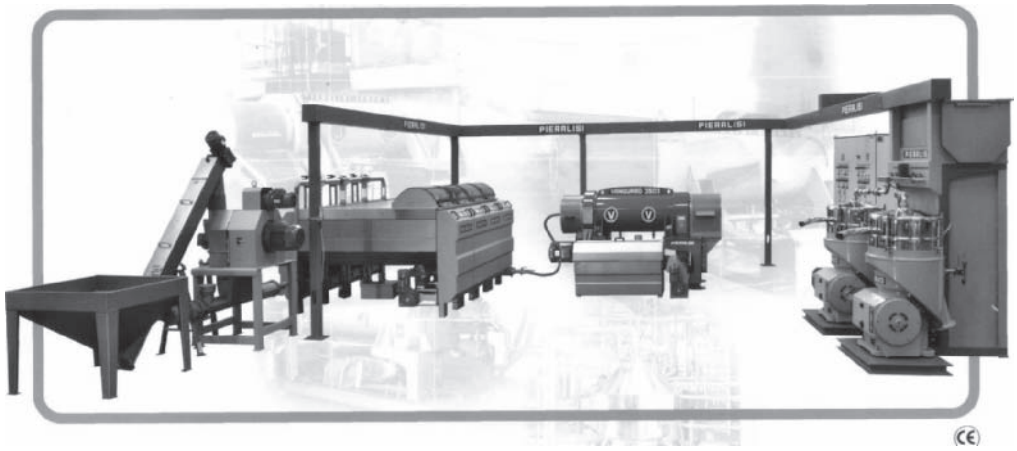

Figure 33.8 A complete olive processing line of the PIERALISI company, showing all the machines of the two phases, centrifugal process. (Courtesy of PIERALISI Co.)

Table 33.2 Fatty acids of olive oil

Acid	Content (%)
Oleic	55.0–83.0
Palmitic	7.5–20.0
Linoleic	3.5–21.0
Stearic	0.5–5.0
Palmitoleic	0.3–3.5
Linolenic	≤1.0
Myristic	≤0.05
Arachidic	≤0.6
Behenic acid	≤0.2
Lignoceric	≤0.2
Heptadecanoic	≤0.3
Heptadecenoic	≤0.3
Eicosenoic (Gadoleic acid)	≤0.4

Adapted from International Olive Oil Council (2008).

(P, palmitic; O, oleic; S, stearic; and L, linoleic acids). The three major triacylglycerols of olive oil are LOO, OOO, and OOP.

Olive oil, like other vegetable oils, shows a high concentration of oleic and low concentration of saturated fatty acids in position sn-2. The determination of palmitic acid in position-2 of olive oil triacylglycerols can be used to detect olive oil adulteration.

Minor Nonglyceride and Glyceride Constituents

Several minor nonglyceride (unsaponifiable constituents are present in olive oil. The nonglyceride fraction of olive oil contains nonglyceride fatty acid esters, hydrocarbons, sterols, triterpene alcohols, tocopherols, phenols, chlorophylls, fl vor compounds, and polar phenolic compounds such as hydroxytyrosol. Mono- and diglycerides, phosphatides, waxes, and esters of sterols are also considered as minor constituents.

Some of the nonglyceride constituents of olive oil are biologically active and analytically very significan in characterizing olive oil because of their distinctive features. Quantitative analysis of certain minor constituents such as *sterols* and *triterpene alcohols* indicates the authenticity of olive oil. Squalene, which is a biochemical precursor of sterols, is an important hydrocarbon of olive oil. Squalene is the major constituent (up to 40% by weight) of olive oil unsaponifiables Olive oil contains the largest amount of squalene among vegetable oils.

Other hydrocarbons such as polycyclic aromatic (phenanthrene, pyrene, fluoran threne, 1,2-benzanthracene, chrysene, etc) were found in olive oil.

Olive oil contains α-tocopherol in a range of 12–150 ppm. Fedeli (1977) reported that the concentration of different tocopherols in olive oil was as following: α-tocopherol: 88.5%, β-plus γ-tocopherol: 9.9%, and δ-tocopherol: 1.6%. Refine olive oil contained very low levels of γ-tocopherol. The tocopherol content of olive oil depends not only on the presence of these constituents in the fruit, but also on several other factors involved during transportation, storage, and processing of the olives.

Saturated straight-chain aliphatic alcohols with even carbon atoms (C18 to C28) are found in olive oil. The main linear aliphatic alcohols present in olive oil are hexacosanol, octacosanol, and tetracosanol. Tricosanol, pentacosanol, and heptacosanol may also be present in traces. The olive pomace oil, obtained by solvent extraction, contains more aliphatic alcohols than virgin olive oil.

Waxes are esters of fatty alcohols with fatty acids. The main waxes found in olive oil are esters C36, C38, C40, C42, C44, and C46. Olive pomace oil contains more waxes than virgin olive oil. The determination of waxes can be used as a method for detecting adulteration of olive oil with solvent extracted oil.

Olive oil contains β-sitosterol, Δ-5-avenasterol, and campesterol (Fedeli 1977; Itoh et al. 1981). Stigmasterol, cholesterol, 24-methylene-cholesterol, Δ-7-campesterol, Δ-5,23-stigmastadienol, sitostanol, Δ-5,24-stigmastadienol, Δ-7-stigmastenol and Δ-7-avenasterol are also present in olive oil but in smaller quantities.

The unique color of virgin olive oil is due to the presence of chlorophyll and pheophytin.

Carotenoids are also responsible for the color of olive oil (Serani and Piacenti 1992). Olive oil contains chlorophyll a and chlorophyll b.

Phenolic Compounds

Olive mesocarp contains both simple and complex phenolic compounds which are water-soluble. Small quantities of phenolics, however, are present in olive oil, which increase its oxidative stability and improve fl vor (Fedeli 1977). Phenolic compounds present in olive oil are characterized as "polyphenols" and cover a big part of the unsaponifiabl fractions.

Phenolic compounds are also present in olive leaves and are a source of radical scavengers throughout the year. The differentiation observed in the levels of individual components depends rather on sampling period than on cultivar or age (Papoti and Tsimidou 2009). Figure 33.9 shows phenolic compounds identifie in olive leaves of three Greek cultivars.

Phenolic compounds have a significan effect on olive oil fl vor and these affect the fla vor stability of olive oil (Kiritsakis 2007). Hydroxytyrosol, tyrosol, caffeic, coumaric, and p-hydroxybenzoic acids have the greatest effect on the fl vor characteristics of olive oil. Montedoro et al. (1978) reported that hydroxytyrosol found in olive oil is of very good quality, while tyrosol and some phenolic acids found in olive oils are of poor quality. Some of these compounds have a sharp negative effect when they are present above certain concentrations.

Flavor Compounds

Aroma and fl vor are distinctive features of olive oil compared to other edible oils, and they are generated by a number of volatile compounds present at extremely low concentrations (Lercker et al. 1973; Fedeli 1977; Montedoro et al. 1978; Kiritsakis and Min 1989; Sanchez Saez et al. 1991; Morales et al. 1994; Blekas and Guth 1995; Aparicio et al. 1996; Kanavouras et al. 2005). Hexanal, trans-2-hexenal, 1-hexanol, and 3-methylbutanol are the major volatile compounds of olive oil. Table 33.3 gives the volatile compounds of virgin olive oil isolated by dynamic headspace thermal desorption (DHS-TD) apparatus using Tenax-TA at different conditions.

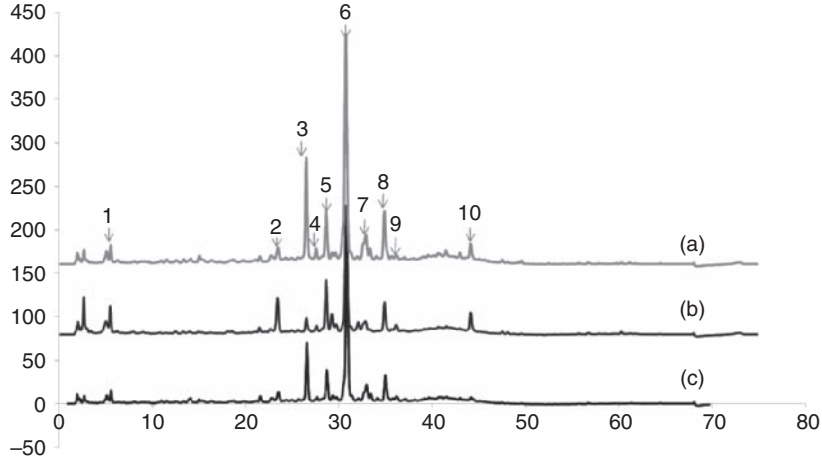

Figure 33.9 RP-HPLC chromatograms of the three cultivars at 280 nm UV absorbance (1: secologanoside, 2: demethyloleuropein, 3: oleuropein diglucoside, 4: luteolin-7-O-glucoside, 5: rutin, 6: oleuropein, 7: oleuroside, 8: quercetrin, 9: ligstroside, 10: verbascoside). (a), Kalamon; (b), Koroneiki; (c), Megaritiki) Adapted from Kiritsakis et al. (2009).

Table 33.3 Volatile compounds of virgin olive oil isolataed by dynamic headspace thermal desorption (DHS-TD) apparatus using Tenax-TA at different conditions*

		GC area (%)					
Compound name	RT (minutes)	1a	1b	1c	1d	1e	1f
Acetic acid	1.57	0.37	9.75	1.57	0.14	0.20	0.11
Ethyl-2-methyl-butyrate	3.95	8.24	1.06	3.95	22.02	30.05	26.2
3-Methyl-butanol	4.5	1.66	3.58	4.5	0.98	0.84	0.71
4-Methyl-2-methyl-butanol	4.75	0.23	0.035	4.75	0.97	0.50	0.55
Ethyl iso butyrate	5.05	0.16	2.90	5.05	0.90	0.28	0.83
l-Penten-3-one	5.58	1.13	0.04	5.58	0.36	7.98	0.32
Hexanal	6.10	0.94	1.64	6.10	15.66	0.005	14.21
(Z)-3-hexenal	7.00	0.037	0.05	7.00	0.10	5.83	0.10
(E)-2-hexenal	7.60	0.04	N.D.	7.60	9.90	0.499	9.04
(Z)-3-hexenol	7.75	0.35	N.D.	7.75	0.95	2.46	0.87
Hexanol	8.50	6.08	0.20	8.50	3.44	0.42	3.01
2-Heptenal	12.56	1.12	N.D.	12.56	0.086	0.11	0.064
a-Farnecene	13.02	0.78	0.99	13.02	0.19	0.05	0.146
Quaiacol	13.60	0.075	0.45	13.60	0.24	0.33	0.166
(Z)-3-hexyl acetate	14.28	1.53	0.12	14.28	0.21	N.D.	0.18
Nonanal	14.85	0.12	0.27	14.58	0.44	N.D.	0.34
2-Octenal	15.46	0.12	N.D.	15.46	N.D.	N.D.	0.14
2,4-Heptadienal	16.36	1.62	N.D.	16.36	0.43	0.10	0.36
2-Pentyl ethyl alcohol	18.80	0.10	1.67	18.80	0.50	N.D.	0.45
2 Decenal	19.60	3.84	0.56	19.6	0.04	0.08	N.D.
(Z)-2-nonenal	20.50	0.13	2.91	20.50	0.037	0.17	N.D.
2-Undecenal	21.42	0.40	1.16	21.42	0.30	N.D.	0.25
(E,E)-2,4-decadienal	24.00	0.69	0.21	24.00	N.D.	0.19	N.D.

*1a, 1b, 1c, 1d, 1e, and 1f represent different applied conditions (sample weight, fl w rate, collecting time). Adapted from Kanavouras et al. (2005).

Formation of Volatile Compounds

Volatile compounds are formed in the olive fruit by enzymic reactions. These reactions proceed at a high rate depending on both pH and temperature. Olias et al. (1993) proposed an enzymic pathway for formation of olive oil fl vor compounds (hexenal, cis-3-hexenal, trans-2-hexenal, and corresponding esters). Triacylglycerols and phospholipids are hydrolyzed to FFA, mainly polyunsaturated, by acylhydrolase. 9- and 13-hydroperoxides are formed by lipoxygenase, from linoleic and linolenic acids. Lyase cleaves the 13-hydroperoxides of linoleic and linolenic acids to form the volatile aldehydes hexanal and cis-3-hexenal, respectively.

Factors Affecting the Formation of Volatile Compounds

According to Lercker et al. (1973), olive oils from different regions of Italy differed quantitatively in their volatile constituents. Figure 33.10 shows that olive oil samples, obtained from olive oil mills in Greece, had different volatile aroma constituents and 2-hexenal was present in the highest concentrations in all the samples (Savvidou 2009).

Different cultivars produce oil of different sensory characteristics under identical conditions of environment and cultivation. Climatic and soil conditions, cultivation practices, maturity of fruit, and storage conditions influ ence the fl vor quality of the oil. Processing techniques and storage conditions also affect the fl vor compounds of olive oil (Kiritsakis 2007).

Although much work has been done to separate and identify the volatile components of olive oil, more research is still needed to determine which factors are responsible, and to what extent, for the unique and delicate taste and fl vor of good quality olive oil.

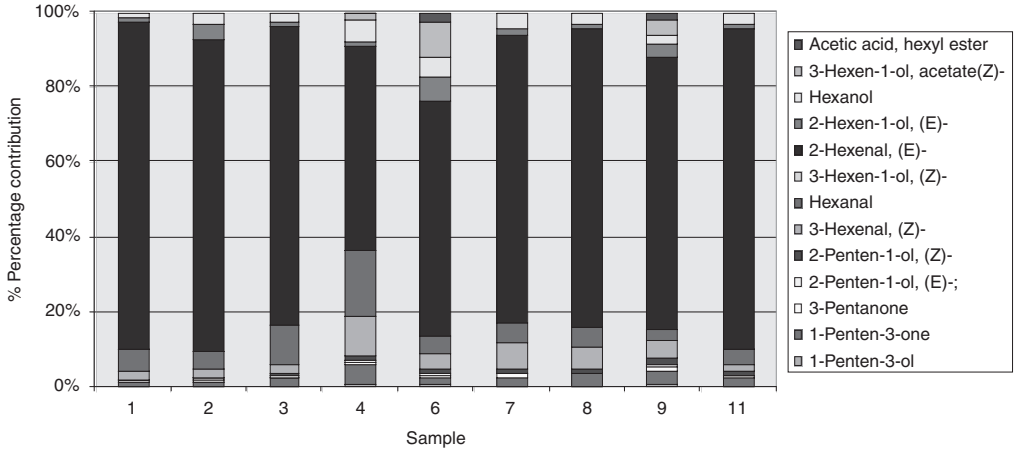

Figure 33.10 Percentage contribution of the main aroma components in different olive oil samples. Adapted from Savvidou (2009).

Storage—Packaging and Bottling

Olive oil must be held at low temperature (around 10°C) and in dark, particularly if stored for several months, to minimize deterioration during storage (Kiritsakis 1998). The degree of deterioration is a continuous and irreversible process of oxidation and depends on the storage conditions. Proper storage temperature in stainless steel tanks extends the shelf life of olive oil.

Physical characteristics of the packaging material may affect significantl the quality of oil depending on the extension of interactions. Permeability, migration, and scalping are interactions that occur between the olive oil and the packaging material (Demertzis and Kontominas 1986a, 1986b) which affect the quality and even safety aspects of the oil.

Material used for bottling and packaging olive oil can be plastic, glass, tinplate, aluminum, stainless steel, fibe glass, and plastic-coated card board.

Glass is one of the most inert materials used for bottling. Transparent glass is widely used for bottling olive oil because the oil is visible by the consumer. This practice, however, leads to the photoxidation (Kiritsakis and Dugan 1985) of olive oil and the reduction of shelf life. The use of colored glass bottles for bottling olive oil prevents or slows down the process of oxidation (Mastrobattista 1990; Kiritsakis 1998; Kiritsakis 2007).

Chestnut and oak wood containers have been used for packaging olive oil but they are no longer in use. Tetra brick cartons are being used recently in Greece, Spain, Italy, and other countries. Tetra brick packaging is inexpensive and is considered suitable for packaging olive oil. Recently, olive oil in the form of spray appeared in the international market. We strongly believe that the use of opaque bottles is a necessity.

Quality and Nutritional Profile of Olive Oil

Quality Criteria Classification

Acidity, oxidation, and sensory characteristics are the basic criteria to be considered when evaluating the quality of olive oil. The determination of polyphenols is also useful for characterizing olive oils (Ingele 1994; Kiritsakis 2007). Acidity has traditionally been used as a basic commercial criterion for grading olive oil. For virgin olive oil, the acidity must be $\leq$2.0% expressed in oleic acid. Determination of oxidation is also a main criterion for evaluating the quality of olive oil.

Oxidation is evaluated by peroxide value (PV) and ultraviolet (UV) absorbance. For virgin olive oil, PV must be ≤ 20 (meq O_2/kg oil).

The color of olive oil is a quality indicator as well. It may vary among olive oils obtained at different harvesting times. It is green at the beginning of the harvesting season when the olive fruit is still immature and the presence of chlorophyll is dominant. As maturity advances, the oil turns golden-yellow because of the carotenes present, while overripe fruit gives olive oil of a light green to brownish color, mainly due to pheophytins present.

Sensory Evaluation of Olive Oil

The above criteria are not enough for evaluating olive oil quality. Sensory evaluation is necessary and is the most important criterion for determining its quality. With sensory evaluation, one can make a judgment on both aroma and taste (fl vor) of the oil.

Volatile compounds (aldehydes, ketones, esters, saturated and unsaturated alcohols, and others) are responsible for the aroma of the oil. The taste of the oil is influence by all of the above constituents. It is also generally affected by fatty acids (mainly oleic and linoleic) and the polyphenols present. Each of the volatile components has its specifi fl vor and aroma (pungent, metallic, fruity, apple, fresh, sweet, etc.). Therefore, the aroma of the oil depends on the predominant volatile components.

For the best sensory evaluation of virgin olive oil by panel techniques, experts from various countries carried out a series of studies under the direction of the International Olive Oil Council. As a result, the "organoleptic assessment of virgin olive oil" was proposed by creating a grading system based on a descriptive analysis of positive and negative attributes of virgin olive oils.

Positive Attributes

Fruity: This characteristic of oil is unique of the olive cultivar and appears if the olive fruit is collected at the optimum maturity stage. It is perceived directly or through the back of the nose.

Bitter: This is the characteristic taste of oils obtained from green olives. It can be more or less pleasant, depending on its intensity. It is well accepted only by some consumers. The consumers should know, however, that bitter olive oil is good for health.

Pungent: Biting tactile sensation characteristic of oils produced at the beginning of the crop year, primarily from olives which are still unripe.

Negative Attributes

Fusty: Characteristic fl vor of oil obtained from olives stored in piles for some time which have undergone an advanced stage of anaerobic fermentation.

Musty-humid: Characteristic fl vor of oils obtained from olive fruit in which a large number of fungi and yeasts have been developed. This is mainly due to storage in humid conditions for several days.

Muddy sediment: Characteristic fl vor of the oil, which has been left in contact with the sediment that settles in underground tanks and vats.

Winey-vinegary: Characteristic fl vor of certain oils reminiscent of wine or vinegar. It is mainly due to the fermentation of olive fruit leading to formation of acetic acid, ethyl acetate, and ethanol in large amounts.

Metallic: Flavor that is reminiscent of metals. Characteristic of oils which have been in prolonged contact with metallic surfaces during olive fruit processing steps (crushing, mixing, pressing, etc.) or during storage of the oil.

Rancid: Characteristic fl vor of oil which has undergone oxidation.

Heated or burnt: Characteristic fl vor of oils, caused by excessive and/or prolonged heating during the malaxation (mixing) of olive paste.

Hay-wood: Characteristic fl vor of certain oils obtained from dried olives.
Rough: Thick, pasty mouthfeel sensation of certain oils.
Greasy: Flavor of oil reminiscent of diesel oil, grease, or mineral oil.
Brine: Flavor of oil obtained from olive fruit preserved in brine.
Esparto: Characteristic fl vor of oil obtained from olives pressed in new esparto mats. The fl vor may differ depending on whether the mats are made of green or dried esparto.
Earthy: Characteristic fl vor of oil obtained from olives which have been collected along with earth or mud on them and have not been washed.
Grubby: Characteristic fl vor of oil obtained from olives which have been heavily attacked by the olive fl .
Cucumber: Flavor produced when olive oil is hermetically packed for too long, particularly in tin containers. This is attributed to the formation of the compound 2,6-nonadienal.

Classification of Olive Oil

Virgin olive oil is the oil obtained from the fruit of the olive tree only by mechanical or physical means and which has not undergone any treatment other than washing, decantation, centrifugation, and filtration The virgin olive oil can be consumed as it comes out from the olive oil mill. According to the authors, the virgin olive oil must be characterized as a natural juice. Some main categories of olive oil are presented here (FAO 2009).

Extra Virgin Olive Oil

Virgin olive oil, which has a maximum acidity, expressed as oleic acid, of no more than 0.8 g/100g, and meets the requirements for the sensory (organoleptic) characteristics and other quality criteria of this oil category.

Olive oil is classifie as *extra virgin* when the median of the defects is equal to 0 and the median of the fruity attribute is more than 0.

Virgin Olive Oil

Virgin olive oil which has a maximum acidity, expressed as oleic acid, of no more than 2.0 g/100 g, and meets the requirements for the sensory (organoleptic) characteristics and other quality criteria of this oil category.

Olive oil is classifie as *virgin* when the median of the defects is more than 0 and less than or equal to 2.5 and the median of the fruity attribute is more than 0.

Olive Oil

Oil consisting of a blend of virgin olive oil and refine olive oil. This oil is not considered virgin, because it contains olive oil which has undergone refinin process.

Bitter oils are usually obtained from unripe olives (some olive cultivars produce oil with more bitterness). Although such oils may be rejected for consumption, they are highly resistant to rancidity. They are often added to other oils of low bitterness. The bitterness decreases with time and the oil ends up with an excellent fl vor.

Improving Olive Oil Quality

Several factors affect the fina quality of olive oil. In order to obtain the best quality of olive oil (low acidity, negligible oxidation, and best sensory characteristics) the following factors must be applied:

1. Protect the olive fruit from any kind of infestation while it is still on the tree.
2. Collect it at the optimum maturity stage with minimum damage (Kiritsakis and Markakis 1984) and store it for the shortest possible time under favorable conditions (cool place) before processing.

3. Use stainless steel equipment for processing; avoid high temperature and excessive exposure to air.
4. Store and pack the oil in proper containers at low temperatures under minimum contact with air and exposure to light (pack under vacuum or inert gas).

Nutritional and Functional Properties of Table Olives and Olive Oil

Table olives are considered one of the basic components of human nutrition, especially in the olive-producing countries. They have a high calorifi value and a pleasant taste and fl vor. They reduce bad cholesterol which is responsible for heart diseases. The nutritional value of olives differs according to cultivar, the processing conditions, and sometimes the ingredients added (garlic, red pepper, etc.).

Olives are an excellent source of oleic acid (an omega-9 monounsaturated fatty acid). The stability of monounsaturated fats exhibit a protective effect on the cell, especially when combined with the antioxidant protection offered by polyphenols and fl vonoids and vitamin E (Visioli and Galli 1998; Fito et al. 2000; Visioli et al. 2000; Bendini et al. 2007). They prevent oxidation of low-density lipoprotein (LDL) (Frarkel et al. 1993; Mateos et al. 1995; Mateos et al. 2001; Covas et al. 2006) and lower the risk of damage and inflammation

Inflammatio has been linked to a wide range of conditions such as heart disease and cancer. An active ingredient, found in greater concentrations in fresher olives, is called oleocanthal, which inhibits the activity of enzymes involved in inflammatio in the same way as anti-inflammator drugs (Beauchamp et al. 2005)

Oleocanthal is a tyrosol ester and its chemical structure is related to oleuropein. It is suggested that long-term consumption of small quantities of oleocanthal from olive oil may account to be the cause for the low incidence of heart disease associated with the Mediterranean diet.

By-products of Oil Olives Processing

Olive pomace and wastewater are the main by-products of the oil fruit processing. Olive pomace is the pulpy material remaining after removing most of the oil from the olive paste. The commercial value of the olive pomace depends mainly on its oil content, which in turn depends on the process (pressure or centrifugation) and other conditions applied. Olive pomace contains fragments of skin, pulp, pieces of kernels, and some oil, while polyphenols and some other constituents may also be found in it.

As indicated before olive fruit contains up to 70% water. This water along with the water added during the processing of olives in the olive oil mill constitutes the wastewater.

Sugars are the most predominant organic substances present in wastewater from the olive oil mill and include readily fermentable sugars (glucose and fructose). Small quantities of mannose and sucrose are also present. Nineteen amino acids have been identifie in the wastewater, where the nitrogen content was 2.5%. Organic acids (acetic, fumaric, glyceric, lactic, malic, malonic, tartaric, tricarballylic, oxalic, etc.) and small amounts of emulsifie olive oil are present. Wastewater also contains significan quantities of inorganic salts, a large proportion of which are soluble (phosphates, sulphates, chlorides) and the remaining (about 20%) are insoluble (carbonates, silicates). Most of the minerals have been found in the wastewater. Sodium, potassium, calcium, and phosphorus have been determined in significan quantities.

Phenols and polyphenols are also found in wastewater (Hamdi 1993). The total polyphenol content of the vegetable water is considerably higher than that of the olive pomace.

Among the polyphenols, caffeic acid, tyrosol, and hydroxytyrosol are found in high quantities. Tannin concentrations range from 8 to 16 g/L. Large quantities of anthocyanin compounds are present in wastewater.

Summary

In recent years, olives and mainly olive oil has received a wide recognition throughout the world for their beneficia effect on our health. The research efforts concerning the production, processing, storage and handling, packaging, and preservation have been supported by improvements and expansions in the fiel of technology allowing more accurate and in-depth studies of important constituents and quality factors. Exchange of information and knowledge between researchers and other people working in the olive technology and nutrition will further assist to create olive products with more functional characteristics to meet the consumer's preferences and demands; for instance, 10% less salt than usual would make table olives tastier and healthier.

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Chapter 34

Potatoes: Production, Quality, and Major Processed Products

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Introduction

Potato (*Solanum tuberosum* L.) is the number one nongrain crop with an estimated world production of about 309 million metric tons (MMT) in 2007. It is believed that potato cultivation originated about 8,000 years ago in the highlands of the Andes Mountains, in what is now Peru and Bolivia. In the sixteenth century, Spanish travelers brought potato to Europe and from there, its cultivation spread to other parts of the world. According to the International Potato Center (CIP, Lima, Peru), potato is grown for food in about 100 countries, under temperate, tropical, and subtropical climates.

Although a subsistence crop, potato and potato products are of great economic and nutritional significance Advancements in agriculture, postharvest handling, and processing have opened opportunities for developing and introducing new potato products with better sensory and nutritional qualities. However, improvement in agricultural and agronomic practices to produce high-yielding, early maturing, disease- and pest-resistant varieties suitable for and processing requires continuous efforts. Potatoes sprout easily, requiring proper pre- and postharvest handling, grading, storage, and transportation infrastructures to extend their shelf life and quality.

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

As we learn more about the benefit of naturally occurring phenolic compounds, the likely contribution of potatoes, having relatively high levels of phenolic compound chlorogenic acid, to our health is of interest. Similarly, other potato constituents such as "resistant potato starch" (having physiological benefits) vitamin C, and lutein (found in yellow-fleshe potatoes, and which may help to slow the onset of age-related macular degeneration of eyes) are important to our health. Nonetheless, there are some health concerns as well, such as reports about potentially carcinogenic acrylamide in high heat processed potato products. In this chapter, we review information related to production, postharvest handling and storage, consumption, physicochemical, functional, phytochemical, nutritional, and processing aspects of potatoes and major potato products.

Production and Consumption

World Production

Although cultivated throughout the world, Food and Agriculture Organization's (FAO) 2007 production estimates showed that more than 80% of the 309 MMT world potato production originated in Asia (116 MMT) and Europe (132 MMT). Figure 34.1 shows the top producers China and India, accounted for 25% of the estimated world potato production in 2007.

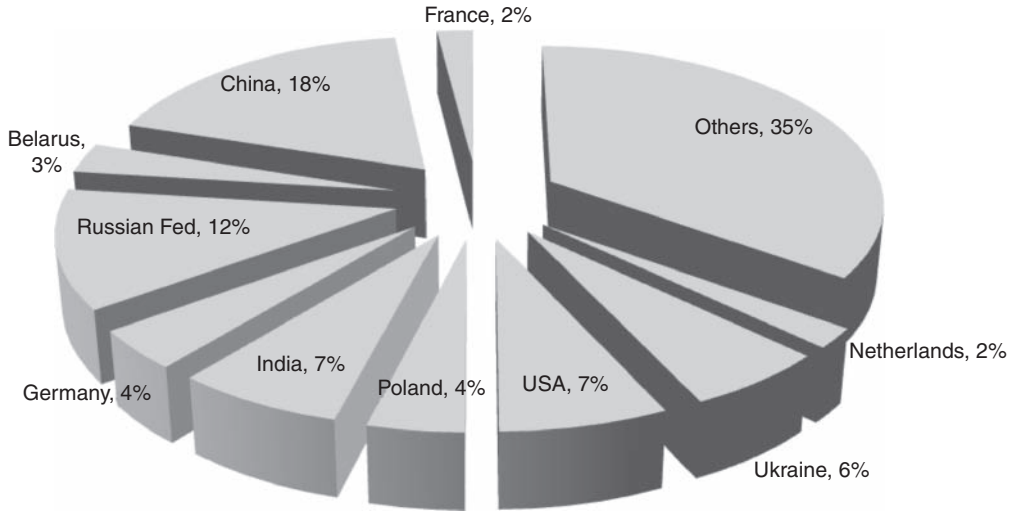

Figure 34.1 World potato production and share of top producing countries.

Potato Varieties and Classification

In the United States, a national network of potato breeders is primarily responsible for the maintenance of parental lines, traditional and novel breeding, fiel trials, and release of potato varieties. University-based research and teaching centers, such as the one at Michigan State University, provide varietal identificatio support to farmers (Coombs et al. 2004). Pest and disease concerns remain very high in the potato industry (Davies et al. 2008). Completion of the potato genome DNA sequencing by 2010 should provide better understanding of resistance or susceptibility of tubers to pests and diseases and suitability for processing into products.

Traditional recombinant DNA technologies have produced transgenic potato varieties having resistance to pests and diseases, and higher yields. For example, Monsanto developed Russet Burbank potatoes containing *Bacillus thuringiensis* (Bt) gene responsible for the production of CryIIIA protein, which causes paralysis and death of susceptible coleopterans like the Colorado potato beetle. Similar techniques have been used to confer disease resistance from viral diseases. Transgenic potatoes also offer opportunities for nutrient fortificatio to alleviate worldwide malnutrition. However, environmental and food safety concerns must be carefully assessed and addressed before their release (Thornton 2003).

Potato varieties can be classifie and grouped according to size, shape, color, texture, taste, and cooking characteristics. Table 34.1 summarizes selected potato varieties according to their use. A majority of commercial potato varieties in North America having white fles are classifie as "white potatoes." Potatoes are also classifie on the basis of their skin color (e.g., reds: Red Ruby; yellows: Yukon Gold; whites: Kennebec); texture (e.g., smooth: Norland; slightly netted: Pike); tuber shape (round, slightly flattened Snowden; oval to round: Atlantic); and fles color (cream: Belrus; light yellow: Yukon Gold).

Classificatio of potatoes can also be based on: (1) the pest and disease resistance, whether tolerant or susceptible (e.g., scab and verticillium wilt tolerant: Atlantic); (2) physiological maturity, e.g., early maturity (harvested within 90–120 days of planting), mid-season (120–150 days), and late

Table 34.1 Selected potato varieties and their utilization

Tablestock					
Baking	Boiled	French fries	Fresh market	All purpose	Chip stock
Yukon gold	Yukon gold	Yukon gold	La rouge	Viking	Snowden
Lemhi russet	Norgold russet	Lemhi russet	Nordonna	Irish cobbler	Gemchip
Norgold russet	Centennial russet	Belrus	Russet norkotah	Katahdin	Norchip
Centennial russet	White rose	Frontier russet	Norking russet	Chieftain	Norwis
Belrus	Krantz	Norland	Red la soda	Castile	Pike
Frontier russet	Norland	Allegany	Sangre	Cascade	Kennebec
White rose		Castile	Goldrush	Allegany	Monona
Russet Burbank		Cascade	Red pontiac	Sebago	Chipeta
Hilite russet		Hilite russet	Century russet	Susset burbank	Atlantic
			Superior	Calwhite	Kanona
			Russet nugget	Century russet	La chipper
			Nooksack	Monona	Castile
			Onaway	Kennebec	Sebago

Source: http://www.umaine.edu/paa/var.htm.

maturity (150–180 days). Early varieties bred for temperate climates require a day length of 15–17 hours, while late varieties produce good yields under long and short day conditions (Anon 2008); and (3) performance during storage to maintain dormant physiological state (e.g., quite long: Norking Russet; medium: Russet Nugget).

Cultural Practices and Yield

Although the potato areas harvested globally declined from 22.1 million hectare (ha) in 1961 to 18.5 million ha in 2007, the average potato yield per hectare has increased from 12.2 metric ton/hectare (MT/ha) to 16.7 MT/ha during this period (FAOSTAT 2009). The top fi e countries with the highest 10-year (1998–2007) average yield were New Zealand (44.0 MT/ha), Belgium (43.9 MT/ha), Netherlands (43.6 MT/ha), United States (41.9 MT/ha), and the UK (41.2 MT/ha).

Potatoes require well-drained and well-aerated soil. The potato plant has a shallow root system; hence, yield response to frequent irrigation such as through a mechanized sprinkler system can be significan (Anon 2008).

Potatoes serve as a host to a variety of pests, weeds, and diseases (Table 34.2) that

Table 34.2 Priority pests, disease, and weeds of potatoes

Rank	Organism	Pest type	Index*
1	Early blight (*Alternaria solani*)	Disease	3.1
2	Late blight (*Phytophthora infestans*)	Disease	2.2
3	Aphids (*Myzus persicae*)	Insect	1.8
4	Colorado potato beetle (*Leptinotarsa decemlineata*)	Insect	1.4
5	Lambsquarter (*Chenopodium album*)	Weed	1.0
6	Pigweed (*Amaranthus* spp.)	Weed	0.9
7	Grasses (annuals)	Weed	0.7
8	Potato leafhopper (*Empoasca fabae*)	Insect	0.6
9	Fusarium rot (*Fusarium* spp.)	Disease	0.5
10	Nightshade (various spp.)	Weed	0.4

Source: Guenthner et al. (1999).
*Average number of annual pesticide applications targeting the particular pest/disease/weed.

have variable impact on its yield and tuber quality. Crop rotation is a standard practice in the production of potatoes to prevent disease and pest buildup, as well as to improve soil fertility (Mazurak et al. 1954; Rees et al. 2002; Po et al. 2009). Rotating potatoes with non-*Solanaceous* crops can break the cycle of disease inocula, reducing diseases in succeeding potato cultivations. In addition, use of disease-free seed potatoes can help reduce pest and disease incidences.

Harvest and Postharvest Handling

Based on physiological maturity, the proper time to harvest potatoes is signaled by yellowing and senescence of potato leaves and plants. However, other considerations include potato pulp temperature, susceptibility to blackspot bruising, and soil moisture (Bohl 2003). Vine kill is usually performed 2 weeks prior to harvest when the potato skin is properly set to improve its defenses against storage diseases and shrinkage. Sulfuric acid, dinoseb [2-(1-methylpropyl)-4,6-dinitrophenol], diquat (6,7-dihydrodipyrido [1,2-α:2′,1′-c] pyrazinediium ion), and endothal (7-oxabicyclo[2.2.1] heptane-2,3-dicarboxylic acid) are active ingredients used in chemical desiccants for vine kill (Haderlie et al. 1989). Blackspot susceptible varieties like Russet Burbank and Ranger Russet need a specifi stage of vine maturity before vine kill is initiated. Irrigating the potato fiel a day or two before harvest for light textured soil (2–4 days for heavier soils) tends to improve the ease of separation of the tubers from the soil. Potato pulp temperature of about 10–15°C is ideal to prevent shattering of hydrated potato tubers at low temperatures. Blackspot bruising is a problem with warm and dehydrated tubers. Simple farm tools (e.g., spading fork) or mechanized farming equipments can be used for harvesting. A tandem of machines which can harvest several hectares a day is typically composed of two eight-row diggers, a harvester with GPS (Global Positioning Systems) aided yield monitors, and trucks to carry harvested tubers from the field (Figure 34.2). Assigning physical fiel coordinates to yield through GPS helps analyze yield data and other production variables (Po 2007).

Upon harvest, potatoes are graded using specifi country standards. The US standards for seed, processing, and chipping potatoes are given in Table 34.3.

It is important to monitor potato harvest for presence of tuber rot diseases that can cause problems during storage. An estimate of the extent of rotting is necessary through test dig prior to harvesting an entire field A threshold of 5% rot or frost damage level, or presence of net necrosis may lead to tubers being sold at harvest.

Figure 34.2 Potato diggers and GPS-equipped harvesters.

Table 34.3 USDA Potato Grades for processing and chipping (USDA 1978, 1983)

Potato usage/grade	Basic requirements	Free from	Diameter (mm)
Processing			
US No. 1	Similar varietal characteristics; moderately firm and fairly well shaped.	Freezing or freezing injury; Blackheart; late blight tuber rot; Southern bacterial wilt; bacterial ring rot; insects, worms or larvae; soft rot and wet breakdown; and, loose sprouts, dirt and foreign material.	50.9
US No. 2	Same as US No. 1 in addition to not seriously misshapen	Same as US No. 1	38.1
Chipping			
U.S. No. 1	Similar varietal characteristics, firm fairly clean, and well-shaped	Freezing; Blackheart; late blight tuber rot; southern bacterial wilt; bacterial ring rot; nuts of nutsedge; tuber moth injury; soft rot, and wet breakdown	47.7
U.S. No. 2	Similar varietal characteristics, fairly firm not seriously damaged by dirt, not seriously misshapen.	Same as US No. 1	44.5

Source: USDA (1978, 1983).

Suberization, Wound Healing, and Storage

Upon harvest, the potato skins are soft and somewhat immature and can be easily bruised or wounded. The maturation and development of corky skin-set is critical to prevent diseases and retain quality during long-term storage of potatoes. Through suberization (enzymatic polymerization of phenolics into cork-like suberin) and wound healing, the potato skin is allowed to fully set and mature before application of sprout inhibitors and storage. Stark et al. (1994) investigated suberization in potatoes by histochemical and high-resolution solid-state nuclear magnetic resonance (NMR). In this process, phenolic substances formed provide protection against microbial invasion and moisture loss. The critical curing period is optimized for wound healing by firs removing fiel heat within 2–3 days of storage through a combination of temperature (10–15°C) and humidity control (~95%). The humidity level can be adjusted if presence of rot organisms is observed. After 2–3 weeks of curing and depending on use, storage temperature can be lowered.

Standard storage temperatures for potatoes are 4.4°C (40°F) for table use, 7.2°C (45°F) for French fry potatoes, and 10–13°C (50–55°F) for chipping potatoes (Swift 2007). It is important to minimize prolonged exposure to light, which causes undesirable greening in potatoes due to formation of glycoalkaloids.

Sprout Inhibitors

Potato tubers enter into dormancy after harvest and during this physiological state they do not initiate bud/sprout formation (Suttle 2004). This is desirable as potatoes are normally stored prior to use and the goal is to have sprout-free potatoes. Storage at low temperature would prolong dormancy, but, as discussed later, for processing potatoes conversion of starch to sugars at low storage temperature can be an issue.

Use of a chemical sprout inhibitor, chloropropham (CIPC), has been effective means of sprout inhibition for the past four decades. It is important to apply CIPC after the curing process, as its mode of action is inhibition of cell division, a critical step in the formation of the new wound periderm. A standard CIPC

application rate is 1 kg of active ingredient to 60 tons of potatoes. CIPC is applied as a liquid aerosol and it is critical that the air ducts of the storage facility are properly situated to ensure even application, otherwise sprout inhibition will not be effective. Other agents that can be used for sprout inhibition are essential oils (e.g., Carvone), peppermint and spearmint oils, and substituted Naphthalenes (e.g., 1,4-Sight and Amplify*)* (Kleinkopf and Olsen 2003).

Potato Consumption and Utilization

According to United States Department of Agriculture's (USDA) vegetable and melons yearbook, potato is consistently the number one vegetable consumed both as fresh and processed. Figure 34.3 shows the utilization of potatoes produced in the United States. According to USDA data, in 2007, Americans consumed 125.5 lb (~57.0 kg) of potatoes of which 39.2 lb (~18.0 kg) and 86.3 lb (~39.0 kg) were fresh and processed, respectively. Frozen potatoes (essentially French fries) top the list with per capita consumption (PCC) of about 24.0 kg, followed by chips (8.5 kg), dehydrated (6.0 kg) and canned (0.4 kg) potatoes. The relatively high consumption of French fries is believed to be due to its convenience and demand for food-away-from home.

The value-added market for potato is ever-expanding. Various product development efforts are aimed at creating low-fat French fries, potato chips, and new products. There is also growth in demand for organically grown and specialty use potatoes with softer skin that can be baked and eaten with skin as a way to provide more fibe in the diet. A variety of recipes are prepared at home, including fries, baked and boiled fresh potatoes, mashed potatoes, potato pancakes, dumplings, soup and salad, twice-baked potatoes, and potatoes *au gratin*. Potatoes are used alongside other meal preparations and in mixed vegetable preparations. According to the FAO latest available data, during 2003, the estimated consumption of potato in the world was about 32 kg/capita/year (or about 88 g/day). However, in Belarus potato consumption was 172 kg/capita/year, followed by Ukraine (140 kg), Latvia (139 kg), Poland (130 kg), and Russian Federation (125 kg).

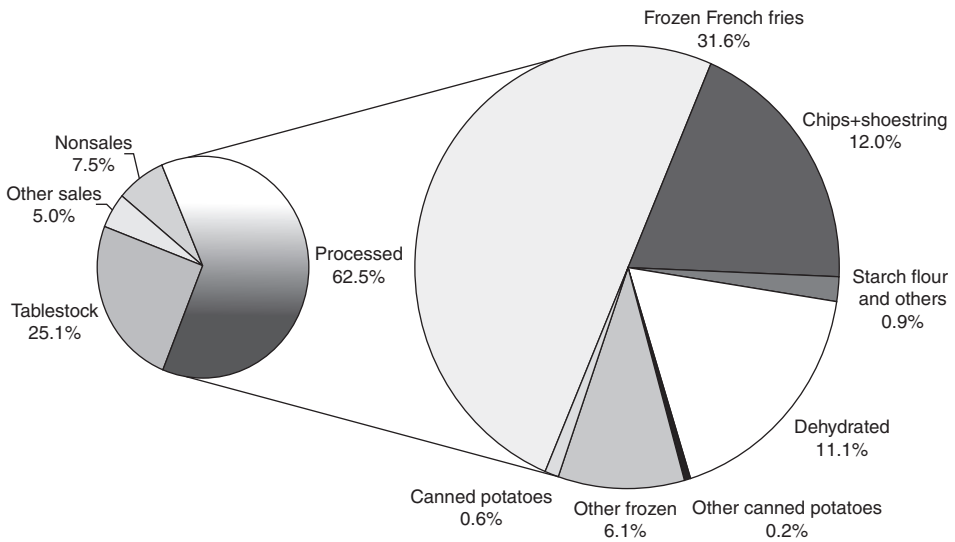

Figure 34.3 Percentage utilization of table potatoes and potato products in the United States.

Physicochemical, Functional, Phytochemical, and Nutritional Qualities

Physicochemical and Functional Qualities

Specific Gravity

Specifi gravity, closely related to the solids content and the dry matter of potatoes, is monitored prior to processing of potatoes into products and as a grading tool. Processors of chips, French fries, dehydrated and other products usually require potatoes with high specifi gravity to obtain better quality and higher yielding finishe product. Further, use of high specifi gravity tubers (less moisture, so less frying time and lower oil uptake) reduces frying oil requirements during potato chip manufacturing. The low specifi gravity tubers are normally used in canning and cooking.

The specifi gravity of potato determined as a ratio of:

$$\frac{\text{(Weight of tubers in air)}}{\text{(Weight of tubers in air)} - \text{(weight of tubers in water)}}$$

can range from 1.060 (16.4% solids) to 1.090 (22.8% solids). Besides variety, harvest maturity, soil nutrition, and irrigation, several other factors such as tuber size, shape, and wetness, defects such as hollow heart, dirt and debris adhering to tubers, tuber and water temperature (ideal temperature for measurement is about 10°C), presence of air bubbles, etc., can affect specifi gravity measurements. Near-infrared spectroscopy has been experimented for nondestructive measurement of specifi gravity of potatoes (Chen et al. 2005).

Starch and Sugars

Depending upon a variety, growing conditions, and physiological maturity, potato tubers contain high levels of dry matter and starch, and low levels of sugars. An early study by Samotus and Schwimmer (1962) showed increase in dry matter (from 16 to 23%) and starch (from 11 to 18.0%), but decrease in sucrose (from 0.8 to 0.4%), glucose (from 0.3 to 0.1%) and fructose (from 0.1 to 0.07%) in White Rose and Kennebec potato varieties harvested after 60 and 102 days of plantings. About 80% of the dry matter in potatoes is starch and unlike cereal starches, the size of potato starch granule is large (5–100 μm). The potato starch contains about 20% amylose, a linear chain of (1->4)-linked α-D-glucopyranosyl unit, and about 80% amylopectin, a large branched chain molecule. The potato amylopectin is unique in having a phosphate ester group attached to one in every 200–250 α-D-glucopyranosyl units (Whistler and BeMiller 1997). The potato starch swells rapidly in warm water, has high viscosity, good clarity, and low rate of retrogradation.

Role of Sugars

Even with a slight increase in sugars, potatoes would produce dark color chips. Therefore, for chipping potatoes, Sowokinos and Preston (1988) suggested sucrose and glucose threshold as 1.0 mg/g fresh weight and 0.35 mg/g fresh weight, respectively. Sinha et al. (1992) showed significan negative correlation between potato chip color and glucose, but not with sucrose.

Starch Sugar Interconversion

Starch to sugar interconversion is a much studied phenomena in potatoes because of their role in storage and processing (Isherwood 1973; Pollock and Aprees 1975; Iritani and Weller 1977; Ewing et al. 1981; Sinha et al. 1990). Several hypotheses have been proposed including permeability changes in the amyloplast surrounding the starch granules. Investigations have also looked at compositional differences between cold-tolerant (low sugar accumulating) and cold-sensitive (high sugar-accumulating)

tubers in relation to chip processing (Blenkinsop et al. 2002). Low storage temperature (3–5°C) with high humidity helps minimize sprouting which causes loss of weight, nutrients, and softening of potatoes during long-term (~8 months) storage. However, there is a "cold sweetening," a build-up of sugars during prolonged low temperature storage of potatoes. Typically, potatoes are treated with sprout inhibitors such as maleic hydrazide (applied to foliage at the time of blossom abscission) and chloropropham (CIPC: isopropyl *N*-3-cholorophenyl carbamate) applied prior to storage, and stored at about 10°C to minimize sprouting and sugar accumulation.

Potato Texture

In a study (Dijk et al. 2002) of a firm a mealy (cooking imparts dry-appearing tissue that crumbles readily), and an intermediate cooking potato cultivar, the dry matter was shown to correlate with sensory-perceived texture. Mealy potato cultivars are liked for baking, mashing, chipping, and frying, whereas waxy (having high amylopectin) potatoes, which when cooked have moist appearance and disintegrate less, are liked for use as salad and creamed potatoes (McComber et al. 1988).

Proximate Composition

Potato tubers are about 80% water. A major portion of potato solids is starch, followed by protein and fibe . Table 34.4 gives the proximate composition of edible portion of a typical potato tuber.

Approximately 6% of a potato tuber consists of peel having slightly higher amounts of ash, crude fibe , protein, ribofl vin, and folic acid (Table 34.5) than the flesh

Potato Protein

As indicated in Table 34.4, potato contains about 2% protein. In comparison to egg protein considered a standard with a protein effi ciency ratio (PER), % biological value (BV), and % net protein utilization (NPU) of 3.9, 94.0, and 93.0, potato protein's PER, BV, and NPU are 2.6, 73.0, and 60.0. The potato protein has relatively better nutritional quality than the rice protein with a PER, BV, and NPU of: 2.2, 64.0, and 57.0 (Belitz et al. 2004). Patatin (MW: 43 kDa), a storage protein which makes up >40% of the total soluble protein in potatoes, has been suggested to have antioxidant activity due to its cysteine and tryptophan amino acid residues (Liu et al. 2003).

Table 34.4 Proximate composition of edible portion of potatoes

Component	Value /100 g
1. Water	78.58
2. Total carbohydrate (by difference)	18.07
3. Starch	15.86
4. Dietary fibe	1.30
5. Sugars	0.61
6. Protein	2.14
7. Total lipids	0.08
8. Ash	1.13

Source: http://www.nal.usda.gov/fnic/foodcomp.

Potato Lipids

Potato contains a very small amount of lipids (Table 34.4) made up of (Prescha et al. 2001) phospholipids (47%), glyco- and

Table 34.5 Selected nutrients and vitamins in flesh and peel of raw potatoes (based on 100 g wet basis)

Component	Potato fles	Potato peel
1. Dry matter (%)	21.6	17.0
2. Ash (%)	0.86	1.67
3. Crude fibe (%)	0.37	1.83
4. Protein (%)	1.81	2.67
5. Ascorbic acid (mg)	14.4	11.8
6. Thiamine (mg)	0.10	0.03
7. Ribofl vin (mg)	0.036	0.058
8. Niacin (mg)	1.57	1.05
9. Folic acid (mg)	12.8	17.3
10. Vitamin B6 (mg)	0.22	0.21

Source: Augustin et al. (1979).

galactolipids, which are membrane structural elements (22%), and neutral lipids such as acylglycerols and free fatty acids (21%). The major fatty acids in potato are (Dobson et al. 2004) palmitic (18–21%), linoleic (43–53%), and linolenic (16–26%). The latter two polyunsaturated fatty acids can oxidize to form short-chain volatiles including aldehydes, ketones, and alcohols, and alkyl furans, which give unpleasant odors in potato products.

Minerals and Vitamins

Although potato contains most of the minerals (iron, copper, zinc, calcium, magnesium, selenium, manganese) of nutritional significanc in relatively small amounts, it is considered a valuable source for potassium (417 mg/100 g of edible portion) in our diet. However, Bethke and Jansky (2008) reported 50–75% losses in potassium in samples boiled immediately after dicing or shredding and suggested boiling, baking, roasting, or microwaving whole tubers to minimize loss of minerals. Potato varieties differ in their mineral composition. Casanas et al. (2002) showed positive correlation between potassium concentrations of fi e potato varieties and their protein and starch contents.

Potatoes contain water-soluble vitamins. As can be true for other nutrients, variety, growing conditions, harvest maturity, storage, and processing conditions affect the vitamin contents of potatoes and its products. About 42% of vitamin C was shown to be lost upon storage, but thiamin, niacin, and vitamin B6 appeared to be stable during storage (Table 34.6).

Table 34.6 Dry matter and vitamins in freshly harvested and stored potatoes*

	Freshly harvested mg/ 150 g wet basis	Stored mg/150 g wet basis
Dry matter	20.96	21.37
Ascorbic acid	36.05	21.15
Thiamin	0.122	0.135
Ribofl vin	0.066	0.057
Niacin	2.46	2.24
Folic acid	0.024	0.019
Vitamin B6	0.258	0.386

*Values are average of 8 commercial potato varieties grown at different location (*Source*: Augustin et al. 1978).

Potato Flavor

Lipid and sugar degradation and/or the Maillard reaction involving reducing sugars and nonsulfur amino acids, sulfur compounds (sulfur amino acids, methionine, and cysteine), methoxypyrazines, and terpenes have been reported as the primary cause of volatile notes in potatoes (Oruna-Concha et al. 2001; Duckham et al. 2002). Table 34.7 lists selected fl vor compounds of importance in potatoes.

Di et al. (2003) reported improvement in the primary fl vor compound methional responsible for the cooked potato fl vor we like (through Strecker degradation involving interaction of Maillard reaction intermediate α-dicarbonyl with methionine), by increasing the level of soluble methionine in fiel grown transgenic potatoes. Potato off-fl vors (POF) have been associated with (E,E)2,

Table 34.7 Selected flavor compounds in potato products

Compound	Flavor
2-isopropyl-3-methoxypyrazine	Raw potato, potato-like, earthy (mainly in skin)
3-(methylthio)propionaldehyde (Methional)	Cooked/baked potato-like
Dimethyl disulfid	Onion-like, cooked cabbage
(E,E)-2,4-decadienal	Oily, deep fried like
2-ethyl-3,6-dimethylpyrazine	Nutty, roasted, earthy, baked potato like
1-octen-3-ol	Mushroom-like
(E)-2-nonenal	Cucumber, cardboard-like (in boiled stored or pre-cooked potatoes)

Source: Oruna-Concha et al. 2001.

4-nonadienal,(E,E)-2,4-decadienal, hexanal, (E)-2-octenal, and (E)-2-nonenal (Jenssen et al. 1999). In boiled potatoes, formation of umami fl vor was reported (Morris et al. 2007) due to umami amino acids, glutamate and aspartate, and the 5′-nucleotides, guanosine monophosphate (GMP) and adenosine monophosphate (AMP).

Phytochemical and Nutritional qualities

Phenolic Compounds and Antioxidant Capacity

Naturally present phenolic compounds with physiologically beneficia effects on oxidative stress-linked chronic diseases (cancer, heart disease, memory loss, aging, etc.) have gained dietary significance A study of potato tubers along with other foods (Wu et al. 2004) indicated total antioxidant capacity of white and red potatoes as approximately 11.0 μmole TE/g fresh weight. The total phenolic content measured as gallic acid equivalent was about 1.5 mg/g fresh weight (Table 34.8). The peel and the cortex tissue just below the peel of the potato tubers contain most of phenolic compounds (Reeve et al. 1969). The free phenolic compounds in potato tubers have been reported (Mendez et al. 2004) as (+)-catechin (11.4 mg/100g wet weight), chlorogenic acid (10.2 mg/100 g wet weight), caffeic acid (0.93 mg/100 g wet weight), p-coumaric acid (0.085 mg/100 g wet weight), and ferulic acid (0.25 mg/100 g wet weight). Depending on the cultivar, potato peel can contain 3–20 times more chlorogenic acid than the pulp (Im et al. 2008).

Nutritional Quality

Table 34.9 gives typical nutritional content as per the nutritional labeling and education act (NLEA) of the United States. As can be expected, potato products are a good source of carbohydrate, but they can be also a good source of protein in our diet. Potato and products are high in potassium. Potato chips are rather high in fat content; thus, there is interest in developing products with lower fat content.

Quality Issues

Chlorogenic Acid and After-Cooking Darkness

Upon exposure to air, undesirable after-cooking darkening (ACD) of boiled and

Table 34.8 Antioxidant capacity and total phenolics of commonly eaten vegetables

Vegetables	%M*	L-ORAC†	H-ORAC‡	TAC§	TP¶
1. Potatoes (white)	81.7	0.49	10.10	10.59	1.63
2. Potatoes (red)	80.9	0.38	10.60	10.98	1.38
3. Onions (red)	87.7	0.11	11.35	11.46	1.26
4. Tomatoes	93.6	0.34	4.26	4.60	1.00
5. Corn	78.1	1.35	5.93	7.28	2.11
6. Carrots	88.7	0.59	11.56	12.15	1.25
7. Beets	88.1	0.09	27.65	27.74	2.44
8. Snap beans	92.8	0.55	2.13	2.67	0.92
9. Broccoli	90.8	1.72	14.18	15.90	3.37
10. Asparagus	92.7	1.02	29.15	30.17	1.41
11. Eggplant	91.8	0.24	25.09	25.33	2.52

Source: Wu et al. (2004).
*Moisture.
†Lipophilic oxygen radical absorbance (μmole Trolox equivalent/gram) capacity.
‡Hydrophilic oxygen radical absorbance capacity (μmole TE Trolox equivalent /gram.
§Total antioxidant capacity (μmol TE/gram).
¶(mg of Gallic acid equivalent/gram).

Table 34.9 Nutritional values per 100 grams in potato and selected potato products

Nutrients/100 gram	Unit	White potatoes (with skin)	Canned potatoes (without salt)—drained	French fries (salt added; frozen)	Potato chips (plain, salted)	Mashed potatoes (dehydrated fla es)
Calories	Kcal	69.00	62.00	133.00	547.00	354.00
Total fat	g	0.10	0.20	3.39	37.47	0.41
Saturated fat	g	0.025	0.051	0.688	10.960	0.169
Polyunsaturated fat	g	0.041	0.085	0.218	12.170	0.143
Cholesterol	mg	0.00	0.00	0.00	0.00	0.00
Sodium	mg	6.00	5.00	317.00	525.00	104.00
Potassium	mg	407.00	229.00	400.00	1642.00	1098.00
Total carbohydrate (by difference)	g	15.71	13.60	23.51	49.74	81.17
Dietary fibe	g	2.40	2.40	1.90	4.40	6.60
Sugar	g	1.15	0.59	0.20	0.37	3.36
Protein	g	1.68	1.40	2.19	6.56	8.34
Vitamin A	IU	8.00	2.0	4.00	0.00	11.00
Vitamin C	mg	19.70	5.1	18.40	18.60	81.00
Calcium	mg	9.00	5.0	9.00	24.00	27.00
Iron	mg	0.52	1.26	0.65	1.61	1.21
Water	g	81.58	84.30	69.29	2.28	6.58

Source: www.nal.usda.gov/fnic/foodcomp.

cooked potatoes has been linked to a ferric iron-chlorogenic acid complex (Friedman 1997). Citric acid and other chelating agents can inhibit this discoloration. Silva et al. (1991) showed that in "Spartan Pearl" potatoes, ACD was highly correlated with phenolic acid measured as chlorogenic acid ($r = 0.85$, $p < 0.01$), and higher levels of ACD were characterized by lower citric acid/phenolic acid ratios.

Potato Polyphenol Oxidase

Enzyme polyphenol oxidase (EC 1.14.18.1) catalyzes two reactions: (a) orthohydroxylation of monophenols to o-diphenols, and (b) dehydrogenation of o-diphenols to reactive o-benzoquinones. Benzoquinones can undergo non-enzymatic oxidation by O_2, and polymerize to form undesirable dark brown melanin pigments, found in cut/bruised potato tissues. Sapers et al. (1989) reported that the tendency to undergo enzymatic browning of different potato varieties was related to: phenolic compounds, amino acid tyrosine, and potato polyphenol oxidase (PPO) activity. For example, Atlantic cultivar was better than Russet Burbank in terms of browning because it had lower PPO activity, total phenolics and tyrosine. The specifi activities of potato PPO in Russet Burbank and Atlantic have been reported to be 4.59 and 2.46, respectively (Hsu et al. 1988). The PPO activity was not a limiting factor for blackspot pigment synthesis, but amino acid tyrosine was the main determinant for the degree of discoloration of damaged cells (Stevens and Davelaar 1997). In a study related to browning development of fresh-cut potatoes, the indicator for browning appearance was Hunter color value L^* (brightness factor; on a 0–100 scale), which decreased from initial of 69 to 60.0 in 6 days at 4°C and 70% relative humidity (RH) in darkness (Cantos et al. 2002).

The browning/darkening problems can be prevented in several ways including vacuum packing, nitrogen purging, temperature control (water blanching at 100°C for about 3 minutes), storage of peeled cut blanched products under frozen (−17.8°C storage), pH

control (pH optima for potato PPO is about 5.5, reducing the pH with the aid of organic acid spray such as citric acid can be helpful), use of sodium chloride (inhibits PPO), ascorbic acid (quinone formed is reduced to original substrate), and sodium bisulfit (forms complex with quinone, thus preventing melanin formation). The ascorbic acid and citric acid combination can be used in place of sulfite to minimize PPO-related browning in potatoes.

Potato Glycoalkaloids

Potato contains glycoalkaloids, α-chaconine, and α-solanine. Because of food poisoning concerns, new potato varieties are tested for glycoalkaloid levels, and if the amount (total of α-chaconine and α-solanine) exceeds 20 mg glycoalkaloid/100 g, or 200 mg/kg tuber on a wet weight basis, the variety will most likely not be released (Bushway et al. 1983). The levels of these glycoalkaloids can vary in potato varieties. The skin contains significantl more glycoalkaloids (12.4–543 mg/kg of wet peel) than the fles (1.3–148 mg/kg). The glycoalkaloid content of potatoes is not affected by baking, cooking, and frying. Thus, potato products having high skin content should be watched (Friedman et al. 2003). Postharvest factors such as low storage temperature, light greening of potato (which is a sign of glycoalkaloid), and mechanical injury can increase glycoalkaloid content in potatoes (Fitzpatrick et al. 1978; Wu and Salunkhe 1978; Griffith et al. 1998).

Acrylamide Concerns in Potato Products

Tareke et al. (2002) reported formation of acrylamide (2-propenamide: CH_2 $CHCONH_2$; a known mutagen in rats and a probable carcinogens in humans), in potato and cereal-based (carbohydrate-rich) products subjected to high heat processing such as frying, grilling, or baking. Acrylamide is primarily formed when carbohydrate-rich foods are heated under high temperatures (in excess of 120°C or 248°F) due to Maillard reaction involving amino acid asparagine and reducing sugars glucose and fructose. Acrylamide is used in production of polyacrylamide (a polymer) which has a variety of uses including food packaging, treatment of drinking water, and industrial wastewater to remove suspended particles and solids. The US Environmental Protection Agency (EPA) requires that when added to water, the amount of uncoagulated acrylamide be less than 0.5 parts per billion (ppb or 0.5 μg/L); the eventual goal is for 0 μg/L.

Amrein et al. (2003) showed that the acrylamide contents of potato products can be reduced by using varieties with low concentrations of reducing sugars for processing into chips and French fries. Although amino acid asparagine is an important precursor in the formation of acrylamide, the availability of reducing sugar glucose can be a limiting factor in acrylamide formation during high heat processing of potato products (Granda et al. 2005). Further, within a variety smaller tubers (<50 mm size) because of higher reducing sugar content were shown to produce more acrylamide (322 ppb) than large (>50 mm size) tubers (148 ppb) (De Wilde et al. 2006).

Process modification such as soaking in acidic solution or blanching to remove reducing sugars or amino acids have been shown to minimize acrylamide formation in potato products. Kita et al. (2004) obtained 50 and 90% reduction of acrylamide in tubers soaked in 0.05 M citric acid and 0.15 M acetic acid for 1 hour at 20°C. Jung et al. (2003) showed 73.1 and 79.7% reduction in acrylamide formed in French fries by dipping potatoes in 1 and 2% citric acid solutions, respectively, for 1 hour before frying at 190°C for 6 minutes 30 seconds.

In 2008, upon settlement of a court case two US potato chip manufacturers, Frito-Lay and Kettle Foods agreed to reduce

acrylamide in their chips over a 3-year period to 275 ppb. Further, Kettle food was asked to place a warning label on its Cape Cod Robust Russets, which contained >7,000 ppb acrylamide. In 2009, Canada placed acrylamide onto Schedule 1 of the Canadian Environmental Protection Act, 1999 in order to minimize the public's exposure to this chemical.

Manufacturing of Major Potato Products

French fries, potato chips, dehydrated and canned potatoes are the major potato products. Besides these retail products, there is a demand for prepeeled packaged potatoes for salad bars. There are also various sizes of IQF (individually quick frozen) potatoes. Processing of potatoes involves preparatory steps of grading, testing, washing, peeling and blanching. Blanching is aimed at inactivating microorganisms and enzymes such as polyphenol oxidase, removing tissue gases, and gelatinizing starch which swells and upon cooling, enables a compact texture. The manufacturing of potatoes into products uses Hazard Analysis Critical Control Points (HACCP) principles, and standard operating procedures to prevent defective and unsafe products from entering into the market. In this section typical manufacturing processes for the major potato products are described.

Frozen French Fries (FF)

In the 1950s, J. R. Simplot Company of USA developed FF (called chips in the UK) for use by fast food and ready-to-eat food outlets and restaurants. Of the frozen potatoes utilized, more than 80% are in the form of FF. Consumers prefer fries that have light golden brown color, cooked potato fl vor, and tender but crisp and mealy (not gummy) texture. Potato varieties such as Russet Burbank, Kennebec, Yukon Gold, Saginaw Gold, etc., which have elongated oval shape, creamy white to golden yellow fles color, low reducing sugars, and high specifi gravity produce good quality fries.

During processing, proper cutting, blanching, and frying are important steps. The thinner and shorter cuts that do not meet grade requirements are used in other forms of frozen products like hash brown and patties. The potatoes can be either hot water or steam blanched (~95°C for 2 minutes). Partial frying (par-fry) is done at 177–190°C (350–375°F) for about 90 seconds (Figure 34.4). However, frying temperature and time would vary according to specifi gravity and reducing sugars of potatoes to achieve a uniform degree of color. Deep-frozen French fries targeting the retail market where cooking is completed by the oven method, are completely fried (5 minutes at 180°C) and packed a shade darker. Deep-frozen partially fried (3 minutes at 180°C) fries for institutional use need additional frying prior to serving, hence packed lighter. Further details of manufacturing frozen FF and frozen FF have been given by Talburt et al. (1987b) and Lisinska and Leszczynski (1989).

Fry color is evaluated as 0 (extra light), 1 (light), 2 (medium light), 3 (medium), and 4 (dark). Other quality characteristics inspected are (a) types: retail or institutional pack; (b) styles: strips (elongated pieces with parallel sides with approximate cross-section dimensions of 1/4″ × 1/4″, 3/8″ × 3/8″, 1/2″ × 3/4″, 3/4″ × 3/4″), straight cut (smooth surface), shoestring (can be either straight or crinkle cut with cross section area (3/8″ × 3/8″), crinkle cut (corrugated cut surface), or slices (pieces of potatoes with two practically parallel sides), dices (cubes), Rissole (whole or nearly whole potatoes); and (c) length (extra long: ≥80% are 2″ long and ≥20% are 3″ or longer; ≥70% are 2″ long, 15% or more are 3″ long; medium ≥50% are 2″ in length, or longer; short ≤50% are 2″ in length) designation for strips.

Hui (2004) and the USDA Standards for Potatoes (USDA 1967) describe the inspection standards and quality evaluation of

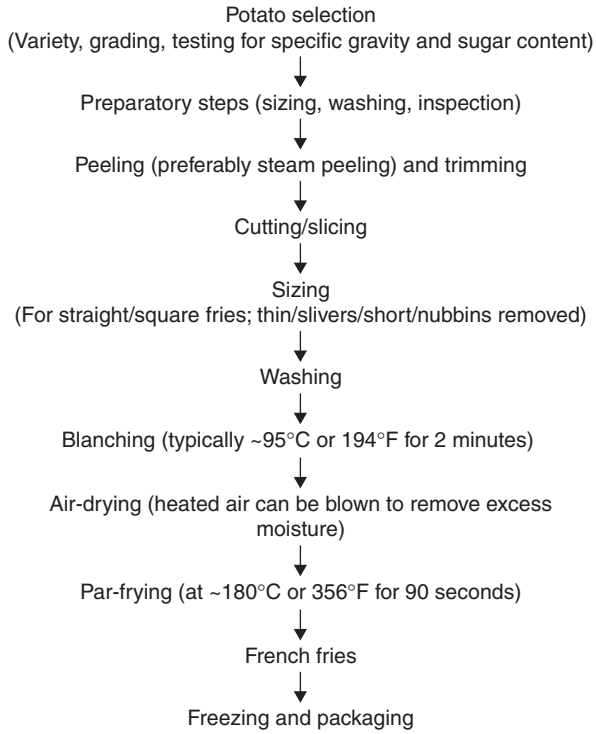

Figure 34.4 Process for making French fries.

French fried potatoes. The grades are: (1) "U.S. Grade A" or "U.S. Fancy" (except for short length) has a score of 90 and above on 100 point scale (color, 30; size and symmetry, 20; absence of defects, 20; texture, 30); (2) US "Grade A" (includes "shorts"): score of ≥90 as above; (3) US "Grade B" (except for "shorts"): having a score of not less than 80; and (4) substandard: does not meet the requirements of "Grade B."

Various other products fabricated from mashed, crushed, cut, or shredded potatoes preformed into various shapes prior to partial frying and freezing, including hash-browns, puffs, patties, are shown in Figure 34.5 and 34.5b.

Potato Chips

Potato crisps or "chips" (in the United Stated) are thin slices of deep-fried potato of about 2% moisture that come in a variety of fl vors—from the traditional salted and barbecue, Ranch and Cheddar favorites, to more gourmet and ethnic fl vors like vinegar and salt, Jalapeno, Mexican, or Thai chili. Figure 34.6 describes a typical process schematic for potato chip production.

Peeling should remove as little of the cortical tissue, which contains 40–50% of the total solids. Rinsing removes surface starch (which prevents potato slices from adhering to each other during frying) and sugars. Different fla vorings are uniformly dusted or sprayed on the chips by a rotating drum. Smith (1987) provided a review of chip manufacturing, different frying methods, use and handling of suitable fats and oils, and packaging. Varieties with high solids content (Sp. gr.∼1.09) produce chips with lower (∼32%) oils in chips and also give higher yields (∼33%). Potato chips are made both by the batch ("kettle

Figure 34.5 (a) and (b), Representative retail potato products.

chips") and continuous frying process. Use of reconditioned potatoes with little reducing sugar produces light colored chips. For health conscious consumers, baked potato chips as well as lightly salted (50% less sodium) versions are available (Figure 34.5b).

Dehydrated Potato Products

Many types of dried potato products including sun-dried potatoes, conventional hot air dried diced potatoes, infused dried potatoes, and potato fla es are manufactured. Since potatoes undergo enzymatic browning, blanching and use of sodium bisulfite sodium acid pyrophosphate or ascorbic acid, citric acid combination can help in the manufacture of dried potatoes. *Slices*/*Dices*/*Shreds* are prepared by slicing, dicing, or shredding peeled potatoes to specification and water blanching to prevent darkening and fl vor loss. The dehydrated products are used in dried or canned soups and stews, potato salads, casseroles, hash browns, extruded snack foods, mixes for dumplings and potato pancakes, as breading or as corn meal replacement.

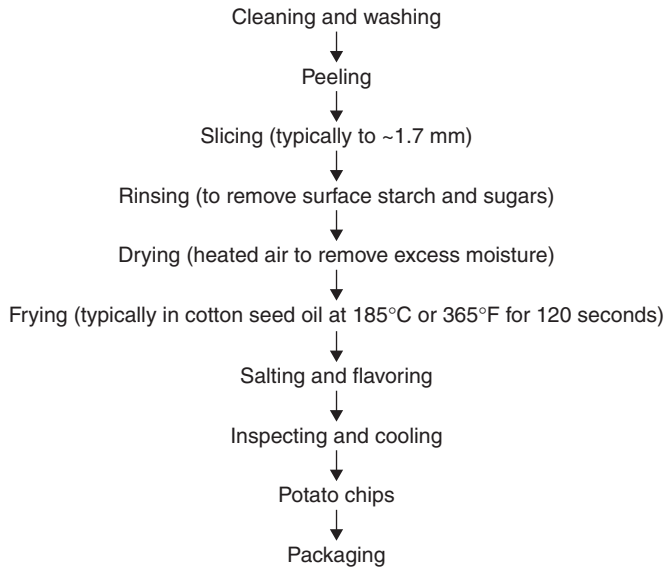

Figure 34.6 Process for making potato chips.

US patent 6,524,640 (Sinha 2003) described a process for high solids vegetables which can be used to make dried diced potatoes. Typically, dried potatoes have about 10% moisture and can be easily rehydrated for use in various food applications. *Dehydrated potato fla es* are reconstituted in hot water for use as mashed potatoes

Figure 34.7 describes typical process schematics.

Precooking gelatinizes the starch within potato cells for retrogradation to take place during cooling, but the temperature is not high enough for the softening of intercellular bonds. Cooling washes away free starch from the surface of blanched potatoes to avoid sticking or scorching during drying. Steam cooking should separate potato cells with minimum rupture, which is immediately followed by the mashing step to avoid cell rupture, which occurs when slices are cooled. Additives and emulsifier include chelating agents, milk solids, antioxidants, and sulfur dioxide. The drum-drying process (Willard et al. 1987) results in dried sheets of potato (5–8% moisture) prior to grinding into fla es.

Standard fla es are bright white in color, and are ground several times to provide a standard or ground standard fla e. Potato fla es are utilized in retail mashed potatoes, and as an ingredient in frozen dinners, snack, and

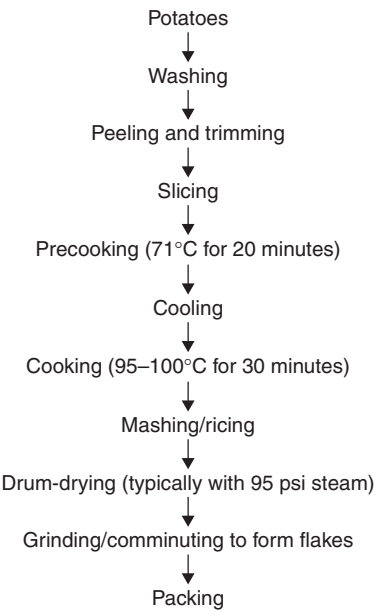

Figure 34.7 Process for making potato flakes.

soup products. Vitamins A and C fortifie potato fla es have been distributed by the U.S. international food assistance for feeding programs.

U.S. patent 6,994,880 (Martinez-Serna Villagram et al. 2006) described the process for preparing dehydrated potato fla es from potato slices, slivers and/or nubbins for use in dough composition used to make fabricated products. U.S. patent 4,241,094 (O'Neil et al. 1980) described a process for dehydrated potato fla es similar in texture and taste to freshly prepared mashed potatoes when reconstituted. In this patent, cooked, riced, and cooled potatoes are combined with another set of potatoes which have been peeled, sliced, blanched, cooled, cooked, riced and then cooled before further drying and flaking

Low peel/low leach fla es (LP/LL) are prepared like standard fla es, except for the elimination of the precooking and cooling steps. The resulting starchy texture is not suitable for mashed potatoes. The light peeling retains more potato fl vor but gives an off-white color. LP/LL fla es are used in sheeted and extruded potato snack products, or mixed with water and other ingredients into dough-formed potato snacks.

Standard granules are prepared using sliced, cooked, and dried potatoes, and the production process is similar to fla es until the mashing stage. The cooked potato mash is gently mixed with dry "add-back" granules, which absorb moisture and produce a dried, granular product with small agglomerates of potato cells. The technique of shearing and pressing of add-back granules against cooked potato tissue minimizes the rupture of potato cells, release of free starch, and a pasty product. Granulation is improved by decreasing the moisture of the mix and lowering the temperature of conditioning, accompanied by a decrease in soluble starch or retrogradation. The resulting mix is air-borne during preliminary drying using an airlift drier to avoid agglomeration. Final drying of the granules to 6–7% moisture is carried out using a fluidize bed drier (Talburt et al. 1987a). Granular form means greater bulk density, better reconstitution because it is cooked and partially rehydrated multiple times.

Granular and fin flou is ground from cooked, dried whole potatoes containing no additives and retains a distinct potato taste. Granular flou and fin flou will pass through 40 mesh (420 μm) and 80 mesh (177 μm) screens, respectively. A stickier product results with liquid, best used in small amounts to extend other flours improve texture of gravies, soups, and baked goods; bind meat mixtures; or to coat fried foods.

Canned Potatoes

Figure 34.8 describes process schematics for manufacturing canned potatoes. Small potatoes, which are not suitable for the fresh market, can be utilized for canning. They can be canned whole if small (< 38 mm), larger size tubers (48–51 mm) can be diced, sliced, or julienned. Potatoes suitable for canning do not easily disintegrate or slough during processing. Greening discoloration, which contributes a bitter fl vor, should be avoided.

The total calcium (calcium chloride, calcium sulfate, calcium citrate, or monocalcium phosphate) added to improve firmnes should not exceed 0.05% of the net weight of the canned potatoes. The recommended (Luh and Kean 1988) minimum drained weights and the processing times (at 121°C), respectively, of US grade canned whole white potatoes are (a) 370 g (307 × 409 cans) for 20 minutes; (b) 540 g (401 × 411 cans) for 25 minutes; and (c) 2 kg (603 × 700 cans) for 35 minutes.

Extruded Potato Products

Potato chips can also be made via a process based on extrusion of rehydrated potato powder, shaping, and deep-frying. Kenawi et al. (1992) described a process for ready-to-eat simulated prebaked potatoes made from extrusion of blanched, culled potatoes. After extrusion, the potatoes were shaped and

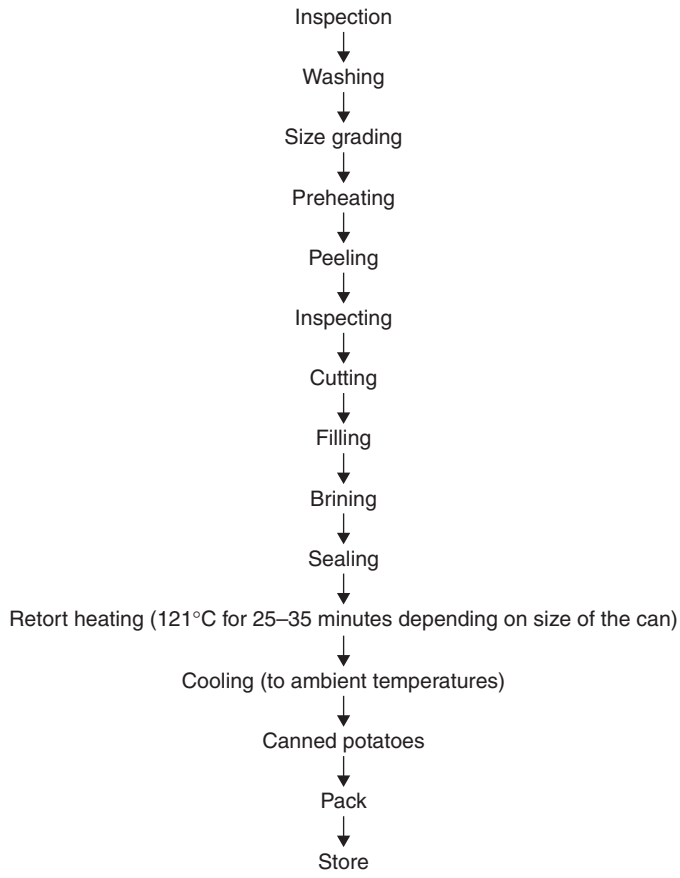

Figure 34.8 Process for canned potatoes.

dipped in batter to form skin and frozen before deep-frying.

Potato Byproduct Utilization

Modern starch processing (Treadway 1987; Lisinska and Leszczynski 1989) can recover as much as 96% of the starch found in raw potatoes. *Potato starch* is used in sauces, stews, cake mixes, etc.

In Eastern Europe and Scandinavia, crushed potatoes are heated to convert their starch to fermentable sugars that are used in the distillation of *alcoholic beverages* such as vodka and *akvavit*.

Summary

As indicated, potato is the number one non-grain food crop in the world. Besides table use, many value-added and convenient products are made from potatoes. Potato is used for both food use and industrial starch production. It is also used for making popular alcoholic drinks. There are several books and journals devoted to various aspects of potatoes; however, this chapter provides a review of information related to production, physicochemical, functional, phytochemical and nutritional properties, and manufacturing of major potato products.

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Chapter 35

Green Leafy Vegetables: Spinach and Lettuce

Gurbuz Gunes and Esra Dogu

Spinach

Introduction

Spinach (*Spinacia oleracea* L.) is thought to be native to Central Asia (Tsao and Lo 2004). It is one of the cool-season vegetables and can be grown in temperate areas all year around with a short growth period of 30–50 days (Conte et al. 2008). Optimum growth temperature is 15–20°C (Tsao and Lo 2004). China is the major producer of spinach in the world followed by United States, Japan, and Turkey (Table 35.1). Overall world production was over 14 million tonnes in 2007.

There are different cultivars of spinach classifie into savoyed type, semisavoyed type, and smooth-leaved (Tsao and Lo 2004). Savoy type is large and suitable for fresh market use and long distance shipment. Semisavoyed type spinach is suitable for both fresh market and processing into frozen packs. Smooth-leaved spinach is easy to wash and suitable for processing (Tsao and Lo 2004). Spinach can be consumed as fresh, canned, frozen, dehydrated forms or pureed into baby food.

Chemical Composition

Selected nutrients in spinach are listed in Tables 35.2–35.4. Spinach is a rich source of calcium, magnesium, phosphorus, potassium, and zinc. Major vitamins of spinach include vitamin C, vitamin A, vitamin E, folic acid, niacin, and vitamin K. Spinach is also rich in carotenoids among which lutein, zeaxanthin, and beta-carotene are the major ones. Glutamic acid, aspartic acid, and leucine are the major amino acids of spinach. Spinach has a total lipid content of 0.39% with a high 18:3 content of 0.138% (USDA 2009). Spinach has a high moisture (91.4%) and dietary fibe content (2.2%) and along with 23 kcal per 100 g, it can be an appropriate food in diet to loose weight. Being high in zinc and folic acid content, spinach is an appropriate food for pregnancy. Although spinach is known for its high content of iron and calcium, bioavailabilities of these minerals are low.

Harvesting, Storage, and Packing

Spinach is harvested before the seed stalks develop. Whole spinach plant is cut off the taproot for fresh market while it is cut off about an inch above the soil for processing by different machines (Singhal and Kulkarni 1998). Spinach should not be harvested after heavy rain as the leaves become crisp and sensitive to break when wet. Leaves and stems should be protected from damaging and bruising during harvesting and handling. Rotten and yellowed leaves should be discarded at the time of harvest as these parts can adversely affect the quality of healthy leaves. Spinach tends to

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Table 35.1 Spinach production quantity (1,000 tonnes) in selected countries and world from year 2000 to 2007

Countries	2000	2001	2002	2003	2004	2005	2006	2007
China	6,961	7,411	9,011	10,011	10,811	11,011	11,612	12,000
USA	346	284	306	362	402	433	345	360
Japan	316	319	312	311	289	298	299	302
Turkey	205	210	220	220	213	238	242	225
Republic of Korea	121	127	113	112	119	109	104	100
France	109	112	114	117	111	117	114	115
Italy	91	90	86	86	95	99	97	90
Belgium	75	43	77	77	85	96	100	101
Pakistan	74	76	78	80	87	87	85	85
Indonesia	66	64	71	109	108	124	149	179
Spain	62	48	56	55	54	62	65	66
Germany	60	59	55	57	59	69	55	59
Netherlands	54	49	43	43	40	43	41	43
Egypt	48	45	45	41	57	49	49	48
Greece	40	37	40	42	42	48	46	44
World (Total)	9,452	9,176	10,826	11,946	12,792	13,101	13,638	14,047

Source: FAO 2009.

Table 35.2 Proximate composition of raw spinach (per 100 g edible portion)

Component	Amount/100 g
Water	91.40 g
Protein	2.86 g
Total lipid	0.39 g
Ash	1.72 g
Total Carbohydrate (by difference)	3.63 g
Energy	23 kcal

(*Source*: USDA 2009).

Table 35.3 Vitamin content of raw spinach (per 100 g edible portion)

Vitamin	Amount/100 g
Vitamin C	28.1 mg
Thiamin	0.078 mg
Ribofl vin	0.189 mg
Niacin	0.724 mg
Pantothenic acid	0.065 mg
Vitamin B_6	0.195 mg
Folate	194 μg
Choline	19.3 mg
Betaine	102.6 mg
Vitamin A	469 μg_RAE
β-carotene	5626 μg
Lutein + zeaxanthin	2198 μg
Vitamin E (α-tocopherol)	2.03 mg
γ-tocopherol	0.18 mg
Vitamin K (phylloquinone)	482.9 μg

(*Source*: USDA 2009).

lose moisture rapidly and sag, so it should be harvested in cooler periods of the day. Spinach is usually washed, repacked in round baskets, crates, and humpers, and iced in a central location before shipping in refrigerated vehicles to storage areas or retail stores.

Spinach is recommended to be cooled rapidly upon harvesting and is recommended to be stored, distributed, and retailed at temperatures near 0°C at high relative humidities (95–98% RH) (Suslow and Cantwell 2009). Major quality losses in spinach during storage include wilting, yellowing, decay, and vitamin C loss. For example, concentration of

Table 35.4 Proximate mineral content of raw spinach (per 100 g edible portion)

Mineral	Amount/100 g
Calcium, Ca	99 mg
Iron, Fe	2.71 mg
Magnesium, Mg	79 mg
Phosphorus, P	49 mg
Potassium, K	558 mg
Sodium, Na	79 mg
Zinc, Zn	0.53 mg
Copper, Cu	0.130 mg
Manganese, Mn	0.897 mg
Selenium, Se	1.0 μg

(*Source*: USDA 2009).

ascorbate in spinach may fall to 50% of its initial, preharvest level, after 2 days of storage (Favell 1998). These losses increase with increased storage temperature and storage period. It has been found that CO_2 levels up to 10% decreased color degradation and increased storage life of spinach. Controlled atmospheres with 7–10% O_2 and 5–10% CO_2 has been recommended with moderate benefi for spinach (Suslow and Cantwell 2009).

Spinach is very sensitive to exogenous ethylene, which results in accelerated yellowing of the leaves. Thus, it should not be stored with ethylene producing fruits or exogenous ethylene must be excluded from the environment.

Spinach is mostly prepacked before being sold to consumers, although they are also sold in unpacked bunched forms in farmers" market, small bazaars, and local markets. Transparent fil bags containing 0.45 or 0.91 kg (1 or 2 lb) spinach with removable crowns is the most common package type used. Individual packs are usually placed in paper boxes during storage or transport. Boxes of fresh spinach can be cooled by placing layer of crushed ice on top of the vegetables or directly mixing the crushed ice with vegetables (Maquire et al. 2004). The icing method is mainly used during transportation and can also be applied in the fiel immediately after harvest.

Spinach to be processed into different products or forms is to be trimmed, sorted/graded, and washed before further processing. Yellow, decayed, bruised leaves should be trimmed off and spinach can be sorted or graded on the basis of size and age of the leaves. The leaves are then washed thoroughly. Washing is a critical process as pathogenic and spoilage microorganisms are eliminated from the product at this step. In fact, there has been a recent foodborne disease outbreak associated with spinach contaminated with *Escherichia coli* O157:H7 in United States and Canada. It has been shown that washing spinach with water is not suffi cient to eliminate the pathogens. Use of disinfectants such as chlorine dioxide, sodium hypochlorite, and ozone have been shown to eliminate the pathogens from spinach effectively (Lee and Baek 2008; Klockowa and Keener 2009). Washing can be done by different types of washers including floating immersion, rotary, and high-pressure sprays (Downing 1996; Parreno and Torres 2006). Only after these preprocessing steps, the fresh spinach is ready for processing into different forms such as fresh-cut or fresh packaged, frozen, canned, or dried. Each of these processes is described in the following sections.

Processing

Spinach is consumed as fresh or processed into different forms including frozen, canned, or dried. Savoy type spinach is usually used for fresh consumption and for long distance shipment while semisavoyed type and smooth leaved ones are preferred for processing (Tsao and Lo 2004).

Minimally Processed Fresh Spinach

Spinach leaves can be cleaned and packaged as whole or precut forms for fresh use. Minimally processed ready-to-use fresh produce is more perishable than intact produce. Thus, it is important to start with a high quality raw material and strictly apply the necessary processing and storage requirements for such products. Minimally processed spinach product can be fresh, whole baby or regular leaves and fresh-cut leaves packaged in modifie atmosphere conditions among which the former is more common. After the leaves are trimmed, sorted, and cleaned with sanitizers as described in the previous section, the leaves are usually used as intact (individual baby leaves) or can also be cut into smaller pieces (not common in practice) for further processing (Figure 35.1). It is important to note that cutting must be done with sharp knives to decrease the degree of physical injuries to the

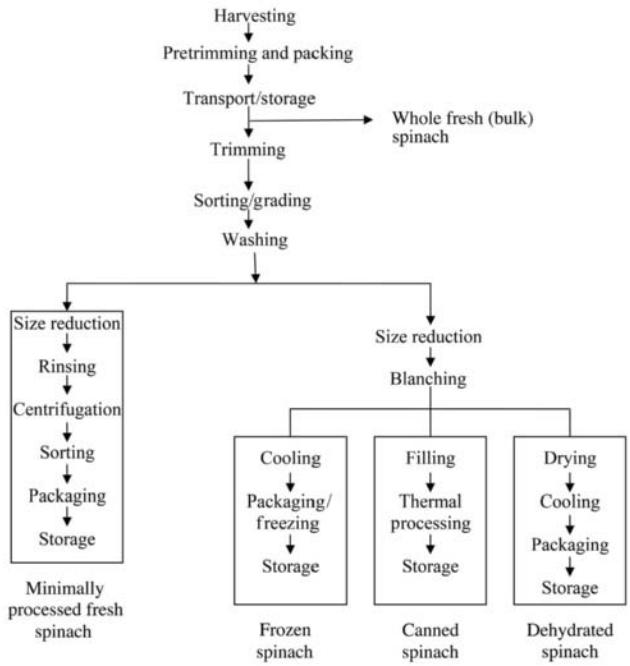

Figure 35.1 A general flow diagram for spinach handling and processing.

tissues. The cut leaves may be treated with antimicrobial and antioxidant solutions to retard microbial and oxidative degradations in the product. If whole intact leaves are to be packaged, they must be rinsed with water containing appropriate sanitizers to reduce the microbial load on them. Excess surface water on the leaves must be removed by centrifugation with a spinner before packaging. Moisture on the surface can increase microbial decay of the product.

Spinach is a highly respiring leafy vegetable with a relatively short storage life. Fresh-cut processing further increases respiration rate and decreases shelf life. Reduced O_2 and elevated CO_2 are usually used to decrease respiration rate of fresh produce. Recommended package atmosphere for spinach is 7–10% O_2 with 5–10% CO_2 (Suslow and Cantwell 2009). It has been shown that low O_2 (0.8%) atmosphere resulted in 1–2 log reduction in microbial counts in fresh-cut spinach at 5°C compared to air while no effect was observed at 10°C (Babic and Watada 1996). In addition, superatmospheric O_2 levels have also shown some benefit on spinach quality in modifie atmosphere packages (Allende et al. 2004). Modifie atmosphere packages are designed for specifi weight of product with an appropriate packaging material so that the recommended gas composition is attained in the headspace at equilibrium at the recommended storage temperature. Packaged spinach must be stored at the suggested temperature during storage, transport, and retailing. Strict temperature control is very important, because temperature can affect respiration rate of spinach and permeability of packaging material differently resulting in alteration of equilibrium atmosphere which becomes anaerobic.

Spinach can be contaminated with pathogens at the field or during postharvest handling and processing. In 2006, there was

a foodborne disease outbreak involving fresh spinach contaminated with *E. coli* O157:H7 in 2006 in United States. Therefore, good manufacturing practices must strictly be applied in minimally processed fresh spinach. In addition, Food and Drug Administration (FDA) approved irradiation (up to 4 kGy) of fresh loose or packaged spinach to control harmful and other microorganisms.

Frozen Spinach

Spinach can be frozen to increase its shelf life. Freezing inhibits growth of microorganisms and retards degradative biochemical and enzymatic reactions in the product. The process involves sorting, trimming, washing, blanching, draining, freezing, and packaging (Figure 35.1). Frozen spinach can be presented in one of the following forms: whole spinach (intact plant with roots removed), leaf spinach (whole leaves separated from the root crown), cut-leaf spinach (parts of leaves larger than 20 mm), chopped spinach (parts of leaves in size between 3 and 10 mm), and pureed spinach (finel chopped spinach with size less than 3 mm) (Annon. 1981). Thus, depending on the type of the product to be produced, a size reduction is applied to trimmed, sorted/graded, and cleaned spinach.

Blanching is one of the most critical steps in freezing of spinach. It involves brief immersion of the fresh product in water at 85–100°C or steaming at 100°C primarily to inactivate enzymes such as lipoxygenases (LO), peroxidases (PO), and polyphenol oxidases (PPO), which cause degradations in color, fl vor, texture, and nutritional value. It also kills vegetative microbial cells and decreases any pesticide residues on the product. Blanching at 90°C for 1 minute has been recommended for spinach (Labib et al. 1997). Blanching with total inactivation in PPO, 83–92% inactivation in PO, and 92–98% inactivation in LO activity provided maintenance of the sensory quality of frozen spinach during 3-month storage (Labib et al. 1997). Spinach contains high levels of galactolipids and phospholipids, which can be hydrolyzed by galactolipases and phospholipases. High thermal stability of these enzymes should be taken into account in selection of indicator enzymes for efficien y of blanching process (Martinez-Romero et al. 2004). Adding salts such as chlorides, sodium and potassium sulphate can reduce the transformation of chlorophyll top pheophytin during blanching (Parreno and Torres 2006).

Blanched spinach is cooled and usually packaged before freezing, although individual quick freezing of unpackaged spinach can also be done followed by packaging. Spinach is usually packaged in high-density polyethylene bags and/or cartoon boxes with aluminium layer.

The rate of freezing is a key factor for high-quality product. Higher freezing rate can be achieved to get large temperature gradient between the product and the freezing medium. Quick freezing results in smaller ice crystals formed in the tissues resulting in less textural damage. Slow rate of freezing causes formation of larger ice crystals which damage the cellular structure in the tissues to a larger extent. Higher cellular damage not only results in textural degradation but also increases degradative enzymatic reactions of LO, PPO, etc. The enzymes and their substrates are located in different parts of cells and damage to the cellular structure can decompartmentalize them resulting in degradative reactions. Therefore, individual quick freezing of spinach before packaging can result in better quality. If the packaged spinach is to be frozen, then the thickness of the package should be small enough to achieve rapid freezing of the package content. Quick freezing can also be achieved by using liquefie gases (cryogenic gases) such as nitrogen and carbon dioxide instead of forced air or plate freezing (mechanical freezing). For instance, in pelletized freezing, spinach puree can be pumped to a conveyor where liquid nitrogen is sprayed onto it and the product is introduced

between two rotating cylinders with cavities to produce small pellets with frozen crust (Arthey 1993). These pellets are further frozen in a conventional freezer until the temperature at the center drops below −18°C. Cryogenic freezing results in faster freezing, smaller ice crystal size, less mechanical damage to tissues, and better retention of moisture and fl vor.

Storage and transport conditions have a great effect on quality of frozen products. Frozen packaged products should be stored at −18°C or above. Temperature fluctuation during storage and transport result in accelerated recrystallization that is an increase in average size of the ice crystal. Recrystallization results in excessive damage to the tissues due to formation of larger ice crystals. Thus, temperature fluctuation during storage and transport should be avoided for better quality product. Frozen product should be properly packaged so that freezer burn is prevented. Freezer burn results from moisture loss on the surface of the product by evaporation of water. Freezer burn causes discolored, dried, and coarse texture. In order to prevent freezer burn, the packaging material must be intact and resistant to the freezing process and storage so that no cracks or damage occurs.

Freezing does not kill microorganisms but only slows their growth. Blanching process alone may not be sufficien to kill all pathogenic microorganisms that may be present in the product. Thus, good manufacturing practices and complying with hygienic rules must be enforced for safety of frozen spinach. Care must be taken during harvesting and washing of unprocessed spinach before freezing.

The processes applied to produce frozen spinach can affect nutritive value of the product. Blanching process can result in losses of minerals and soluble vitamins such as vitamin C and phenolics (Lopez-Ayerra et al. 1998; Giannakourou and Taoukis 2003; Bunea et al. 2008; Lisiewska et al. 2009).

Dehydrated Spinach

Large-leafed spinach is preferred for production of dehydrated spinach. The processing steps in drying spinach are illustrated in Figure 35.1. The spinach is trimmed and sorted carefully to remove roots, older yellowed or decayed leaves before washing. The leaves are dried at 80°C until the moisture content drops to below 6.5% (Cai et al. 2004). Drying can also be conducted with microwaves at 750 W power level, which can be advantageous in terms of drying time, energy consumption, ascorbic acid, and color retention (Ozkan et al. 2007; Karaaslan and Tunçer 2008). Premium quality dried spinach can be produced by freeze drying which retains the valuable nutrients and color to a larger extent. The dried spinach must be packaged in high moisture barrier packages to prevent moisture absorption from environment.

Dehydrated spinach leaves can be introduced to consumer as dried leaves or in powder form. Dried spinach can be used as a substitute for fresh spinach or as a nutritious additive or coloring agent in various foods such as soups, infant foods, pasta, bakery products, and pies.

Canned Spinach

Harvested spinach in crates, directly from the fiel or in boxes, can be preserved by canning. The processing steps are shown in Figure 35.1. Spinach is trimmed, sorted, and graded to remove the crowns, heavy stalks, decayed and yellowed leaves followed by washing. Washing is generally done by passing the leaves through a revolving reel immersed in water with additional sprays or through a tank on a mesh belt to remove soil, dirt, and insects thoroughly (Larousse and Brown 1997). Hot water revolving drum or draper belt blanchers are used for blanching of the washed leaves for a few minutes at 71–99°C (Larousse and Brown 1997). Steam blanching can also be used to reduce leakage of nutrients from

Table 35.5 Lettuce and chicory production quantity (1000 tonnes) in selected countries and world from year 2000 to 2007

Countries	2000	2001	2002	2003	2004	2005	2006	2007
China	7,255	7,605	9,005	10,005	10,505	11,005	11,605	12000
USA	4,452	4,472	4,541	4,737	4,507	4,606	4,339	5,106
Spain	1,015	994	1037	1,045	1,048	993	1,070	1,070
Italy	969	925	916	922	996	1,010	965	850
India	785	790	790	790	790	790	790	790
Japan	537	554	562	549	509	552	549	560
France	509	491	488	461	472	469	470	471
Turkey	333	350	345	340	362	372	391	382
Republic of Korea	204	183	179	190	205	167	160	158
Mexico	192	213	228	243	247	275	274	275
Egypt	175	180	144	142	136	140	150	145
Germany	174	193	219	202	255	242	303	312
Australia	152	153	135	122	127	132	179	185
United Kingdom	155	145	126	140	150	140	135	117
Portugal	95	95	95	95	95	95	100	105
World (Total)	18,297	18,654	20,057	21,236	21,750	22,293	22,771	23,863

(*Source*: FDA 2009).

the leaves and wastewater. Blanched spinach should be tender, but not mushy or disintegrated, and should have a bright green color (Downing 1996). Low temperature blanching (71–77°C) takes relatively long time but gives the best color in the canned product (Downing 1996).

The blanched spinach is dewatered gravimetrically or by pressing out the excessive water. They are then fille in cans (Larousse and Brown 1997). Tinplate cans with enameled bodies and ends are used for spinach. Blanched spinach is inspected on a conveyor belt to remove discolored or unwanted pieces. The leaves must be packed or compressed into the cans so that the required amount of product is obtained. Hot brine (2.5–3.5% salt) at 93°C or above is added to fil the cans. The cans are exhausted when the temperature drops to 60–77°C and then sealed (Downing 1996). Drained weight and net weight are important for canned spinach. FDA has set a maximum drained weight of spinach and a minimum net weight of the entire contents for each size of can. The sealed cans are thermally processed in retorts usually at 122°C for sufficien time depending on size of the cans so that a 12D process for *Clostridium botulinum* is achieved (Larousse and Brown 1997). Blanched spinach tends to stratify horizontally in large cans, so it is recommended that these cans be processed in a horizontal position at which heat penetration is more rapid (Downing 1996). The processed cans are cooled and removed from the retorts.

Lettuce

Introduction

Lettuce (*Lactuca sativa* L.) is a cool-season crop grown in many countries throughout the world. Major lettuce producer is China followed by United States, Spain, and Italy (Table 35.5). The world production of lettuce and chicory (*Cichorium intybus*, a somewhat related species with bitter taste liked in some parts of the world) in 2007 was over 23.5 million tonnes.

Lettuce is the most popular salad vegetable and is usually eaten raw. There are several types of lettuce such as crisphead (iceberg), romaine, butterhead, leaf type, and curled (stem) lettuce. The leaf color can range from dark green to red. Crisphead is one of the most common fresh market lettuce. It has

Table 35.6 Proximate composition of raw lettuce (per 100 g edible portion)

Component	Butterhead	Romaine	Green leaf	Iceberg	Red leaf
Water (g)	95.63	94.61	95.07	95.64	95.64
Protein (g)	1.35	1.23	1.36	0.90	1.33
Total lipid (g)	0.22	0.30	0.15	0.14	0.22
Ash (g)	0.57	0.58	0.62	0.36	0.55
Total Carbohydrate (g)	2.23	3.29	2.79	2.97	2.26
Energy (kcal)	13	17	15	14	16

(*Source*: USDA 2009).

crisp, light green leaves compacted tightly into a head. Romaine has dark green long leaves, which are compacted tightly in the inner part into an upright head, but loose leaves are present at the outer part. The inner core leaves are yellow as opposed to dark green colored outer leaves. Butterhead is a loose-heading type with large thick leaves loosely packed. It is very common in salads. Leaf type lettuce can be both green and reddish, commonly used in salads and sandwiches.

Chemical Composition

The composition and nutrient levels in lettuce are illustrated in Tables 35.6–35.8. Lettuce is low in calories with around 95% water content. It is a good source of potassium, calcium, phosphorous, and iron. It also contains significan amount of folate, vitamin A, vitamin K, beta-carotene, and vitamin C. The nutrient content is the highest in the darker green, outer leaves (Kovatch 2003).

Harvesting, Storage, and Packing

Leaf lettuce is harvested when it is large enough (12.5–15 cm which is about 5–6 inches). Lettuce heads are harvested when the heads become firm Lettuce should be harvested in the cool periods of the days and should be cooled as soon as possible. Vacuum cooling is an effective method to remove the fiel heat, which cools the lettuce to near about 0°C (Ozturk and Ozturk 2009). Rapidly cooled head lettuce can be stored up to 3 weeks at 0°C and 98% RH while other types of lettuce have shorter shelf life. Storage temperature should not drop below −0.2°C, where freeze damage can occur resulting in darkened translucent or water-soaked areas (Cantwell and Suslow 2009).

Head lettuce can be wrapped in macroperforated plastic film while leaf lettuce can be placed in open-topped plastic bags to prevent moisture loss and wilting. Lettuce is sensitive to exogenous ethylene, which causes

Table 35.7 Mineral content of raw lettuce (per 100 g edible portion)

Mineral	Butterhead	Romaine	Green leaf	Iceberg	Red leaf
Calcium, Ca (mg)	35	33	36	18	33
Iron, Fe (mg)	1.24	0.97	0.86	0.41	1.20
Magnesium, Mg (mg)	13	14	13	7	12
Phosphorus, P (mg)	33	30	29	20	28
Potassium, K (mg)	238	247	194	141	187
Sodium, Na (mg)	5	8	28	10	25
Zinc, Zn (mg)	0.20	0.23	0.18	0.15	0.20
Copper, Cu (mg)	0.016	0.048	0.029	0.025	0.028
Manganese, Mn (mg)	0.179	0.155	0.250	0.125	0.203
Selenium, Se (μg)	0.6	0.4	0.6	0.1	1.5

(*Source*: USDA, 2009).

Table 35.8 Vitamin content of raw lettuce (per 100 g edible portion)

Vitamin	Butterhead	Romaine	Green leaf	Iceberg	Red leaf
Vitamin C (mg)	3.7	24.0	18.0	2.8	3.7
Thiamin (mg)	0.057	0.072	0.070	0.041	0.064
Ribofl vin (mg)	0.062	0.067	0.080	0.025	0.077
Niacin (mg)	0.357	0.313	0.375	0.123	0.321
Pantothenic acid (mg)	0.150	0.142	0.134	0.091	0.144
Vitamin B_6 (mg)	0.082	0.074	0.090	0.042	0.100
Folate (mg)	73	136	38	29	36
Choline (mg)	8.4	9.9	13. 4	6.7	11.8
Betaine (mg)	0.1	0.1	0.2	0.1	0.2
Vitamin A (μg_RAE)	166	436	370	25	375
β-carotene (μg)	1987	5226	4443	299	4495
Lutein + zeaxanthin (μg)	1223	2312	1730	277	1724
Vitamin E (α-tocopherol) (mg)	0.18	0.13	0.29	0.18	0.15
γ-tocopherol (mg)	0.27	0.36	0.37	0.09	0.24
Vitamin K (phylloquinone) (μg)	102.3	102.5	173.6	24.1	140.3

(*Source*: USDA 2009).

russet spotting on midribs of lettuce leaves. Thus, it should not be stored or transported with ethylene-producing fruits such as apples, pears, and tomatoes.

Low O_2 (1–3%) atmosphere can decrease respiration rate and deterioration of lettuce at temperatures of 0–5°C. Elevated CO_2 above 2% level can result in physiological disorders and brown stain in intact lettuce. However, fresh-cut lettuce for salad products is commonly packaged in lower O_2 (0–3%) and higher CO_2 (10–15%) atmospheres at 0–5°C to control enzymatic browning on the cut surfaces (Ben-Yehoshua et al. 2005). Enzymatic browning on cut surfaces occurs more rapidly and extensively than symptoms of brown stain caused by elevated CO_2 (Cantwell and Suslow 2009).

Minimal Processing

Lettuce is consumed as fresh and can be marketed to fina consumers in different forms. It can be sold in wraps or loose bags directly from the field These forms of lettuce should be trimmed manually at the harvest and before prepackaging to remove yellowed, decayed leaves. Alternatively, a further trimming can also be applied to remove all decayed and low-quality leaves followed by packaging before retailing. Washing with appropriate sanitizers can also be done before packaging. A good example for this type of product can be lettuce heart made from romaine lettuce. This product contains only a few heads of tightly bound inner leaves packed together. Minimally processed lettuce has become very popular because of the increasing consumer demand for convenient fresh products. Lettuce can also be retailed in fresh-cut forms such as chopped lettuce or shredded lettuce as plain or mixed with other salad vegetables. The overall lettuce processing steps are summarized in Figure 35.2 for all forms of product.

Trimming is very important in fresh-cut lettuce manufacturing. Decayed or discolored low quality leaves must be removed before lettuce is processed into fresh-cut forms. Trimming can be done manually or mechanically. There are machines designed for trimming and cored iceberg lettuce, which can be used in large-scale production of fresh-cut products.

Washing is another important step in fresh-cut lettuce products. Cutting releases nutrients from the damaged tissues, which support growth of microorganisms. Fresh-cut lettuce is usually washed with cold chlorinated water prior to packaging. It has been shown

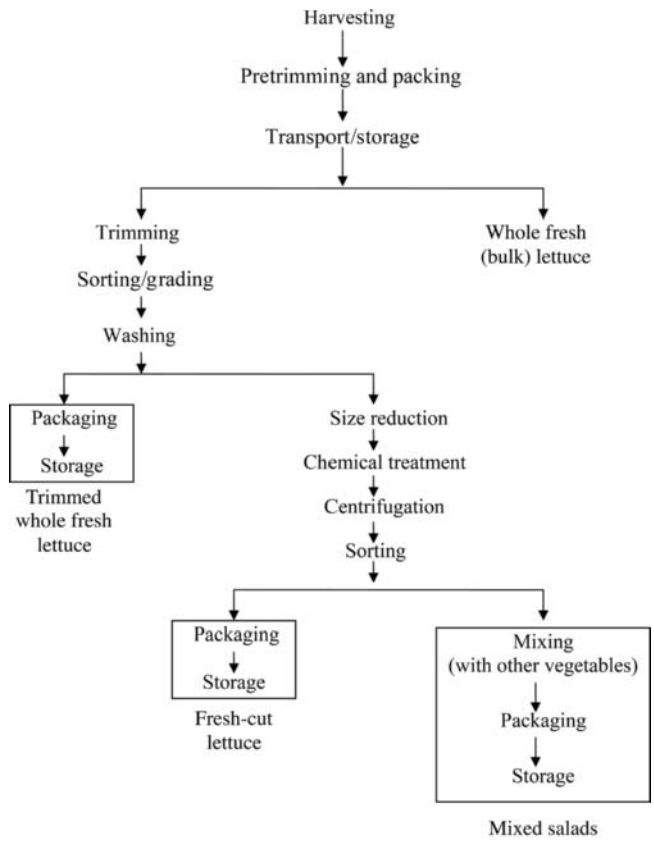

Figure 35.2 A general flow diagram for lettuce handling and processing.

that washing with warm chlorinated water was better in reducing microbial population on fresh-cut lettuce than with warm water without chlorine or chlorinated water at 20°C (Li et al. 2001). There are different types of sanitizers (chlorine, acidifie chlorine, ozone, acidic electrolyzed water) suitable for washing lettuce. Commercial sanitizing agents, which are mostly chlorine-based, have been introduced for use in fresh-cut industry and have been shown to be effective on fresh-cut lettuce (Keskinen et al. 2009; López-Gálvez et al. 2009). Washing with sanitizers not only decreases the overall microbial count but also inactivates potential pathogens such as *E. Coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* on the product. Natural antimicrobials such as nisin and other bacteriocins can also be used to inactivate pathogenic microorganisms in fresh-cut lettuce (Randazzo et al. 2009).

Methods of size reduction affect quality of fresh-cut produce. Size reduction must be done in a way that results in minimal damage to tissues. This can be achieved by using sharper knives. Respiration rate, enzymatic browning, and textural degradations increase with increased tissue damage.

Chemical treatment is required to maintain quality of fresh-cut lettuce. Fresh-cut lettuce degrades biochemically and microbiologically. Enzymatic browning is one of the most important reactions to be controlled on cut surfaces of lettuce. Softening of tissues by pectic enzymes is another problem in fresh-cut lettuce. Cutting releases nutrients from

the damaged cells promoting growth of microorganisms. In order to control these degradations, fresh-cut lettuce should be treated with antibrowning, antisoftening, and antimicrobial agents such as ascorbic acid with or without citric acid, cysteine, calcium lactate, calcium chloride, chlorine, or natural antimicrobials (bacteriocins) (Li et al. 2001; Ihl et al. 2003; McKellar et al. 2004; Martin-Diana et al. 2005; Altunkaya and Gökmen 2008). Solutions of these chemicals can be combined with mild heat treatment to get synergistic effects (Martin-Diana et al. 2005).

Packaging is the essential part of minimal processing of lettuce. Physiological degradations, enzymatic browning and softening, and moisture loss in fresh-cut lettuce can be controlled by modifie atmosphere packaging. Reduced O_2 and elevated CO_2 in packages can decrease respiration rate and enzymatic degradations. Moisture loss can be inhibited by packaging the product with a high moisture barrier material. Modifie gas levels can also inhibit growth of spoilage and pathogenic microorganisms in the product. Recommended package atmosphere for fresh-cut lettuce is 0.5–3% O_2 with 5–15% CO_2 along with storage at 0–5°C (Gorny 2001; Ben-Yehoshua et al. 2005). Benefit of superatmospheric O_2 have also been reported for lettuce (Escalona et al. 2006). For mixed salads, the required gas composition in packages may change depending on other vegetables in the packages. Since temperature affects respiration rate and permeability of packaging materials at different rate, it is important to keep the storage temperature of the packages at the suggested level. Exposing packaged fresh-cut lettuce to higher temperature for extended period results in anaerobic condition in the packages. This causes off-fl vor and off-odor formation and physiological damage making the product unacceptable.

Lettuce, like other leafy vegetables, can be contaminated with pathogens at fiel from soil, or from employers and machines used during postharvest handling and processing. Foodborne disease outbreaks associated with lettuce contaminated with *E. coli* O157:H7 was reported in 2006 in United States. Contamination of lettuce with *Listeria* and *Salmonella* is also possible and can pose a public health problem. Therefore, good manufacturing practices must strictly be applied for minimally processed lettuce. Irradiation of bagged lettuce can be an effective tool to ensure safety and quality. In fact, FDA recently approved irradiation of lettuce along with spinach (loose or bagged) up to 4 kGy to control harmful bacteria and other microorganisms.

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Chapter 36

Sweetpotatoes

V. D. Truong, R. Y. Avula, K. Pecota, and C. G. Yencho

Introduction

Sweetpotato, *Ipomoea batatas* L. (Lam.), is an important economic crop in many countries. In terms of annual production, sweetpotato ranks the fift most important food crop in the tropics and the seventh in the world food production after wheat, rice, maize, potato, barley, and cassava (FAOSTAT 2008).

Sweetpotato roots have high nutritional value and sensory versatility in terms of taste, texture, and fles color (white, cream, yellow, orange, purple). The varieties with high dry matter (>25%), white-cream fles color, and mealy fir texture after cooking are preferred by the consumers in the tropics. These varieties are known as "tropical sweetpotato" (for example, "bianito," "batiste," or "camote"). The purple-fleshe sweetpotato varieties with attractive color and high anthocyanin content are the specialty type in Asia. In the United States, the commercially popular type is the orange-fleshe sweetpotato with low dry matter content (18–25%), high β-carotene level, sweet and moist-texture after cooking. This sweetpotato type is imprecisely called "yam" which is not the true tropical yam of *Dioscorea* species. Many years ago, African American in Louisiana referred this moist-sweetpotato as "nyami" because it reminded them of the starchy tuber of that name in Africa. The Senagalese word "nyami" was eventually shortened to the trademark "yam" popular in the United States. Commercial packages with "yam" labels are required by the US Department of Agriculture to have the word "sweetpotato" in the label to avoid confusion to the consumers.

Depending on the fles color, sweetpotatoes contain high levels of β-carotene, anthocyanins, phenolics, dietary fibe , vitamins, minerals, and other bioactive compounds. The β-carotene in orange-fleshe sweetpotatoes can play a significan role as a viable long-term food-based strategy for combating vitamin A deficien y in the world. Studies in Africa demonstrated that consumption of 125 g of orange-fleshe sweetpotatoes improved the vitamin A status of children, pregnant women, and lactating mothers (Low et al. 2001; Van Jaarsveld et al. 2005). Further, polyphenolics from purple-fleshe sweetpotatoes exhibited strong radical scavenging activity, which helps reduce the risk of stress-related diseases (Suda et al. 2003). Sweetpotato has a strong potential to contribute to better nutritional quality of our diets around the world. This chapter provides a contemporary review of production, quality, and processing aspects of sweetpotatoes.

Production and Consumption

Sweetpotato has wide production geography, from 40° north to 32° south latitude of the globe, and it is cultivated in 114 countries with a total annual production of 120–140 million metric tons in recent years (Figure 36.1). About 93% of the global sweetpotato

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

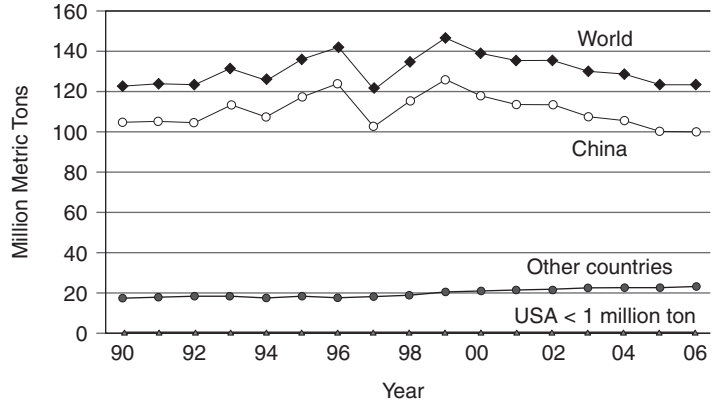

Figure 36.1 World sweetpotato production 1990–2006 (FAOSTAT 2008).

production is from Asia and Pacifi Islands while only 5.5% and 1.5% are produced in Africa and Latin America. The main sweetpotato producer is China that accounts for about 80% of the global production. Japan and the United States produce 0.8% and 0.6%, respectively. Countries in the southern hemisphere such as Argentina and New Zealand produce 272,000 and 17,000 metric tons sweetpotatoes annually. Only two countries in Europe, Spain and Portugal, grow about 25,000 metric tons each, annually.

In comparison to other major staple food crops, sweetpotato has good adaptability to marginal growing conditions, short production cycle, and high yield potential. The average world yield of sweetpotato is about 14 tons per hectare. Under subsistent conditions in many areas of the tropics, the average sweetpotato yield is about 6 metric tons/hectare, far below 20–26 metric tons/hectare obtained in China, Japan, and the United States, where the improved varieties, fertilizer applications, and cultural managements have been introduced.

The per capita consumption is highest in places where sweetpotatoes are consumed as a staple food, e.g., Papua New Guinea at 550 kg per person per year, the Solomon Islands at 160 kg, Burundi and Rwanda at 130 kg, and Uganda at 85 kg. The average annual per capita consumption of sweetpotato is estimated at 18 kg in Asia, 9 kg in Africa, 5 kg in Latin America, and 2.3 kg in the United States (FAOSTAT 2008; USDA 2010).

Classification and Origin

The sweetpotato (*I. batatas* L.) is a dicotyledonous plant belonging to the morning glory or Convolvulaceae family. It is a new world crop, though there is disagreement as to the origin. Using data from morphology, ecology, and cytology, Austin (1988) has postulated that cultivated sweetpotatoes originated somewhere in the region between the Yucatan Peninsula of Mexico and the mouth of the Orinoco river in northeastern Venezuela. Molecular marker analysis places Central America as the region with the most genetic diversity and probable origin (Huang and Sun 2000; Zhang et al. 2000). Remains of dried sweetpotato roots found in Peru have been radiocarbon dated back to 8,000–10,000 years old, though it is unknown if these were collected from the wild or were domesticated (Engel 1970). Sweetpotato was widely established in tropical regions of the new world around 2500 BC (Austin 1988). It was established in Polynesia, prior to European arrival, though it is unclear as to how it got there. Europeans in the 1500s spread the sweetpotato to Africa and India, with it arriving in China prior to 1600. Secondary centers of

diversity include New Guinea, the Philippines, and parts of Africa (Yen 1982; Bohac et al. 1995).

Botany and Physiology

The sweetpotato is a herbaceous perennial that is grown as an annual by stem cuttings or plants sprout from storage roots. It has a predominately prostrate growth habit typically with 1–5 m vines that grow horizontally on the ground. The plant can be grouped into three parts: the leaves acting as the photosynthetic canopy, the stems which transports energy to the roots, and water and minerals from the roots, and the root system which absorbs water and nutrients from the soil, anchors the plant, and can act as a storage site for energy via the development of fles y storage roots. Sweetpotato possesses three types of roots: storage, fibrous and pencil (Kays 1985a; Firon et al. 2009). Young adventitious roots develop out of both the nodal and the internodal regions of an underground stem portion of a vine cutting. Roots from the internodal regions normally become fibrou roots and have a tetrarch arrangement of their primary vascular tissue. Roots from the nodes are pentarch or hexarch and have the potential to develop into enlarged storage roots; however, unfavorable conditions can cause many or all of these to develop into primary fibrou roots or to lignify and produce pencil roots. Pencil roots are much greater in diameter than fibrou roots, but much thinner than storage roots, or about the thickness of a pencil. Some of the firs roots to emerge from the nodal regions are the roots that will develop into storage roots, making it important to minimize stress during the firs month after transplanting, to ensure good storage root development. Minimizing stresses such as high nitrogen levels, low oxygen or dry conditions impacts many of the cultural practices for sweetpotato in highly developed production systems.

Storage root initiation varies widely among cultivars occurring between 1–13 weeks after planting by which time the number of storage roots per plant is determined (Ravi and Indira 1999). Length of the storage root is determined before width, with shape being determined by the differential rates of longitudinal and lateral growth (Wilson 1982). Root set even in the same fiel and cultivar is highly variable in sweetpotato, making it difficul to optimize size and shape uniformity (Firon et al. 2009).

Air and soil temperatures affect storage root formation and growth. Night air temperature seems to be the most critical factor for storage root growth. Night temperatures between 15 and 25°C promote storage root formation and growth while temperatures above 25°C suppress storage root formation and favor shoot growth. Night air temperatures lower than 15°C suppress storage root formation, growth, and yield. Air temperatures >30°C reduce storage root formation and growth, and promotes shoot growth. Soil temperatures between 20 and 30°C favor storage root formation and growth while a soil temperature of 15°C favors fibrou root formation. Soil temperatures >30°C promotes shoot growth at the expense of storage root growth. Long photoperiod favors storage root growth.

Storage root bulking is determined by the duration and rate of storage root growth, which varies by cultivar. Growth occurs over an extended period of time and can stop due to unfavorable growing conditions and restart once conditions improve. Cultivars exhibiting fast initiation and rapid bulking may reach a maximum yield in 12–16 weeks, while long duration bulking types require a >21-week period for maximal development. Storage root bulking rate is positively correlated with rainfall and relative humidity.

The storage roots, not to be confused with tubers, which are modifie stems, range in shape from spindle-shaped to almost spherical, to irregular in length from a few centimeters to greater than 30 cm, and in weight from 0.1 kg to several kilograms. Since they are perennial, they will continue to grow, but unless protected, will often rot or be

discovered by rodents. The skin and fles contains carotenoid and anthocyanin pigments, which when combined, determine a continuum of colors from whitish to yellow, orange, and red to purple. Most cultivars have a uniform fles color but landraces and breeding materials can be multicolored or patterned. Roots, when cut, ooze sticky white latex from laticifers present throughout the flesh The latex turns black as it dries and cannot be removed from the root surface without removing the skin.

Vines are usually prostrate, though some may twine, and form a shallow canopy. Vines are indeterminate and will root at the nodes, often producing a secondary set of storage roots. Stems range from green to purple, and in thickness from a few millimeters to 1.5 cm. Internode distances vary considerably and have to be considered when planting transplants. Leaves are arranged spirally on the stem and are variable in size and shape, even on the same plant. Leaves range from deeply lobed to entire with many plants showing a range of shapes. Most leaves are green but may contain purple pigmentation. Recently, ornamental sweetpotatoes have been released with solid purple leaves and stems, others with light green foliage. Many of these also have compact, well-branched, and somewhat upright plant architectures.

Flowering is mostly short day, but long day and day neutral clones exist. Flowering and seed set in field cultivated by indigenous cultures may have played a major role in the appearance of new varieties that are then propagated via cuttings. Flowering is increased during stress periods and can reduce yield, though there are high-yielding fl wering varieties.

Breeding

Sweetpotato is a hexaploid with a basic chromosome number of $n = 15$ and 6 sets of chromosomes ($2n = 6x = 90$). There is still disagreement as to which specie(s) are the most likely progenitors of cultivated sweetpotato (Bohac et al. 1995; Firon et al. 2009). Only a few other *Ipomoea* species have polyploid forms and few successful crosses with diploids or other *Ipomoea* species have been made. Recent molecular genetic studies suggest that cultivated sweetpotatoes are most likely autopolyploids, with some evidence of restricted recombination (Kriegner et al. 2003; Cervantes et al. 2008).

Due to the high levels of heterozygosity present in the germplasm, there is great genetic diversity within sweetpotato, which is steadily being developed by breeders. This diversity appears to be the result of a number of factors. It has been domesticated for a long time and spread through a large number of environments for selection. It is at least partly autopolyploid, so that there is great redundancy in the genome allowing for regions to change without compromising the basic systems of the plant. Sexual reproduction in cultivated field would allow for new types to be evaluated, and then clonally propagated, and finall , there is a fairly high rate of somatic mutation, especially when sprouted from storage roots.

Because sweetpotato is a polyploid with high levels of heterozygosity and it is mostly an obligate out-crossing species with numerous mating incompatibilities, breeding in this crop is fairly difficul (Jones 1986; Collins et al. 1999). Most traits of economical signifi cance exhibit quantitative inheritance. Breeding efforts begun in the 1930s in the United States and elsewhere have significantl improved fungal, bacterial, and nematode resistance, beta-carotene, and anthocyanin levels, yields, storage ability, size and shape uniformity, and starch characteristics. Considerable work continues on insect and virus resistance, processing qualities, and findin regionally adapted cultivars that match consumer preferences.

Despite its worldwide importance as a food crop, funding for genetic and molecular genetic research have been very limited.

Consequently, key research to understand the inheritance of economically important traits that could help developing more efficien breeding strategies has lagged behind to that of other important crops. To date, only a few molecular genetic studies of sweetpotato have been published, with most being limited to phylogenetics and germplasm evaluation (He et al. 1995; Prakash et al. 1996; Zhang et al. 2000; Hu et al. 2004; Zhang et al. 2004), and genome characterization (Villordon and LaBonte 1995, 1996). The genetic maps of sweetpotato were recently constructed by Cervantes et al. (2005) and Kriegner et al. (2003) represent the most comprehensive genetic maps of sweetpotato. Traits of economic importance or quantitative trait loci (QTL) are now being placed on the map developed by Cervantes et al. (2005).

Soil and Climate

Sweetpotatoes are grown from 40°N to 32°S, and from sea level to 3,000 m in the tropics. Growth is negligible below 10°C and best above 24°C. Frost will kill the plants and cold temperatures damage storage roots, though the damage may not be seen until after a couple months of storage. Thus cultivation is limited to temperate regions with a minimum frost-free period of 4 months. Multiple crops per year can be grown in tropical regions with sufficien rainfall. Optimal rainfall is approximately 50 cm during the growing season. Once established, the crop can handle severe drought and resume growing when rain occurs, but drought during establishment can cause poor stands and poor root set. The best soils are sandy loams with permeable subsoils. Sweetpotatoes do not tolerate waterlogged soils well, especially near harvest where roots may rot in the fiel or in subsequent storage. Soils with higher bulk densities or poor aeration cause irregular shapes and poorer root set. Cultural management using mounds or ridges can allow productive use of these soils. Sweetpotatoes can tolerate a wide range of soils, with pH from 5.0 to 7.5 considered optimal, as long as there are no mineral deficiencie (Bouwkamp 1985a).

Sweetpotatoes are a relatively low input crop in terms of fertilizers. Soils with moderate fertility rarely show a yield response to additional N or P fertilizers. In deep sandy soils with low cation exchange capacity, fertilizer responses are more common especially where high-density plantings are made. Potassium usage is high and yield responses to additional K are common. Nutrient deficien cies for other elements have been described (O'Sullivan et al. 1997) and estimates of minimal tissue mineral concentrations reported (Bouwkamp 1985). Response depends largely on cultivar and growing system. Cultivars developed in low input systems will often show negative storage root yield responses when grown in high input systems, and produce excessive vine growth.

Cultural Practices

In tropical regions, sweetpotato planting is generally done by hand with timing early in the rainy season so that it dries out by harvest. In areas with a long rainy season, planting will be delayed. Some areas can produce more than one crop per season. Plants are taken from existing plantings or nurseries used to maintain plants. In temperate regions, plants are produced in the spring by firs presprouting storage roots at 29°C for 10–20 days and then bedding them by laying out on soil, almost touching for large roots and 2–4 cm between small roots, and covering them with 2–4 cm of soil and clear or black plastic to keep them warm. Covers are removed as plants sprout, and plants may be mowed to maintain an equal plant height. Plants are cut above the soil line to prevent disease spread and when they are 25–30 cm tall transplanted to the field Plants can be stored in cool conditions, 15°C, and 85% RH for up to a week with no loss of yield potential. Land preparation usually involves producing a raised bed

or mound. The mounding increases drainage, and temporarily lowers soil bulk density providing more uniform root development. In tropical regions, planting is usually done by hand while mechanical transplanters are the norm in temperate regions. Water will be added at transplanting if soil moisture is low. The vine canopy should cover the ground in 6–8 weeks, after which minimal weeding is needed. Normally, depending on cultivar and region sweetpotato roots can be ready to harvest 3–8 months after planting. In Papua New Guinea, where it is a subsistence crop, individual roots are harvested from a plant as needed, and then vines are covered with soil to encourage new storage roots to develop. In tropical regions, it is common to dig only what can be marketed at that time, so no storage is necessary. In temperate regions, the harvest is timed to optimize yield of the highest value size grade and before cold weather compromises storage ability. Here roots will be dug, often mechanically or a combination or mechanical digging and hand harvest, depending on the amount of skinning.

Japan has developed an alternative production system using cut seed pieces for the production of high starch processing lines. Storage roots are cut into 25–50 g pieces, and planted mechanically eliminating the bedding, plant cutting, and transplanting operations used in temperate production areas. Shapes are not as consistent as roots produced from plant cuttings, but this does not matter since the crop is processed. This type of system is being investigated in other temperate regions for processing types and clones suitable for ethanol production.

Common Diseases and Pests

Sweetpotato weevils (*Cylas* spp.) are the most important worldwide pests of sweetpotato. *Cylas formicaries* Fab. is the major weevil in most countries. They attack nearly all parts of the plants with larvae developing on mature stems and storage roots both in the fiel and in the storage. Larvae burrow throughout the storage root making it unmarketable, and, in response, the roots produce toxic sesquiterpenes leading to a bitter fl vor that is also toxic to livestock. Damage can be extensive both in the fiel and in the storage. Control through integrated pest management (IPM) strategies has been demonstrated (Talekar 1991). The combination of several techniques were necessary to provide good control, the two most important being preventing infestations of new field by using weevil free cuttings and by eliminating immigration of weevils from alternate hosts and weevil infested crops. Other techniques include crop rotation, sanitation, and chemical insecticides, and the use of sex pheromones to monitor weevil populations. Timing of insecticides is critical since once weevils are present inside the stems or storage roots they are difficul to reach. Biological control and breeding for resistance have not been very successful to date. In areas without the weevil, the use of sex pheromone traps to monitor for introduction and vigorously enforced quarantines can be used to prevent weevil spread.

The second most damaging insect pests are vine boring lepidopterans *Omphisa anastomasalis* (Guenee), *Megastes grandalis* Guenee, and *M. pucialis* Snell causing up to 30–50% yield losses (Talekar and Pollard 1991) in Asia, and certain parts of South America. Virus problems are severe in certain regions, but considered minor in other regions. Sweetpotato virus disease (SPVD), a combination of two viruses, causes up to 80% yield losses in parts of Africa. Viruses are found in nearly all commercial plantings because they are vegetatively propagated and rapidly spread by aphid and whitefl vectors. Quarantines restrict the free movement of planting material among countries, with most requiring plants to be virus-free before shipping. In the 1990s, most major production regions began to set up virus indexed programs to get virus indexed plants into the hands of growers. Virus assay kits have been developed for some viruses.

Postharvest Handling Practices

Storage

In temperate regions where production is limited to a summer season and marketing is continuous, sweetpotatoes are stored year round. Varieties have been selected for both low respiration and low water loss giving a storage life up to 13 months or until the next crop is harvested. Careful handling of sweetpotatoes is critical to ensure long-term storage. Bruising and skinning in the fiel is minimized by hand harvest or by using a combination of mechanical and hand harvesting. Roots exposed to bright sun for more than 30 minutes may have a darkening of skin called sun scalding, which is a cosmetic defect but can also be a site for postharvest decay. Roots should not be harvested when the weather is too cold. Chilling injury is a function of temperature and duration of exposure. Temperature below 10°C will cause chilling, though cooler temperatures will cause more damage. Chilling injury may not be seen for weeks after the chilling occurs and can be expressed by various symptoms including increased respiratory rate, greater susceptibility to decay, surface pitting, internal breakdown, hardcore and reduced culinary quality.

After harvest, roots are immediately "cured" at 29–33°C and 85–90% RH with proper ventilation for 4–7 days. Curing heals wounds that occur during the harvest, firs by a lignificatio beneath cells damaged at harvest, and second by the formation of a wound periderm beneath the lignifie cells in a process called suberization. The healing provides a pathogen barrier and reduces desiccation at the wound site resulting in less weight loss during storage. Uncured roots do not store well but properly cured roots stored at 13–15°C and 85–95% relative humidity will be marketable for up to 12 months (Edmunds et al. 2008). Good airfl w is essential to maintain oxygen and carbon dioxide exchange and allow for heat transfer. Cultivars vary tremendously as to how long they will store and maintain the necessary quality. Curing also produces changes in the culinary characteristics increasing moistness and sweetness (Walter 1987).

Sweetpotatoes continue to respire during storage, converting starch to sugar, which is then oxidized to carbon dioxide and water providing energy for the living cells. Over time, the loss of dry matter will cause pithiness, a textural defect caused by an increase in intercellular space, up to the point where there are air pockets in the root tissue. This is greatly accelerated by warmer temperatures. Once temperatures go above 16°C, the roots will begin to sprout which greatly increases the respiration rate and weight loss (Edmunds et al. 2008). Large commercial storage facilities in developed nations can maintain very precise conditions to optimize root storability and quality. In developing countries, storage of sweeetpotatoes has been done for hundreds of years and is still practiced using various pit, or underground storage structures. The success of these structures depends on how close they come to maintaining the ideal temperature, moisture, and oxygen levels as described. Storage losses due to rodents, weevils, and rots tend to be high, and the length of time often limited to a few months.

Packing and Shipping

Market requirements, especially shape and size requirements, for sweetpotatoes vary by region. Where it is a subsistence food, shape and size are not as important, but where it is a luxury item, appearance is very important. In the United States, highly mechanized packing lines are used to grade for strict size and shape parameters. Lines typically start with a tank of water into which roots are dumped, this wets the roots for washing and allows roots to be metered onto a conveyor system. Roots go through water rinse to remove soil followed by an eliminator to remove trash and small unmarketable roots, usually accomplished by going across a set of rollers at a

specifie width. Roots are then sorted, usually by hand, to remove decaying or otherwise unmarketable roots. Roots that will be shipped for retail are then generally treated with a fungicide to reduce decay. This is followed by sizing into various classes, some by diameter, or with electronic sizers measuring both length and diameter. Roots are put into boxes, and boxes onto pallets for efficien handling.

Bruising on packing lines can greatly affect shelf life of the sweetpotatoes and care should be taken in design and setup of the packing lines to reduce any impacts. The dump tank, drops off and onto conveyors, turns, and packing line speed and length account for much of the damage and should be minimized (Edmunds et al. 2008). Market life, which begins when roots are removed from bulk storage bins, of a sweetpotato is generally 2–3 weeks. The most common disease in storage and packed sweetpotatoes is Rhizopus soft rot caused by the fungus *Rhizopus stolonifer*. Present in most stored sweetpotatoes, it will contaminate packing lines and enter through wounds produced during packing. Sanitation and minimizing wounds on packing lines is the most effective control, and the main reason for the fungicide treatment. Care must be taken to ensure that shipping containers are maintained at 13°C to prevent excessive respiration or chilling damage.

Nutritional Composition of Sweetpotatoes

All the plant parts, roots, vines, and young leaves of sweetpotatoes are used as foods and animal feeds around the world. The nutritional values of sweetpotato roots and leaves are shown in Table 36.1. In Asia and Africa, the sweetpotato leaves are eaten as green vegetables. Almazan et al. (1997) reported the nutrient content of sweetpotato greens on dry weight basis as 25–37% protein, 23–38% total dietary fibe , 60–200 mg/100 g ascorbic acid, and 60–120 mg/100 g carotene. They are also rich in calcium (480–740 mg), iron (11–18 mg), potassium (3,380–5,230 mg), and magnesium (270–550 mg). The high level of phenolics (1.4–17.1 mg/100 g dry weight), anthocyanins, and radical-scavenging activities in sweetpotato leaves indicates their potential benefit on human health and nutrition (Islam 2006). The sweetpotato greens is very rich in lutein, 38–51 mg/100 g fresh leaves which are even higher than the lutein levels in the vegetables which are known as a source for lutein, e.g., kale (38 mg/100 g) and spinach (12 mg/100 g) (Menelaou et al. 2006).

Table 36.1 Nutrient content (g/100g fresh weight) in raw sweetpotato roots and leaves

Nutrient	Roots	Leaves
Water	77.28	87.96
Energy, kcal	86.00	35.00
Protein	1.57	4.00
Lipid	0.05	0.30
Ash	0.99	1.36
Carbohydrate*	20.12	6.38
Total dietary fibe	3.00	2.00
Total sugars	4.18	n.a.
Sucrose	2.52	n.a.
Glucose	0.96	n.a.
Fructose	0.70	n.a.
Starch	12.65	n.a.

Source: USDA Agricultural Research Service Nutrient Data Laboratory, 2009, http://www.nal.usda.gov/fnic/foodcomp/search/
n.a., not analyzed.

The nutrient composition of sweetpotato roots varies widely depending on the cultivar, growing conditions, maturity, and storage. Overall, sweetpotato roots have a high moisture level with an average dry matter content of 25–30%. Tsou and Hong (1992) reported a wide range of dry matter content of 13–41% from a sweetpotato germplasm collection. Sweetpotato roots are good source of carbohydrates and generally low in protein and fat. Protein content ranged from 1.73 to 9.14% on dry weight with substantial levels of nonprotein nitrogen (Yeoh and Truong 1996). Sweetpotato protein overall, however, is of good quality and the levels of essential

Table 36.2 Phytonutrients in orange- and purple-fleshed sweetpotato roots

Varieties	Flesh color	Dry matter (g/100g)	β-carotene (fwb) (mg/100g)	Antho-cyanins*	Total phenolic†
Beauregard	Orange	20.5	9.4	n.a.	88.9
Covington	Orange	20.3	9.1	3.8	58.4
Stokes purple	Dark purple	36.4‡	n.a.	80.2	401.6
NC 415	Dark purple	29.0‡	n.a.	69	652.5
Okinawa	Light purple	30.0‡	n.a.	21.1	458.3

Sources: Truong et al. 2007; Steed and Truong, 2008; Yencho et al. 2008.
*mg cyanidin-3-glucoside/100g fw.
†mg chlorogenic acid/100g fw.
‡Dry matter adjusted to 18-20% for fl wable purees; n.a. = not analyzed.

amino acids compare significantl to the FAO reference protein (Walter et al. 1983).

Most of the dry matter in sweetpotatoes consists of carbohydrates, primarily starch and sugars and to a lesser extent pectins, cellulose, and hemicellulose. Dietary fibe in sweetpotato roots range from 2 to 4% of fresh weight (Huang et al. 1999). Starch comprises 60–70% of the total dry matter, but the values vary for different types of cultivars. As with other starches, sweetpotato starch granules are made up of amylose (20%) and amylopectin (Woolfe 1992). Much variability in sugars exists between sweetpotato types. Truong et al. (1986) found total sugars to vary from 5.6% in a Filipino cultivar to 38% in a Louisiana cultivar on a dry weight basis (db). Sucrose, glucose, and fructose made up the majority of the total sugars in raw sweetpotato roots. During cooking, amylases act upon the gelatinized starch resulting in the formation of maltose in cooked sweetpotatoes.

Ash content of sweetpotatoes is approximately 3% of the dry weight or between 0.3% and 1.0% of the fresh weight basis (fwb) (Table 36.1). Potassium was the element with the greatest concentration in sweetpotato roots with an average of 396 mg/100 g fresh weight. Phosphorous, calcium, magnesium, iron, copper, and magnesium are also present in significan amounts (Woolfe 1992).

Sweetpotato roots also contain vitamins such as ascorbic acid, thiamin (B1), ribofl vin (B2), niacin (B6), pantothenic acid (B5), folic acid, and vitamin E. Bradbury and Singh (1986) reported values between 9.5 and 25.0 mg/100 g (fwb) for ascorbic acid and 7.3–13.6 mg/100 g (fwb) for dehydroascorbic acid resulting in a total vitamin C range of 17.3–34.5 mg/100 g for the sweetpotato roots. Orange-fleshe sweetpotatoes are rich in β-carotene (Table 36.2). A wider range of β-carotene content in cooked orange-fleshe sweetpotatoes, 6.7–16.0 mg/100 g fwb, has been reported by different investigators (Huang et al. 1999; Bovell-Benjamin 2007). The sweetpotato carotenoids exist in an all *trans* configuration which exhibits the highest provitamin A activity among the carotenoids. van Jaarsveld et al. (2005) advocate the increased consumption of orange-fleshe sweetpotatoes as an effective approach to improve the vitamin A nutrition in the developing countries. Epidemiological studies indicated the beneficia effects of high carotene diets in reducing the risks of cancer, age-related macula degeneration, and heart diseases (Tanumihardjo 2008).

Purple-fleshe sweetpotato roots have attractive reddish-purple color with high levels of anthocyanins and total phenolics (Table 36.2). The fl wable purees with a solid content of 18% processed from this sweetpotato type had total phenolic and anthocyanin contents of 314 mg chlorogenic acid equivalent/100 g fwb and 58 mg cyanidin-3-glucosdie equivalent/100 g fwb, respectively. The 2, 2-diphenyl-1-picrylhydrazyl (DPPH)

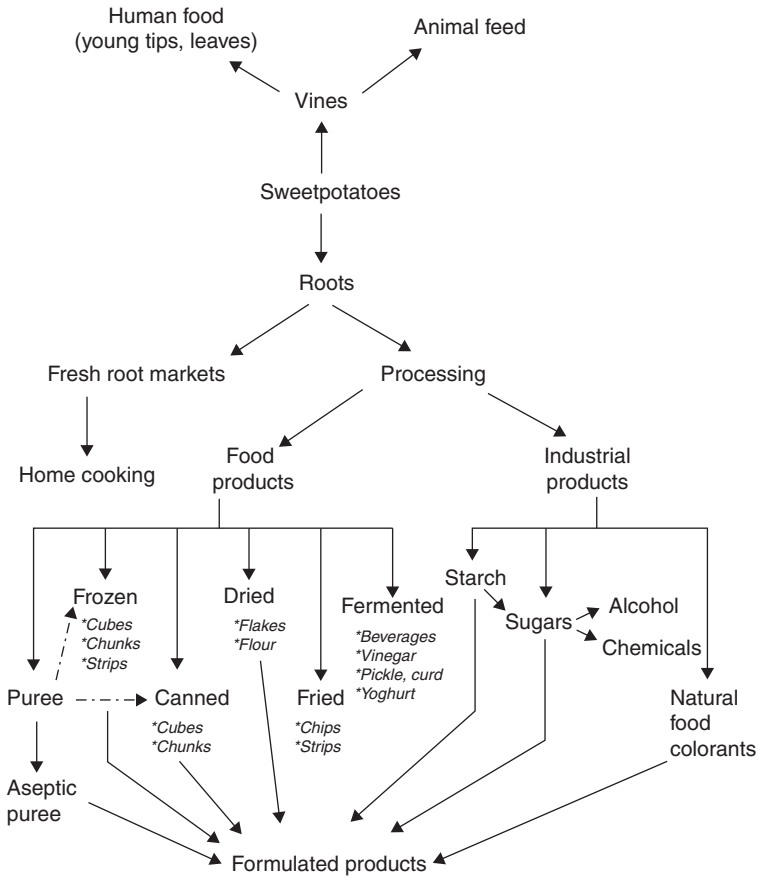

Figure 36.2 Various processing and utilization of sweetpotatoes.

radical scavenging activity was 47 μmol trolox equivalent/g fwb and oxygen radical absorbance capacity (ORAC) of 26 μmol trolox equivalent/g fwb (Steed and Truong 2008). The purple-fleshe sweetpotatoes have polyphenolic content and antioxidant activities in a competitive level with other food commodities known to be a good source of antioxidants such as black bean, red onion, black berries, cultivated blueberries, sweet cherries, and strawberries. Several clinical studies indicated that consumption of purple-fleshe sweetpotatoes may have potential health benefit against oxidative stress associated with liver injury (Suda et al. 2008) and other chronic diseases (Suda et al. 2003).

Processing and Utilization

Sweetpotato roots and other plant parts are used as human food, animal feed, and processing industry. Various processing technologies that convert sweetpotatoes into functional ingredients, food, and industrial products are summarized in Figure 36.2. For industrial processing, starch, sugars, and natural colorants are the major intermediate products that can be used in both food and nonfood processing industry. Sweetpotato varieties with high levels of dry matter (35–41%), total starch (25–27%), and extractable starch (20–23%) are available for starch processing (Brabet et al. 1998). There

are many small and medium factories in Asia producing about 26% of starch production (Bovell-Benjamin 2007). The process for manufacturing sweetpotato starch is basically similar to the starch extraction from other sources. The roots are ground in limewater (pH 8.6–9.2) to prevent browning due to polyphenol oxidase, to dissolve pigments, and to flocculat the impurities. The extracted starch is separated from the pulp by thoroughly washing over a series of screens, bleaching with sodium hypochlorite, and then settling by gravity or centrifugation. In small-scale establishments, starch is stored wet in concrete tanks or sun-dried to a moisture content of about 12%, pulverized and screened. Centrifugation and mechanical drying, such as flas drier, are commonly used for medium-scale factories. Sweetpotato starch is used in the production of traditional noodles, vermicelli, thickening agents, or converted into sugar syrups which are used in many processed food products. The sweetpotato starch and sugars are also utilized in the production of fuel alcohol, monosodium glutamate, microbial enzymes, citric acid, lactic acid, and other chemicals (Kotecha and Kadam 1998; Padmaja 2009). In Japan, the orange- and purple-fleshe sweetpotatoes have been used in commercial production of natural beta-carotene and anthocyanin pigments in beverages and other food products. The following sections describe recent developments in processing of sweetpotatoes into functional ingredients and common food products.

Purees

Processing

The use of sweetpotatoes in the food industry often involves processing of the roots into purees that can be subsequently frozen, canned, or packaged in aseptic conditions to produce shelf-stable products for year-round availability. In puree processing, roots of all sizes and shapes can be utilized and, therefore, the entire harvested crop is utilized including the 30–40% off-grade from the fresh root markets (Kays 1985b; Walter and Schwartz 1993). The challenges in puree processing industry are: (1) the difficult in adjusting the process to account for differences in cultivar types, root handling, curing, and storage; and processing techniques in order to produce consistent, and high quality puree; and (2) the preservation technology that could produce shelf-stable product for convenient incorporation in processed foods.

Several techniques have been developed for puree processing in order to produce purees with consistent quality, despite the variations due to cultivar differences in carbohydrate content, starch degrading enzyme activities, and postharvest handling practices (Kays 1985b; Collins and Walter 1992). Process operations for pureeing of sweetpotatoes include washing, peeling, hand-trimming, cutting, steamed blanching or cooking, and grinding into purees which can be subjected to canning or freezing for preservation (Figure 36.2). Raw sweetpotatoes can be peeled by abrasive rollers, lye solution, or steam flashing Lye peeling is no longer a common method in the industry due to the issues on equipment corrosion and waste disposal. The peeled sweetpotatoes are then washed thoroughly to remove all disintegrated peel, followed by trimming, cutting into slices or dices. The purees can be simply produced by steam cooking of the chunks, slices, strips, cubes, or ground particles, and passing the cooked materials through a pulp finishe . Hoover and Harmon (1967) developed an enzyme activation technique using the endogenous amylolytic enzymes for starch hydrolysis in sweetpotato puree processing, and this process is now commonly used in the food industry. As shown in Figure 36.3, the peeled sweetpotatoes can be either cut into cubes of 2 cm, strips of $2 \times 2 \times 6$ cm, and slices of 0.5–0.95 cm thickness (Walter and Schwartz 1993) or mashed using a hammer mill with rotating blades to chop and push the materials

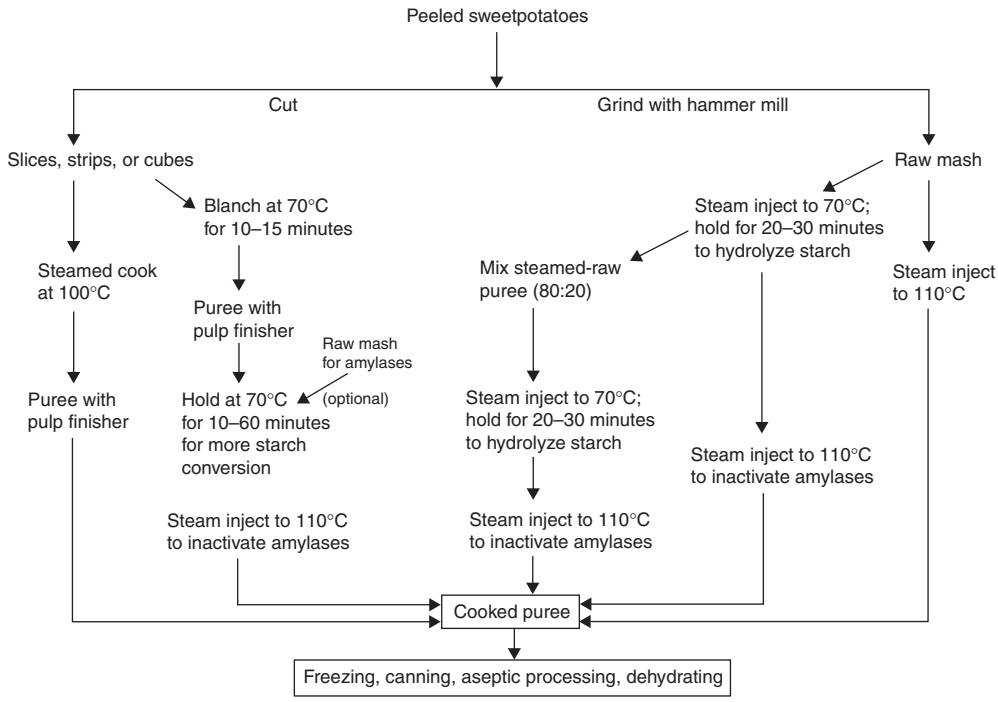

Figure 36.3 Different processes for sweetpotato puree production (Truong and Avula 2010).

through a 1.5–2.3 mm mesh screen (Szyperski et al. 1986). Next, the materials are steamed blanched at 65–75°C which activates the amylases and gelatinizes the starch for hydrolysis. For the process with slices, strips, and cubes, comminuting the blanched materials into puree is carried out at this point using a hammer mill. The blanched puree is pumped into a surge tank and hold at 65–75°C for further starch hydrolysis depending on the targeted maltose levels. Raw sweetpotato mash as a source of amylases can be optionally added at this stage to increase starch conversion. α- and β-amylases hydrolyze the starch producing maltose, maltotriose, glucose, and dextrins.

Packaging and Preservation

The finish-coo ed puree can be packaged in cans and retorted to produce shelf-stable product. The puree can also be fille in plastic containers for refrigerated or frozen storage (Kays 1985; Collins and Walter 1992; Walter and Wilson 1992; Pérez-Díaz et al. 2008).

Preservation by canning for low acid food such as sweetpotato purees (pH, 5.8–6.3) usually involves high thermal treatment of the product because heat transfer in the puree is mainly by conduction. High thermal treatment (e.g., 165 minutes at 121°C for an institutional #10 can size) also results in severe degradation of color, fl vor, texture, and nutrients. The slow rate of heat transfer from the wall to the center of the can to attain commercial sterilization of the product limits the maximum can size of number 10 for canned sweetpotato purees. This size limitation is another obstruction for the wider uses of sweetpotato purees as a food ingredient in the food industry. Nevertheless, canning does not have the need for special storage; lower capital investment and unit of production is less when compared to refrigerated and frozen puree. On

the other hand, frozen puree is an established method for preservation and provides least degradation of nutritional and sensory quality as compared to canning. However, preservation by freezing requires considerable investment in frozen distribution and storage as well as space, energy, time, and requires defrosting before use. Currently, only limited amount of canned and frozen sweetpotato purees are commercially produced by a few companies in the United States and Japan.

Aseptic processing is considered as a potential alternative to overcome the stated problems associated with canning and low-temperature preservation. As opposed to conventional canning, the use of high temperature ($\geq$125°C) for a short period of time in aseptic processing can produce a higher quality product with equal or better level of microbiological safety as that in a conventional canning system. A process for rapid sterilization and aseptic packaging of the orange-fleshe sweetpotato purees using a continuous fl w microwave system operated at 915 MHz has been successfully developed by Coronel et al. (2005). This process has the advantage of avoiding long retort processing schedules, maintaining high quality retention, and producing shelf-stable products. The resulting product packed in fl xible plastic containers had the color and viscosity comparable to the nonsterilized puree and was shelf-stable for at least 12 months. Purple-fleshe sweetpotato purees were also successfully processed into high quality aseptic product using the continuous fl w microwave system (Steed et al. 2008). With this technology, shelf-stable purees with consistently high quality can be packaged into various container sizes (up to 300 gallons) for conveniently utilizing as food ingredients in the food processing industry. This technology can be extended to highly viscous biomaterials and purees from other fruits and vegetables (Kumar et al. 2008). In this new process, sweetpotato puree is loaded into a hopper, and pumped through the system. Microwaves from a generator are delivered to sterilize the puree at 130–135°C, to retain in the holding tube for 30 seconds, to rapidly cool in a tubular heat exchanger, and then to aseptically package in aluminum-polyethylene laminated bags (Simunovic et al. 2006). The firs commercial venture on aseptically packaged sweetpotato puree using this microwave-assisted sterilization technology has been carried out. With rapid heating, high retention of carotene and anthocyanins (>85%) in the purees can be achieved, and this development opens up a new market opportunity for the sweetpotato industry.

Sweetpotato purees has been used as an ingredient in numerous formulated food products, including baby food, casseroles, puddings, pies, cakes, ice cream, leather, bread, patties, and soups (Hoover et al. 1983; Collins and Washam-Hutsell 1986; Collins and Walter 1992; Truong and Walter 1994). The sweetpotato purees are also used in fruit/vegetable-based beverages and restructured products (Truong 1992; Truong et al. 1995; Utomo et al. 2005). Other commercial utilization of sweetpotato puree includes jam and ketchup (Truong 1994; Fawzia et al. 1999). The uses of sweetpotato purees in various fermented food products are described in a section below. With the recent commercial development of the microwave-assisted processing and aseptic packaging of sweetpotato purees, it is expected that more processed food products from the puree will be developed. In the United States, sweetpotato puree has been used for dehydrating into fla es or powder for various food applications.

Frozen Products

Sweetpotatoes can be frozen in different forms such as whole roots, halves, quarters, slices, cubes, French fries, paste, or as puree. The processing steps include peeling, sizing, cutting, blanching or cooking, packaging, and freezing. Sizing is important to assure appropriate blanching or cooking and freezing

time when the roots are to be frozen whole (Bouwkamp 1985b). Packaging may precede freezing such as frozen purees or may follow freezing when the roots or cut pieces are individually quick frozen (IQF). In Japan, sweetpotato slices/crushed roots mixed with 35% sugar are packed in plastic bags and blast frozen at −40°C (Woolfe 1992). In large-scale production of French fries, partially fried products are frozen for distribution to institutional and retailed consumers. Good quality fries could be produced by blanching the strips in 60% sucrose solution for 4.5 minutes or for 3 minutes in boiling water containing 0.25% sodium acid pyrophosphate (SAPP) and 0.25% calcium chloride (Padmaja 2009). Textural properties of the frozen French fries are affected by root storage, and the problem can be overcome by calcium treatment and low-temperature blanching. Loss in ascorbic acid and color score were reported for French fries stored frozen for 1 year (Schwartz et al. 1987). Discoloration is a major problem for frozen sweetpotato products. Enzymatic discoloration caused by polyphenol oxidase is characterized by a brown, dark gray, or black color. This discoloration can be minimized or prevented by heat inactivation of the enzymes prior to peeling, soaking the cut pieces in solutions containing sulfite and acidulants. The nonenzyamtic discoloration is caused by phenolics complexing with iron and other metals, which can be prevented by pyrophosphates in the blanching medium or added directly into several products (Walter and Wilson 1992).

Canned Products

Canned sweetpotatoes are widely consumed among the sweetpotato products available to consumers in the United States. Sweetpotatoes can be canned whole, halved, or cut into chunks, either in syrup or water. Sweetpotatoes can also be pureed and canned as a solid pack. The unit operations leading to the production of canned sweetpotato roots include peeling, cutting, sizing, blanching, filling syruping, exhausting, and retorting. Blanching in water at 77°C for 1–3 minutes is done to drive out gases, maintain can vacuum, and increase the initial temperature of the contents of the cans (Bouwkamp 1985b; Padmaja 2009). However, low-temperature blanching at 62°C increases firmnes and intactness retention of canned sweetpotatoes as compared to the unblanched samples or samples blanched at higher temperatures (Truong et al. 1998). Immediately after blanching, the material is packed in cans and covered with syrup at 95°C to prevent discoloration. Sugar (20–40%) or water is used depending on consumer preferences. Cans should be exhausted long enough for the internal temperature to reach 77°C to ensure a good vacuum of the finishe cans (Bouwkamp 1985b). After closing, the cans should be retorted according to the processing schedules, quickly cooled after retorting to an internal temperature of 35°C to avoid "stackburn" and slow drying of the can which may lead to rusting. Firmness is one of the most important attributes determining the quality and marketability of canned sweetpotato roots. Firmness was slightly greater for sweetpotatoes packed with sucrose than with corn syrup, and canning in syrups with high sugar concentrations produced firme roots. Variations between the same cultivars grown in different locations, application of fertilizers, and irrigation influenc firmnes (Bouwkamp 1985b). Sweetpotatoes canned immediately after harvest are firme than those previously cured or stored. Changes in pectic fractions are responsible for the decreased firmnes of previously stored, canned roots. Adjustment of pH in sweetpotato tissue by acidificatio or alkali treatment and calcium treatments improved the firmnes of canned products and French fries processed from cured and stored roots (Walter et al. 1998).

Dehydrated Forms: Slices, Granules, Flakes, Flour

Sweetpotato roots are processed into dehydrated forms such as dried chips, cubes,

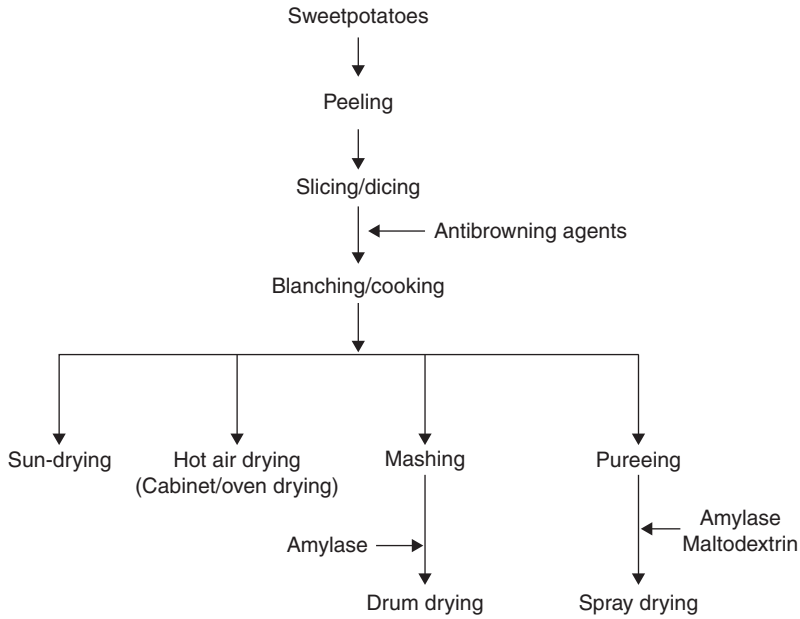

Figure 36.4 Drying technologies applied to dehydrated sweetpotato products.

granules, fla es, and flou for storage and use in food preparations including soups, bakery products, vermicelli, noodles, extruded snack foods, and breakfast cereals (Peters and Wheately 1997; Padmaja 2009; Truong and Avula 2010). Drying produces a light, compact, relatively inexpensive, easily stored, and transported material. Processing methods vary in sophistication from simple slicing and fiel sun-drying of roots as practiced at the village levels in many tropical countries to the large-scale, multistage production of dehydrated products by large food companies (Figure 36.4). Functionality, nutrient retention, and product storability of dehydrated products of sweetpotato roots are important to provide competitiveness of these ingredients in food processing.

Sun- and Solar Drying

Sun-drying has long been practiced in developing countries, where there is a pronounced dry season, to produce dried chips and flou from both white- and colored-fleshe sweetpotato varieties. Sweetpotato roots are cut into 2–3 mm thick slices and optionally blanched in boiling water for several minutes. The slices may be subjected to metabisulfit treatment before or during blanching to prevent browning. The blanched or unblanched slices are sun-dried until the slices reached a moisture content of about 6–10%. Drying times vary from 4 hours to 5 days depending on climatic conditions, and the dried slices are ground into flou . To inhibit microbial growth during drying, fresh roots are soaked in 8–10% salt solution (Winaro 1982). Owori and Hagenimana (2000) developed processes for small-scale production of flou with the desired degree of odor, color, and nutritional and microbiological quality. In Indonesia, sun-dried chips are fried and packed in polyethylene for retail sale (Kotecha and Kadam 1998). Sweetpotato flou has been produced for decades in Peru to use in the wheat-sweetpotato bread (van Hal 2000). However, poor control of energy input and product quality, interruption of drying caused by cloud, rain, and nightfall, and frequent

contamination by microorganisms, dust, and insects are the disadvantages of sun-drying (Woolfe 1992). Microbial evaluation of sun-dried sweetpotato slices showed the presence of 12 fungal species whereas the oven-dried slices had no fungal growth (Okungbowa and Osagie 2009). These problems can be overcome by using modern solar-assisted dryers that effectively utilize solar energy for control drying, resulting in good quality products. Several types of solar dryers with external means, like fans, furnace, for moving solar energy in the form of heated air from the solar collector to the drying bed that have been used for fruits and other vegetables (Lopez-Malo and Rios-Cass 2009), can be applied in drying sweetpotatoes.

Mechanical Drying

Mechanical driers such as cabinet, tunnel, drum, or spray driers are used in large commercial enterprises. Cabinet and tunnel drying are based on the same principle as solar drying, except that the air is heated by fuel. The dehydration conditions such as drying temperature, drying time, and air velocity can be controlled in these driers. As in puree processing, raw sweetpotatoes can be peeled by abrasive rollers or steam flash ing, followed by washing, trimming, cutting into slices/dices, soaking in solution containing antibrowning substances such as sulfite SAPP, and steam-blanching for about 7 minutes. The slices/dices are spread on trays and dried in the cabinet or tunnel dryers at about 50–80°C for 4–12 hours to a moisture content of less than 7%. The drying ratio of fresh to finishe product is about 3:1 to 5:1 depending on the dry matter content in sweetpotatoes. To produce good quality flou , sweetpotato roots should be low in total free sugars, reducing sugars (<2%), ash content, amylase activity, polyphenol oxidase content, and should have high dry matter with white color (Bovell-Benjamin 2007). The dehydrated product should be suitably packaged in aluminum-laminated packages or plastic containers to exclude air and moisture for good storage stability (Avula et al. 2006; Hathorne et al. 2008). A high temperature-short time drying process, 150°C for 10 minutes, was developed by Antonio et al. (2008) for osmotic dehydration of sweetpotatoes.

Drum drying of sweetpotato purees is commercially practiced in the United States for producing sweetpotato fla es/powder which can be reconstituted into mashed sweetpotatoes or incorporated into a variety of other products such as pies, pastries, cakes, casseroles, and other food preparations. The cooked and comminuted sweetpotatoes are dried in a double drum drier heated with steam. The fla es were milled into <60 mesh particles and stored under nitrogen at −20°C (Valdez et al. 2001). Szyperski et al. (1986) developed an alternative drum drying process to produce a consistent product independent of raw material variations. A commercial α-amylase was used to hydrolyze a part of the pregelatinized puree, which is then blended with the untreated portion. SAPP or citric acid is added to the puree before drying to control non-enzymic browning which causes discoloration of the reconstituted fla es. Avula et al. (2006) prepared drum dried flou by subjecting sweetpotato mash to a double drum drier of 60 cm width and 35 cm diameter. The speed of the drum was maintained at 3 rpm with a clearance of 0.3 mm and at a steam pressure of 6 kg/cm^2. The sheets of dried sweetpotato were collected, crushed, and milled into flou in a hammer mill provided with a 500 μm sieve. Drum drying caused a reaction of the ε-amino group of lysine with reducing groups of carbohydrates, which caused the lysine to be destroyed irreversibly and formation of browning compounds (Walter et al. 1983).

Spray drying of sweetpotato purees was reported by Grabowski et al. (2006). The puree was subjected to pretreatment with α-amylase to reduce viscosity and maltodextrin was used to aid in spray drying. Maltodextrin facilitates product recovery by raising the glass

transition temperature of the product thereby reducing stickiness and partially encapsulating the material. The puree was spray dried using a dryer equipped with a rotary atomizer and a mixed-fl w air-product pattern. The fina characteristics and functionality of the spray-dried sweetpotato powders are affected by predrying treatments and spray drying temperature. Rheological properties of the reconstituted slurries from spray-dried sweetpotato powders behaved similarly to the pregelatizied starch (Grabowski et al. 2008). It was demonstrated that good quality sweetpotato powder produced by spray drying has potential applications in food and nutraceutical products.

Fried Products: Chips, French Fries

Sweetpotato chips and French fries are popular in many countries. In the past few years, several food companies in the United States have ventured into processing of sweetpotato chips and French fries with high beta-carotene content from orange-fleshe sweetpotatoes in response to the growing demands of the consumers on healthy foods. Reconstituted sweetpotato chips were developed in China, and extruded snack products with alternative shapes to those of conventional chips were produced in Japan, with characteristics similar to those of extruded potato snacks (Woolfe 1992).

For chip processing, unpeeled or peeled roots are sliced into 0.8–2.0 mm thin chips which are blanched for 2 minutes at 93°C, then drained and partially dehydrated using heated forced air at 119°C. The thickness of the chip is important since it affects the length of cooking and the quality of the finishe product. Partial drying has a pronounced effect on the appearance, fl vor, and texture of the finishe product. Optimum frying temperature was between 143 and 154°C (Hoover and Miller 1973). Picha (1986) reported that color of the chips was positively related to reducing sugars. However, recent screening on various sweetpotato genotypes with a wide range of reducing sugar content indicated that other substances such as amino acids may significantl contribute to the browning of fried chips. Following frying, the chips are drained and salted/sugared. After cooling, the chips will be packaged immediately to exclude water and oxygen. For French fries, sweetpotato roots are cut into strips 1.9 cm thick × 6.4 cm thick, blanched in boiling water containing 1% SAPP to inhibit polyphenolic discoloration, followed by partial drying at 120°C for 5 minutes, frozen, and stored at −34°C until the slices are fried for consumption (Schwartz et al. 1987). Partial drying reduces oil absorption and increase sensory quality of French fries (Walter and Hoover 1986). Coating of sweetpotato strips with starch-based materials improved appearance and textural properties of sweetpotato French fries (Truong and Thibault 2009).

The quality of fried chips and French fries are affected by sweetpotato varieties, postharvest handling, and storage conditions. Changes in reducing sugars, amino acids, and other substances involved in the discoloration of sweetpotatoes affect the color of this product type. Textural properties and oil content of the fried products are influence by dry matter and starch content. An integrated approach including selection of suitable varieties, growing conditions, and appropriate postharvest handling and storage conditions should be considered in order to produce sweetpotato chips and French fries with consistent quality all year round.

Fermented Products

Being rich in starch, sugars, and other nutrients, sweetpotatoes have been used in the production of many fermented products. In Japan, high-starch sweetpotato varieties are used in "shochu" fermentation. Shochu is traditional distilled liquor from sweetpotatoes or other sources such as rice, barley, corn, or potato (Sakamoto and Bouwkamp 1985).

Sweetpotato shochu is very popular, especially in southern Japan. The process involves the inoculation of steamed sweetpotato slurry with a starter "Koji" containing *Aspergillus niger* or *A. kawachii* as an enzyme source for starch conversion to sugars followed by fermentation to alcohol by yeast *Saccharomyces cerevisiae*. The whole process usually takes 12–14 days to yield a broth having 13–15% alcohol, which is then distilled and blended to produce shochu with 20–40% alcohol.

Wine and beer are the recent alcoholic beverages from the orange- and purple-fleshe sweetpotatoes (Yamakawa 2000). Red vinegar with high antioxidant activity and antihyperglycemic effect made from purple-fleshe sweetpotatoes was developed (Matsui et al. 2004). Sweetpotatoes also used as substrates in soy sauce fermentation (Data et al. 1986). Other fermented sweetpotato products rich in carotene and anthocyanins that have been developed in recent years include yogurt (Collins et al. 1990), curd (Mohapatra et al., 2007), fermented beverages (Saigusa et al. 2005), lacto-pickle (Panda et al. 2009a), lacto-juice (Panda et al. 2009b) and probiotic milk-sweetpotato drink (Perez and Tan 2006). The application of bioprocessing technology and the progress in the development of fermented products from sweetpotatoes was recently review by Ray et al. (2010).

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Chapter 37

Tomato Processing, Quality, and Nutrition

Ali Motamedzadegan and Hoda Shahiri Tabarestani

Introduction

Tomato (*Lycopersicon esculentum* L) is both qualitatively and quantitatively a worldwide important vegetable, with an annual estimated production of 88 million tones (Eipeson 2003). The word "tomato" is derived from the Mexican Nahuati Indian word "*tomati*." It originated in the Andes of South America and evolved from the cherry tomato (*L. esculentum* var. *cerasiforme*) (Jy et al. 2004).

Tomato, a warm-season crop, belongs to fruit vegetables, and the *Solanaceae* family. It requires day temperatures of 25–30°C and night temperatures of 16–20°C for optimal growth (Rubatzky and Yamaguchi 1997; Decoteau 2000). The fruit set is best between 18 and 24°C, the night temperatures being more critical than day temperatures. The tomato fruit is classifie botanically as a berry, the size varying from small cherry types, with only two divisions of the ovary (locules), processing tomatoes, to commercial cultivar for fresh market with 4–6 locules (Benton-Jones 2008). This chapter reviews the production, processing, biochemistry, and nutritional aspects of tomatoes.

Production

The estimated world tomato production in 2007 was 133.26 million metric tons. The major tomato producing countries are listed in Table 37.1, along with the production data and their share of the total world production. The top four countries—China (25.2%), USA (10.6%), India (7.5%), and Turkey (7.5%)—accounted for more than half of the world tomato production.

Tomatoes are not only consumed as a raw fl vorful food due to their desirable nutritional and organoleptic properties, but they are also used in the form of a variety of processed products. A major percentage of tomatoes are used for processing into juice, paste, puree, soup, ketchup, sauce, and as canned tomatoes.

Harvest, Postharvest Handling, and Storage

Harvesting at the right stage of maturity is critical for the intended use of tomatoes, i.e., whether for the fresh market or processing. At harvest time, tomatoes should be fir and free from bruising during handling, grading, and packing. Titratable acidity is lower in fruits harvested at the fir red stage, which decreases during storage (Chiesa et al. 1998). The best-fl vored tomatoes are those that ripened fully on the plant. In many countries, tomatoes are harvested by hand. However, for tomatoes intended for processing, large-scale harvesters are commonly used. For efficien mechanical harvest, vine size is important due to its effect on the machine design, ease of vine pick up, and effectiveness of fruit removal (Gould 1983, Thompson 2003).

Handbook of Vegetables and Vegetable Processing. Edited by N. K. Sinha.

Table 37.1 Leading tomato producing countries and their share of the total world production in 2007

World rank	Country	Production ("000" MT)	Share of world production (%)
1	China	33,597	25.2
2	USA	14,185	10.6
3	India	10,055	7.5
4	Turkey	9,945	7.5
5	Egypt	8,639	6.5
6	Italy	6,530	4.9
7	Iran	5,000	3.8
8	Brazil	3,431	2.6
9	Spain	3,664	2.7
10	Mexico	3,150	2.4
11	Russian Federation	2,306	1.7
12	Uzbekistan	1,680	1.3
	World Total	133,259	–

Source: FAOSTAT (http://faostat.fao.org/).

Raw tomatoes are handled using hampers, lug boxes, plastic boxes, or bulk containers (bulk boxes, water tanks, and bulk trailers) (Gould 1983). Efficien bulk transport represents another step toward complete mechanization of harvest and handling. Once at the plant, they are processed immediately or stored in the shade. The relative storage life of fresh tomato fruit in air at near optimum storage temperature and relative humidity (RH) is about 2–4 weeks, depending on the ripeness stage. The optimum storage temperature for ripe tomatoes is 45–50°F (7.2–10°C), with a RH of 85–96%. The mature green fruit can be stored at 55–60°F (12.8–15.6°C) for several days without significan quality loss (Benton-Jones 2008).

Tomato respiration, transpiration, and ethylene production are major factors implicated in quality deterioration. Refrigeration is the most important technology for extended shelf-life fresh tomato. A broader range of postharvest technologies is commonly used for extending the shelf life; e.g., edible coating, use of modifie atmospheres storage, and innovative packaging. Reduction of respiration rate is often the most important parameter affected by altered atmospheres (Banks et al. 1993). The most common storage technologies used for fresh tomatoes are controlled atmosphere (CA) storage and modifie atmosphere packaging (MAP). Partially ripe tomatoes, packed in suitable permeable plastic fil giving 4–6% CO_2 and 4–6% O_2 with about 90% RH, at ambient temperature, have 7 days longer shelf life than those unwrapped (Thompson 2003). Tomatoes characteristically follow a climacteric ripening pattern, which is controlled by ethylene; thus, most of the postharvest storage technologies are focused on controlling biosynthesis and action of ethylene in order to delay spoilage (Martinez-Romero et al. 2009).

Tomato Biochemistry and Nutrition

Composition and Nutritional Quality

The yield and quality of tomato products depend in great measure upon the composition of the raw material. The proximate composition, minerals, and vitamins content of raw tomatoes and commercially processed tomato products are shown in Table 37.2 (USDA 2009). The percentage of solids in tomatoes varies due to variety, character of soil, and specially, the amount of rainfall during the growing and harvesting season (Gould 1983). About half of the soluble solids are composed of reducing sugars, glucose and fructose. Acids contribute about one-eighth of soluble solids, considered to be almost entirely citric while traces of malic, tartaric, succinic, acetic, and oxalic acids have also been reported. Higher solids content of tomato usually causes stronger fl vor. Polysaccharides, pectins, arabinogalactans, xylans, and arabinoxylans, are present to a varying concentration (Leoni 2002). Tomato firmnes is dependent on an increase in total pectin, presence of some minerals (Ca and Mg), or decrease in degree of pectin esterificatio (Belitz et al. 2009). Tomatoes are a rich source of lycopene, an antioxidant. The concentration of lycopene varies with the stage of maturity, with the highest concentration in

Table 37.2 Effect of processing on proximate, vitamin, and mineral composition in selected tomato products (per 100 g)

	Unit	Raw-red tomatoes	Tomato juice	Tomato sauce	Tomato paste	Canned tomatoes) (stewed)	Sun-dried tomatoes
Proximate:							
Water	g	94.5	93.9	91.12	73.5	91.54	14.56
Energy	kcal	18	17	24	82	26	258
Protein	g	0.88	0.76	1.32	4.32	0.91	14.11
Lipid/fat	g	0.2	0.05	0.18	0.47	0.19	2.97
Dietary fibe	g	1.2	0.4	1.5	4.1	1	12.3
Carbohydrates	g	3.92	4.24	5.38	18.91	6.19	55.76
Minerals:							
Calcium	mg	10	10	13	36	34	110
Magnesium	mg	11	11	16	42	12	194
Phosphorus	mg	24	18	26	83	20	356
Potassium	mg	237	229	331	1,014	207	3,427
Sodium	mg	5	10	524	98	221	2,095
Manganese	mg	0.114	0.07	0.107	0.302	0.059	1.846
Vitamins:							
Vitamin C	mg	12.7	18.3	7	21.9	7.9	39.2
Folate, total	μg	15	20	11	12	5	68
Choline	mg	6.7	6.8	9.9	38.5	10.4	104.6
β-Carotene	μg	449	270	259	901	103	524
Vitamin A	IU	833	450	433	1,525	172	874
Vitamin K	μg	7.9	2.3	2.8	11.4	2.4	43

Source: USDA National Nutrient Database for Standard Reference, Release 22 (USDA 2009).

fully ripe red tomatoes (Figure 37.1, USDA 2009).

Dietary intakes of tomatoes and tomato products containing lycopene have been related epidemiologically to lower incidence of cardiovascular disease and of prostate, gastrointestinal, and epithelial cell cancer (Ishida and Chapman 2004; Rao and Rao 2007). Its organic acids contribute to acid–base balance for consumer acceptability (Adedeji

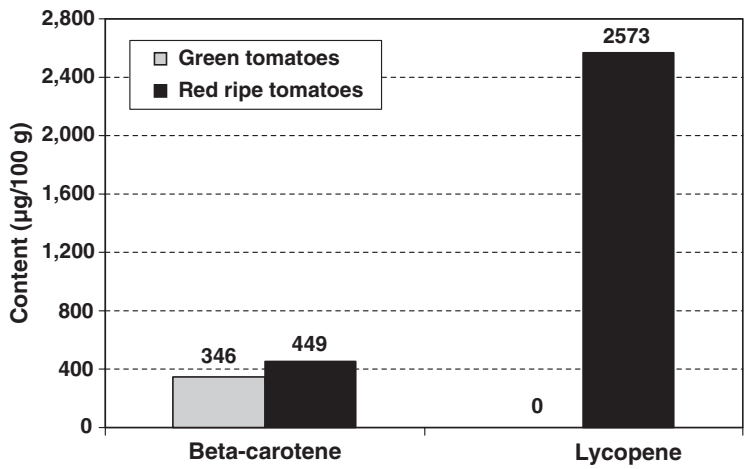

Figure 37.1 Effect of maturity on beta-carotene and lycopene content of tomatoes (Source: adapted from USDA 2009).

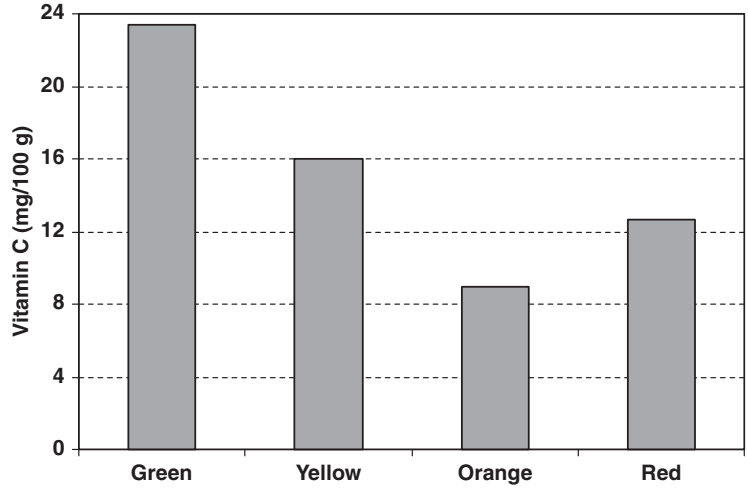

Figure 37.2 Vitamin C content of different raw tomato varieties (Source: adapted from USDA 2009).

et al. 2006). In addition to lycopene, tomato is a good reservoir of diverse antioxidant molecules, such as ascorbic acid, vitamin E, carotenoids, and fl vonoids. The nutritional composition of tomatoes varies with the color of a particular variety. Figure 37.2 shows vitamin C content in green, yellow, orange, and red tomatoes (USDA 2009).

Changes in Nutritive Value during Processing

The nutritive value of processed tomato products depends both on nutrients in fresh tomato and on the effects of processing and storage of the finishe product. In general, food processing supposes to decrease the nutritional value of staples due to the loss of certain compounds, such as vitamins (Klopotek et al. 2005). Any unit operation, which incorporates air into the juice or heat treatment, will accelerate oxidation of ascorbic acid. Therefore, it is important that juice be brought to desired temperature as quickly as possible. It has been reported that food processing renders lycopene more available in processed tomato products than in raw tomatoes (Gartner et al. 1997). Table 37.2 summarizes effect of processing on nutrient composition of commonly processed products.

The amount of lycopene present in raw tomatoes and processed tomato products is shown in Figure 37.3. Lycopene has been shown to be stable to heat treatment and storage (Trifir et al. 1998). Exposure to oxygen, high temperature, and low water activity may cause lycopene degradation (Leoni 2002). Cooking or canning does not usually cause large changes in total lycopene content. During conventional tomato management, most of lycopene may be converted from the all-*trans* form into the less bioactive, *cis* isomer (Muratore et al. 2008).

Preprocessing Unit Operations

Grading: Grade standards vary from country to country or along individual companies. For example, the US standards provide an inspection procedure based on two factors: (1) classificatio of defects including worms, worm damage, freeze damage, stems, mechanical damage, anthracnose, mold, and decay into various categories; and, (2) optional color determination by use of either a color instrument or visual evaluation of fruit. The

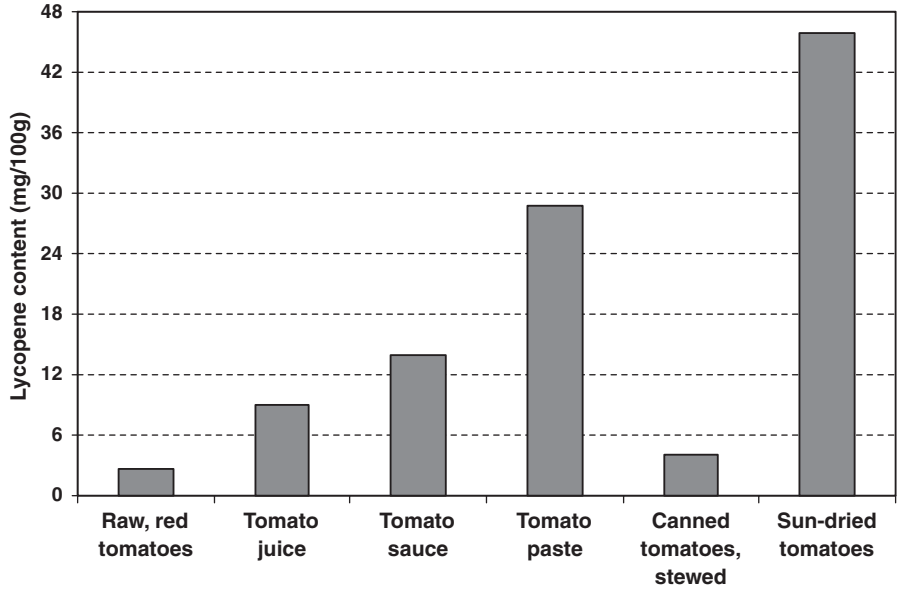

Figure 37.3 Effect of processing of lycopene content of selected tomato products (Source: adapted from USDA 2009).

United States Department of Agriculture (USDA) divides tomatoes for processing into categories A, B, C, and culls (USDA-AMS 1983). Tomatoes may also be classifie according to total soluble solids (°Brix). Tomatoes for canning (whole, sliced, or diced) are graded on the basis of color, firmness defects, and size (Barringer 2003a). The firmnes is important to ensure that tomato will survive canning. Soft, watery cultivars or cultivars possessing large seed cavities give an unattractive appearance and, therefore, receive a lower grade. Fresh tomato used for manufacturing into dehydrated tomato halves or wedges needs to be consistent in size, free from blemishes, red in color but not too ripe, fir with thick-walled flesh and most importantly, free from mold and bacterial rot.

Washing: The tomatoes arriving at the processing plant are automatically unloaded into the holding tank with water (Figure 37.4a). Water is used both for conveying and cleaning of tomato. The efficien y of the washing process is a critical control step in producing quality tomato products (Barringer 2003a). The washing operation involves two phases: soaking and spray-rinse. Soaking may be as simple as soaking the tomato in static tank or uses more complex modern devices with high-pressure water jets and agitation within the tanks by compressed air. The most commonly used method to control microbial populations in water for washing tomatoes is the addition of hypochlorite, equivalent to 100–300 ppm of available chlorine, which is well above the minimum lethal dose for spores (Barringer 2003a). Following the soak, a thorough rinsing with fresh water using pressurized spray nozzles is necessary.

Sorting and trimming: The purpose of sorting and trimming is removal of off-color and defective fruit or parts (rotten areas, mold portions, insect damage, or sunscald). For higher efficien y, and

(a)

(b) (c)

Figure 37.4 (a) Receiving and unloading tomato to soaking vat, (b) manual sorting, and (c) sterilization unit (Source: Rojin-Taak Agroindustry, Kermanshah, Iran).

adequate sorting, roller conveyors are used as sorting belts (Figure 37.4). This task requires skill in differentiating between product that should be completely discarded and that only require trimming to remove partly defective parts (Barringer 2003a). Several kinds of sorters are used such as the hydrosorter, size sorter, and texture sorter. Nowadays, photoelectric color sorters are used before and after peeling step. The initial sorter removes green tomatoes, and the second one is used for removal of peeled pink tomatoes using a proper sensor (Barringer 2003a). Any partially green tomatoes, which are not suitable for canned stewed products, can be used for making juice or sauces.

Coring: Extreme care should be exercised to remove only the core tissue. If excess fles tissue is removed, low drained weight and low wholeness scores may result. In the past, tomatoes were cored by machine, or more frequently by hand to remove the stem scar (Barringer 2003a). The modern tomato varieties have been bred with very small cores so that this step is no longer needed.

Peeling: Tomatoes are usually peeled before further processing. Steam, lye, and infrared are the major peeling methods. In steam peeling, tomatoes are exposed to live steam for 30–60 seconds depending on variety, fruit size, and maturity to completely loosen the skin; the typical blanch temperature is around 205°F

(∼96°C). The higher the temperature, the shorter the time, and the more complete the peel removal. In lye or caustic peeling, the tomatoes pass on a conveyor belt under spray-jets of hot lye (NaOH) or through a lye tank in a continuous operation. The lye dissolves cuticular wax, hydrolyzes pectin, and removes tomato peel. Steam peeling gives a higher total tomato yield but removes much less of the peel than lye (Schlimme et al. 1984). Infrared radiation peeling involves exposing tomatoes to four gas-fire red burners at high temperatures; tomatoes are revolving on a spindle to allow more surface to be directly exposed to the infrared heat. Other proposed peeling methods are cryogenic scalding, hot calcium chloride, and peeling with gas.

Processed Tomato Products

Tomato is a versatile vegetable from which a variety of processed products are produced. The most common processed products are juice, sauce, paste, ketchup/catsup, soup, and canned tomatoes. Figure 37.5 shows an overview of the processing of various tomato products; a detailed discussion about these processed products follows.

Tomato Pulp (Puree) and Paste

The definitio of tomato pulp (puree) under the Food and Drug Administration (FDA) is the food prepared from one or any combination of the following ingredients: (1) the liquid obtained from mature tomatoes of red or reddish varieties; (2) the liquid obtained from the residue from preparing such tomatoes for canning; (3) the liquid obtained from the residue from partial extraction of juice from such tomatoes; and (4) salt. In the case of tomato paste, the preliminary options (1–4) are the same; additionally, it may contain (5) spices, (6) fl voring, and (7) baking soda. Tomato puree or paste is finel dispersed slurry from which skins and seeds have been removed by passing the mashed tomatoes through a pulper or finishe . Tomato paste differs from tomato puree only in the degree to which the concentration is carried. Product must contain at least 24% of natural tomato soluble solids (NTSS) for tomato paste and at least 8% salt-free tomato solids for tomato pulp (Gould 1983). At the end of trimming belt, tomatoes go through a break system to be chopped. Crushed (chopped) tomatoes can be processed into juice by either a hot-break or a cold-break method. The unit operation in pulp, paste, and juice processing are as follows:

Break (hot and cold): The selection of type of operation depends on the quality of raw tomatoes. Some break systems operate under vacuum to minimize oxidation. In an industrial process under vacuum, degradation of ascorbic acid is minimal during the break process. In absence of vacuum, greater loss of ascorbic acid takes places due to higher break temperatures (Trifir et al. 1998). In the hot-break method, red-ripe tomatoes are chopped and heated rapidly to at least 180°F (82.2°C) before pulping. The preliminary heat given to the tomatoes inhibits pectolytic enzymes and protects the constituents of the tomato (especially pectin) from enzymatic changes, which results in maximum viscosity of finishe product. Thus, to get higher viscosity, juices are commonly produced under hot-break at 200–210°F or 93–99°C (Barringer 2003b). In cold-break systems, tomatoes (green and immature type) are chopped at 140–151°F (60–66°C). The chopped tomatoes fall into a holding tank, where they are held for varying times so as to facilitate the breakdown of pectin catalyzed by the enzymes released by crushing process (Gould 1983). Cold-break juice has a lower destruction of color and fl vor.

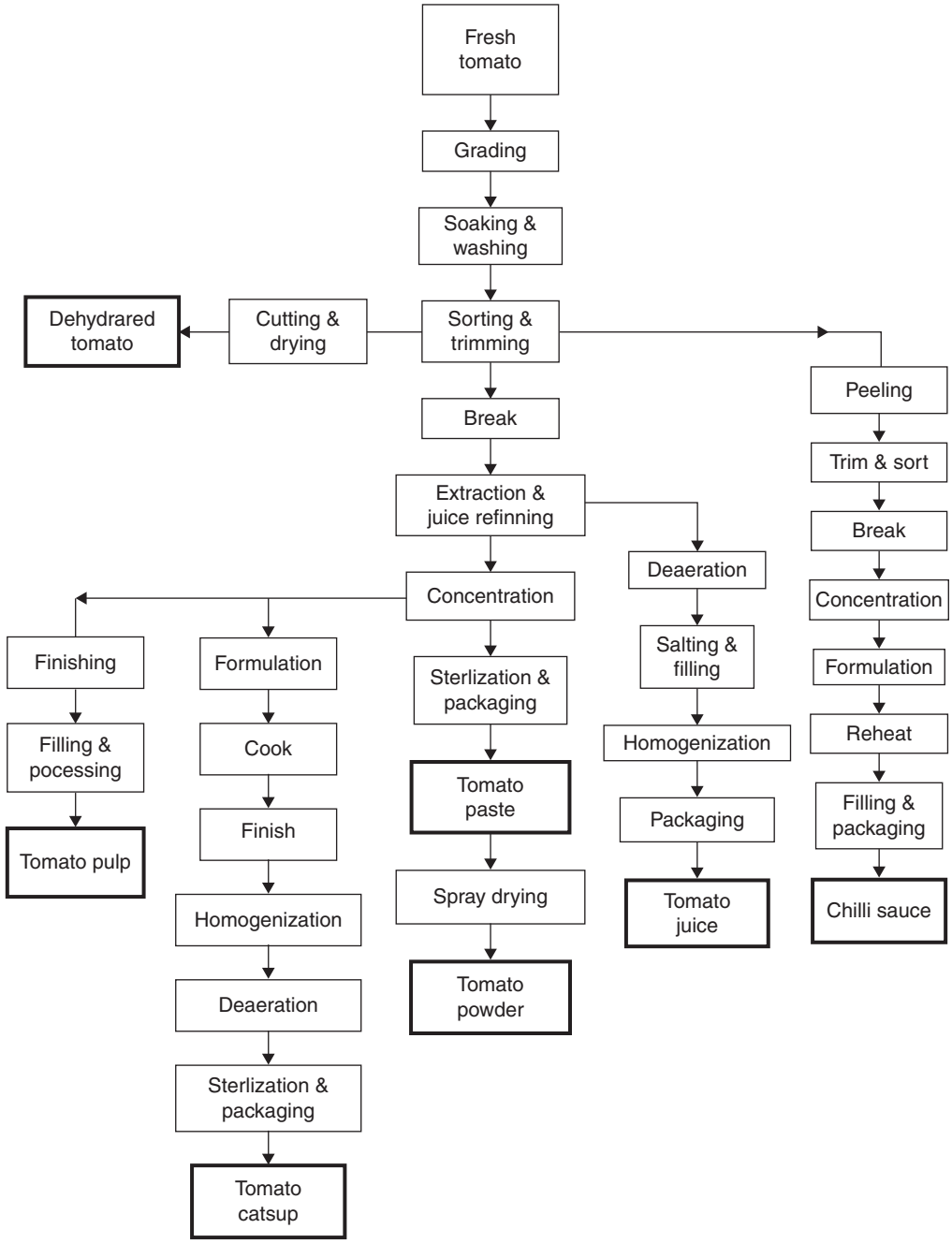

Figure 37.5 Process flow diagram of tomato products (Source: Rojin-Taak Agroindustry, Kermanshah, Iran)

Extraction and refinin (filt ation) of juice: The preheated tomato pulp is run through a series of extractors or cyclones to remove the seeds, skins, and any other pulp and impurities. Juice extraction may be accomplished by the screw- or the paddle-type extractors (Trifir et al. 1998). The screw-type extractors press the tomatoes between the screw and the screen. The screw-paddle-type extractors beat the tomato against the screen. The beating action of a paddle pulper and a paddle finishe gives a relatively higher juice yield than the screw-type juice extractor (Gould 1983). Air incorporation during extraction should be minimized since it oxidizes both lycopene and ascorbic acid. The screen size determines the finish or particle size, which will affect the viscosity and texture (Barringer 2004a).

Concentration (evaporation): The concentration process results in progressive increase in solids content of pulp to get a paste with desired concentration, and viscosity (normally about 24–38% solids). The method by which the juice is concentrated varies from tanks with coils in batch-type vacuum evaporators to continuous vacuum evaporators with a series of effects. The temperature is raised as the juice goes to each successive effect; Barringer (2004a) described the typical temperature range of 118–180°F (47.8–82°C) for this process. In order to adjust total soluble solid in tomato juice and improve fl vor, 1.5–1.7% NaCl is added to the juice. The use of noncellulosic membranes, having high retention of low molecular weight organics, and good physical and chemical stability, enabled reverse osmosis to be used on a commercial scale for the concentration of tomato juice (Pepper et al. 1985).

Sterilization and packaging: The tomato paste is packed either conventionally or aseptically (Figure 37.4c). Canned tomato paste is usually hot-fille at a minimum temperature of 194°F (90°C) into cans. It is then sealed without further heat treatment and passed through a water spray to remove any residue on the outside, cooled, and packed. Aseptic packaging of tomato paste usually involves heat treatment at 105–110°C for 2.25 minutes or 96°C for 3 minutes, cooling to 35–38°C, and fillin aseptically into high-barrier aseptic bags. Aseptically processed products must be cooled before fillin to maintain high quality. An aseptic bag-in-drum or bag-in-crate fille may be used for this purpose. Bulk paste is typically sold in 55-gallon drums or 300 gallon bag-in-boxes (Barringer 2004a).

Canned Whole Tomatoes

Peeling, sorting, and filling Tomatoes must be peeled before processing into canned products—whole or stewed. The main defects of concern are those included in the USDA grading standards for canned products: presence of peel, extraneous vegetable material, blemished areas, discolored portions, and objectionable core material (Downing 1996). Inadequately peeled, blemished, small, and misshapen fruit are diverted to the juice line. Filling the cans with tomatoes is an important unit operation. Fancy whole, evenly colored, large tomatoes are packed by hand, but due to labor costs, almost all manufacturers use mechanical filling In this case, peeled tomatoes are placed into a hopper and a mixture of whole tomatoes and juice fill the enameled cans automatically. The California standard-pack canned tomatoes consist of a mixture of peeled tomatoes and tomato puree (Gould 1983).

Additive: Firmness is a major factor in determining the quality of canned whole

tomatoes. The addition of calcium salt, mainly in the form of $CaCl_2$, cause the formation of a calcium pectate gel or pectinate, which improves product firm ness (Gould 1983). The fina amount of calcium cannot exceed 0.045% by weight in whole tomatoes or 0.08% in dices, slices, and wedges. The standard of identity allows using calcium, any edible organic acids (to lower the pH as needed), sweeteners (to offset the tartness from the added acid), salt (for taste), spices, fl voring, and vegetables (US-CFR 2000).

Exhausting and sealing: Exhausting, which helps create vacuum upon sealing, prevents seal damage during heat treatment. The center of the can should reach at least 130°F (54.4°C) and the length of the exhaust should be adjusted to accomplish this temperature. Too short an exhaust may cause "springers" or "flip pers" through overfillin (Gould 1983). Four methods are available for exhausting: mechanical vacuum, thermal exhausting, hot filling and steam fl w closing. Cans are typically exhausted and sealed at the same time. Without adequate headspace the ends of the can will bulge out. This is referred to as a "flip per" if the end can be pushed back down, or a "hard swell" if it cannot (Barringer 2003a). An airtight (hermetic) seal for cans is achieved by a double-roll seaming process.

Thermal processing: Tomato products can be hot fille and held, or processed in a retort as needed to minimize spoilage. The agitating continuous retort for tomatoes operate at 212°F (100°C) and is the most commonly used for tomato products. Continuous rotary retorts set at 220°F (104°C) for 30–40 minutes. High temperature and short time in flame are also common. The process time and temperature of canned tomato depends on the type of equipment, and the can size (Barringer 2003a). However, it is essential to check the temperature of the processed cans in its cold point to ascertain the efficien y of the process.

Cooling, labeling, and packing: Cans are cooled completely and quickly to a temperature below 100°F or 37.8°C after thermal processing. This avoids "stack burning," which results in lower drained weight, browning of the color, and loss of fl vor. When cooling water is used, it should be chlorinated to 15 ppm free chlorine to maintain a zero or low bacterial count (Downing 1996). The containers are then labeled and stored.

Other Canned Products

Diced tomatoes, sliced tomatoes, and tomato wedges are some other canned products. Diced tomatoes have become very popular because of the increase in salsa consumption, and are processed in a similar manner to canned tomatoes. Calcium treatment, either by bath or immersion, is necessary to maintain firmness/t xture. Calcificatio can occur by conveying the dices through a calcium bath. Immersion causes a significan loss of acid and sugar compared to addition of calcium to the can. However, immersion results in significantl firme tomatoes for the same fina calcium content (Villari et al. 1997). In general, calcium concentration in the dipping solution is the most important factor.

Tomato Juice

Tomato juice is define as the unconcentrated liquid extracted from mature tomatoes of red or reddish varieties, with or without scalding followed by straining. Such liquid is strained free from skins, seeds, and other hard substances but carries finel divided insoluble solids from the fles of the tomato. In manufacturing tomato juice, the tomatoes are subjected to the same unit operations as previously described in the preparation of tomatoes for paste or canning.

Crushing, breaking, and extraction: Crushing and hot break may be applied without any water added. In this case, heat treatment in a rotary coil tank followed by a heat exchanger and holding tube would be suitable for inactivation of the pectic enzymes fast enough to retain 90% of the potential serum viscosity in the original fresh tomato (Tressler and Joslyn 1971). Cold-break tomato extract pass directly to the inspection belt to chopper and then extractor. Quick processing/extraction of juice is necessary to produce high-quality tomato juice by cold-break procedure.

Deaeration, salting, and filling Air removal is important from nutritional point of view, especially in preventing ascorbic acid reduction during heat treatment. This could be avoided by using a vacuum deaerator immediately after extraction of the juice. Normally a 100°C flas is sufficien to remove the dissolved and occluded air. Deaeration also prevents foaming during concentration. Salt may be added by dropping tablets to each can, or injecting concentrated brine into tomato juice or serum (Tressler and Joslyn 1971). The sodium chloride added to tomato juice ranges from 0.5 to 1.25% by weight with an average content of 0.65% for commercial samples (Gould 1983).

Homogenization and thermal processing: Tomato juice is sometimes homogenized before canning in a homogenizer. Homogenization, generally used for cold-break juice, prevents settling of the solids and produces a thicker-bodied juice and minimizes solids separation. Tomato juice may also be milled to assist in control of separation and product consistency (Gould 1983). Commercially, canned tomato juice should be heated either before or after fillin to prevent spoilage. The following methods are currently employed: (1) In-can processing which may be accomplished by (a) pressure processing in continuous retort, (b) atmospheric processing in continuous agitating retort, (c) Boiling water process, or (d) hot fil followed by steam processing at atmospheric pressure; and (2) Bulk processing method by either (a) flas sterilization followed by hot fill-hold- ater cool, or (b) hot fill hold-air cool.

The quality evaluation of tomato juice as affected by processing methods especially high intensity pulsed electric fiel (HIPEF) has been researched extensively. According to Odriozola-Serrano et al. (2009), HIPEF-processed tomato juices maintained higher content of carotenoids (lycopene, neurosporene, and gamma-carotene), quercetin, higher values of lightness and viscosity (Aguilo-Aguayo et al. 2008), and higher lycopene and vitamin C content (Odriozola-Serrano et al. 2008b) during storage than thermally and untreated juices. The HIPEF technology has a potential to be an alternative to thermal treatment to obtain tomato juice with a high presence of health-related compounds. Moreover, HIPEF and pressure processing induced a specifi range of reduction in peroxidase and polygalacturonase (Aguilo-Aguayo et al. 2008; Hsu 2008).

Tomato Catsup

According to FDA, catsup, ketchup, or catchup is the food prepared from one or any combination of the following ingredients: (1) the liquid obtained from mature tomatoes of red or reddish varieties, (2) the liquid obtained from the residue from preparing such tomato for canning consisting of peeling and cores with or without such tomatoes or pieces thereof, and (3) the liquid obtained from the residue from partial extraction of juice from such tomatoes. Tomato ketchup may be made directly from fresh or concentrated pulp. The use of tomato pulp powder can be used as a

thickening agent in the formulation of tomato ketchup (Farahnaky et al. 2008). Manufacturing steps for producing tomato catsup are described below (Gould 1983).

Crushing, breaking, and pulping: Following washing, sorting, and trimming, the tomatoes are normally chopped, and heated as described for hot-break juice and paste, then put through pulper. Tomatoes may be treated by food-grade acid or alkali solution to obtain a pH of 4.2 ± 0.2, prior to straining. The liquid product is then pumped to the concentration tanks or continuous evaporators.

Formulation: In addition to tomato paste, the constituents used in the manufacture of catsup include water, sugar, salt, vinegar, spices, fl vorings, onions, garlic, and stabilizers. It is to be noted that the definitio of tomato catsup does not permit the use of artificia color, artificia preservatives, or added thickeners of any kind. Sweetener is added gradually and preferably during the latter part of cooking. Catsup diversity mostly comes from its spices and fl vorings. Spices (high grade or extract) may be used either in the form of whole or ground spices which should be used at the beginning of the cook or in the form of volatile spice oils before finishin the catsup. The addition of garlic and onions can be made with the spices or in a separate bag, after cooking for 20–30 minutes.

Cooking, finishin , and homogenization: A high steam pressure, 90–120 psi, is the best way to prevent burning and sticking on kettles or coils. It ensures circulation in the batch and so there will be no need for installing propeller. The evaporation of a batch should not take more than 45 minutes. It should not be less than 30 minutes if whole spices are used. A long slow cook gives a fla soggy body, whereas one of less than 30 minutes may fail to extract the spices. Catsup goes through the finishe to give a smooth body right after concentration. For controlling the consistency of bottled catsup, mechanical cell fragmentations by homogenizer and milling processes are currently used after finishers Further, the higher pressure and temperature in milling result in the higher consistency of tomato catsup due to extracted pectin.

Deaeration, fillin , sterilizing, and cooling: From the milling process, the catsup is placed in a holding tank supplying the fillin machine. Air removal is essential before filling The presence of air may result in excessive headspace or endanger the desirable bright color of the product, i.e., a relatively frequent defect called "black neck." Each charge, which is usually made batch wise, is fed via a plate-type heat exchanger (90°C) and a degassing device to a hot-fillin apparatus with subsequent cooling. Further heating is unnecessary because it may impair the color of the product.

Chili Sauce

This product is of the same general character as catsup, but is made from peeled and cored large to medium-sized tomatoes without removing seeds. It contains added sugar and onions and, is sometimes made hotter in fl vor than catsup. The cooking and handling are the same whereas the finishin operation is eliminated for chili sauce. Some sauces are made directly from fresh tomatoes during the tomato season, but this is less common. Sauce production from paste by mixing it with water, particulates, and spices is more common. The sauce may be aseptically packaged, or immediately fille into the fina container. Depending on ingredients used, the product may not undergo any further heat processing (Barringer 2004b).

Dried Tomato Products

Dehydrated Tomatoes

Dehydration is an appropriate technique for preserving nutritional components that are naturally present in different vegetables (Heredia et al. 2009). In manufacturing of dehydrated tomato, the washed fruit is typically cut prior to the drying process. Over the decades, the technology of dehydrated foods has improved tremendously. A great variety of sophisticated drying techniques have been developed to retain product quality and to improve energy efficien y. Freeze-drying is the most promising method due to its superior end product quality, but it is an expensive process. Hot-air-drying is by far the dominant and most economical system used in food industry. Hot-air-drying has been shown producing high-quality fina product. Also, osmotic dehydration step prior to air-drying of fruits and vegetables has been suggested by a number of authors to yield good quality, fully dehydrated, or intermediate moisture products of improved stability (Nsonzi and Ramaswamy 1998). Osmotic dehydration apparently had no effect on the carotenoid content of the processed products and could be considered to be an efficien method, allowing for water removal without changing the nutritive value (Tonon et al. 2007) and that temperature, concentration, thickness, and solution movement significantl influence water loss and solid gain during the osmotic dehydration of tomato in sucrose (Bui et al. 2009). The osmotic pretreatment was shown to be effective for enhancing drying rate, reducing drying time by approximately 30% (Al-Muhtaseb et al. 2009).

The combination of osmotic dehydration and microwave drying is a potential new process that could improve the quality of dried tomatoes. Heredia et al. (2007) found that water solution containing 27.5% sucrose, 10% salt, and 2% calcium lactate combined with microwave-assisted air-drying made it possible to obtain dried and intermediate moisture tomato products that are shelf stable and have better quality than the traditional product. According to Reyes et al. 2007, dielectric properties of tomatoes can be modifie by controlling osmotic process variables in order to improve their further drying with microwaves. Pani et al. (2008) found that application of sugar osmotic solutions, with reduced sweetening capacity and using $CaCl_2$, improves color stability and surface area retention of tomato slices during subsequent air dehydration, respectively.

Tomato Powder

Further concentration of tomato solids, from 30 to 40% in tomato paste to about 97%, results in tomato powder. The raw material used for tomato powder is tomato paste that is usually prepared by the hot-break method. It shows more desirable characteristics on reconstitution than cold-break paste. Roller-drum-dryer, foam-mat-dryer, and spray-dryer are common in drying. Of all the drying techniques tried, spray-drying appears to be the most suitable to produce high-quality powder. Owing to the thermoplastic characteristics of tomato powder, the drying chamber must be designed in a way that prevents drying of droplets under overheated conditions. In addition, the system needs to be designed to handle the hygroscopic nature of the finishe product from the drying chamber to the packing stage, without contacting the surrounding air (Goula and Adamopoulos 2005). Two of the most important factors affecting the shelf life of the finishe product are the exclusion of oxygen and the temperature of storage. Vacuum packaging and hermetic seals are important in maintaining the required shelf life of tomato powder (May 2004).

Frozen Tomatoes

Tomatoes are frozen on a very limited basis as compared to other processed tomato products.

For freezing, tomatoes are washed, sorted, blanched, peeled, sliced, diced, or left whole, inspected, and frozen on an individually quick frozen (IQF) belt freezer. The whole peeled tomatoes are fluidize and quickly crust frozen in the firs zone. The product is finis frozen on a second belt to 8°F (−13°C). A similar product was developed but not marketed in the United States. The tomatoes were sliced, blanched, and cryogenically frozen. The company reported that the product remained firm but it had to be stored below 8°F (−13°C) and was too expensive (Barringer 2003b). The results of research done by Dermesonlouoglou et al. (2007) indicated that osmodehydrofrozen compared to conventionally frozen sliced tomatoes show improved quality and functional characteristics for prolonged storage period.

By-Products from Tomato Processing Waste

In the case of tomato, the solid waste or pomace, remaining after the juice/pulp extraction process, consists of skin, seeds, fibrou matter, trimmings, cores, and cull tomato, which can be used for producing value-added products. Tomato pomace leftover, as a waste after extraction of tomato juice, constitutes about 20–30% of the raw material and may be used as a substrate for the production of vitamin B_{12} (Haddadin et al. 2001). The pomace essentially consists of seeds and skin. The seed component of the waste, which accounts for about 55% of the total mass, has received considerable scientifi investigation. Bread supplemented with tomato seed had improved loaf volume, texture, and crumb quality, because of antistaling properties (Sogi et al. 2005).

Because of the growing demand for natural lycopene, considerable interest has been directed toward obtaining lycopene from tomato pulp, tomato paste, and tomato processing wastes. However, the available solvent extraction technologies do not seem to allow a fast and economic recovery of its carotenoids. For example, only about 50% of total lycopene was extracted from tomato processing waste using supercritical CO_2 at 60°C and 30 MPa (Sabio et al. 2003). The results indicate that a mild enzymatic treatment can lead to significantl more lycopene recovery (70–98%) from tomato peels (Sogi et al. 2005). However, using a new high-pressure process, it is possible to recover all-*trans* lycopene (>98% purity) from industrial tomato by-products (Naviglio et al. 2008b). Lycopene is transferred, due to the high pressure used, in the form of molecular aggregates into water as dispersion, while apolar compounds remain in the matrix. The aggregates are easily purifie in a single subsequent step using methanol, thus obtaining lycopene at 98% chromatographic purity or higher (Naviglio et al. 2008a).

Tomato and Tomato Products: Quality Aspects

Fresh Produce: Quality Criteria

The quality of tomato covers a number of different characteristics important for fresh market or intended for processed products (Table 37.3; Gary and Tchamitchian 2001). Nutritional value, freedom from insecticides and fungicides, and whether the fruit was organically grown are important from consumer point of view (Barringer 2004a). The feasibility of minimal processing and MAP (5% O_2+5% CO_2) to preserve color attributes and bioactive compounds of fresh-cut tomato has been evaluated by Odriozola-Serrano et al. (2008a), through storage under refrigeration, and it has been found that neither the content of health-related compounds (lycopene, vitamin C, and phenolic compounds) nor the antioxidant capacity changed significantl between whole and just-processed fresh-cut tomatoes.

Appearance and color: Appearance is the key factor for consumers in fresh

Table 37.3 The quality variables of tomato fruit, their major sources of variability and their significance (low* to high***) for their intended use.

	Source of variation				Significanc for:	
Quality variable	Genetics	Climate	Fertilization	Crop management	Fresh market	Processed Products
Fruit grade	X	X		X		
Uniform color	X	X			***	***
Cracking		X	X	X	***	*
Blossom end rot		X	X	X	***	**
Shelf life	X				***	*
Dry matter content	X	X	X	X	*	***
Sugar content	X	X	X	X	**	**
Acid content	X	X	X	X	**	**
Aroma content	X	X	X		**	**
Texture	X	X	X		***	*
Antioxidants	X	X		X	**	**

Source: Gary and Tchamitchian (2001).

fruit market. Vital components of visual quality include color, color uniformity, glossiness, and absence of disease, and defects in shape/skin. In the case of tomato, fruit color is a strong indicator of eating quality and shelf life. In most products, the peel will be removed, and so purely surface blemishes will be of little consequence. Internal fles color is usually more important than peel color (Aked 2002).

Texture: Eating quality includes a complex of textural properties which are not readily define or measured. Texture is equally important, giving the fruit firmnes (the ratio of walls, gel, and core), along with other important factors such as skin toughness and "mouth feel" (Benton-Jones 2008). The pectin has a distinct role in tissue firmnes of vegetables. Some aspects of texture can be judged visually. The most common method of assessing firmnes is based on penetrometers such as the Magness-Taylor firmnes tester or the Effegi penetrometer. The test may be carried out through the peel or after peeing (Aked 2002).

Flavor*:* Of all aspects of tomato quality, fl vor is one of the most important to the consumer. Flavor is a complex of taste and aromatic components. Good tomato fl vor is based on the ratio of sugars and acids, being high at the time that fruit is at the orange-red stage. It was found that fructose and citric acid were more important to sweetness and sourness rather than glucose and malic acid. The most important volatiles in fresh tomato are *cis*-3-hexenal, 2-isobutylthiazole, beta-ionone, hexenal, *trans*-2-hexenal, *cis*-3-hexenol, *trans*-2-*trans*-4-decadienal, 6-methyl-5-hepten-2-one, and 1-penten-3-one (Petro-Turza 1987; Brthakur and Nelson 1996). In the fresh produce, fl vor is normally indicated by the °Brix measurement. It is found that organic and greenhouse tomatoes have higher °Brix than that for nonorganic or fiel grown tomatoes, respectively (Benton-Jones 2008).

Processed Tomato Products: Quality Parameters and Changes During Processing

Color: Color is often used as an indication of quality and freshness for foodstuffs, including tomato products for which the perception is "the redder, the

better" (Barringer 2004a). It has become important for tomato processors to be able to evaluate and grade their products based on color. Traditionally, the color of tomato products was measured subjectively; often, a Maxwell Disk Colorimeter was used. The results of this test were very inconsistent. In July 2003, the USDA approved Hunter Lab's ColorFlex45/0, D25A, and LabScan XE (as well as the tomato score formulas optimized for each instrument by Hunter Lab) as suitable for the evaluation of color to be used in grading processed tomato products (Anon 2008). Red color of tomato or tomato products is due to lycopene. Tomato industry interest in measuring lycopene began in the early to mid 1990s. There is roughly linear correlation of a/b value and the lycopene content in tomato juice. The color loss is accelerated by high temperature and exposure to oxygen during process. Also, the use of fin screens in juice extraction enhances oxidation because of the large surface area exposed to air and metal (Kattan et al. 1956). Processing also affects color due to the formation of brown pigments. Excessive heat treatments can cause browning due to sugars caramelization. Amadori products, representing the onset of the Maillard reaction, occur during process (Eichner et al. 1996).

Viscosity and consistency: Viscosity is second to color as an initial measure of product quality. It's also an integral part of the USDA's quality grade standards for products such as ketchup and tomato sauce. In addition, viscosity has economic implications for processors as it largely determines processing yields and quality. Apparent viscosity is determined by analytical rheometers, while consistency is an empirical measurement. The instrument best suited to measure the viscosity or consistency of a given product usually depends on the rheological properties of that product. Conditions during processing, such as temperature, size of fin isher screen, milling, blade speed, and method of preparing the pulp will affect the fina viscosity. Hot-break pulp and juice give a better texture than cold-break types. Moreover, prolonged heating at high temperatures causes a reduction in viscosity due to denaturation of pectin.

Total acidity and pH: The range of pH in tomato fruit is between 4.0 and 4.5—the lower the pH, the greater the tartness—a factor by which some consumers judge the quality of the tomato fruit. The critical issue with tomatoes is to ensure that they have a pH below 4.6, so that they can be processed as high-acid foods. At lower pH levels, greater inhibition of *Bacillus coagulans*, and fla sour spoilage microorganisms occurs. The acids present are largely responsible for the tart or sour fl vor.

Hot-break juice has a lower titratable acidity and a higher pH than cold-break juice (Barringer 2004a).

Flavor: Processed tomato products have a distinctively different aroma than fresh tomatoes. This is due to both the loss and creation of volatiles. Many of the volatiles responsible for the fresh tomato fl vor are lost during processing, especially *cis*-3-hexenal and hexenal (Buttery et al. 1990). Heating causes degradation of some fl vor volatiles as well as inactivation of lipoxygenase and associated enzymes. These enzymes contribute fl vor development in fresh tomatoes (Goodman et al. 2002). Oxidative decomposition of carotenoids causes the formation of terpenes and terpene-like compounds. The breakdown of sugars and carotenoids produces

compounds responsible for the cooked odor. Dimethyl sulfid is a major contributor to the aroma of heated tomato products. Pyrrolidone carboxylic acid, which is formed during heat treatment, has been ascribed to an off-fl vor that occasionally appears (Barringer 2004a).

Serum separation: Serum separation can be a significan problem in tomato juice. Serum separation occurs when the solids begin to settle out of the solution, leaving the clear straw-colored serum as a layer on top of the product. Preventing serum separation requires insoluble particles to remain in a stable suspension throughout the serum. Generally, at higher viscosities, less serum separation occurs. Factors that affect the quantity and quality of the solids determine the degree of serum separation. At higher break temperature, less serum separation occurs (Barringer 2004a). The cellulose fibe may be more important in preventing serum separation in tomato juice than the pectin. Also, homogenization increases the number of particles in solution and creates cells with ragged edges that reduce serum separation. Evaporator temperature during concentration has little effect on serum separation (Trifir et al. 1998).

Total solids and sugar content: Tomato solids are important because they affect the yield and consistency of the finishe product. Due to the time required to make total solids measurements (TSS), soluble solids are more frequently measured. TSS is measured using a refractometer or a hydrometer. Soluble solids are sugars, so refractometers are calibrated directly in sugar percentage or °Brix. NTSS is the same as °Brix, minus any added salt. The sugar content reaches a peak in tomatoes when the fruit is fully ripe (Hobson and Grierson 1993). During heat treatment, the reducing sugar content decreases due to caramelization, Maillard reaction, and formation of 5-hydroxymethyl furfural. The amount of sugar lost depends on the process. Studies have reported as much as a 19% loss in processed tomato juice and a 5% loss during spray drying (Barringer 2004a).

Summary

Tomatoes are a widely grown and consumed vegetable. A variety of processed tomato products are available in the market. The health-beneficia properties of lycopene, an antioxidant, found in tomatoes have further heightened interest in this commodity. Transgenic research has brought promising means of enhancing color and firmnes as exemplifie by the FlavrSavr tomato. Also, genetic improvement of cold tolerance in tomato might facilitate extension of its geographic distribution and increase crop performance in open fiel cultivation, especially early in the growing season in temperate regions. Tomatoes and tomato products give a distinctive fl vor to the food products. Fresh-cut tomatoes have gained popularity among consumers due to their convenience of use in salad and cooked entrees.

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