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Postharvest Biology and Technology: An Overview

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Losses in quantity and quality affect horticultural crops between harvest and consumption. The magnitude of postharvest losses in fresh fruits and vegetables is an estimated 5 to 25% in developed countries and 20 to 50% in developing countries, depending upon the commodity, cultivar, and handling conditions. To reduce these losses, producers and handlers must first understand the biological and environmental factors involved in deterioration, and second, use postharvest techniques that delay senescence and maintain the best possible quality. This chapter briefly discusses the first item and introduces the second, which is covered in detail in subsequent chapters.

Fresh fruits, vegetables, and ornamentals are living tissues that are subject to continuous change after harvest. While some changes are desirable, most—from the consumer's standpoint—are not. Postharvest changes in fresh produce cannot be stopped, but they can be slowed within certain limits. Senescence is the final stage in the development of plant organs, during which a series of irreversible events leads to breakdown and death of the plant cells.

Fresh horticultural crops are diverse in morphological structure (roots, stems, leaves, flowers, fruits, and so on), in composition, and in general physiology. Thus, commodity requirements and recommendations for maximum postharvest life vary among the commodities. All fresh horticultural crops are high in water content and are subject to desiccation (wilting, shriveling) and to mechanical injury. They are also susceptible to attack by bacteria and fungi, with pathological breakdown the result.

BIOLOGICAL FACTORS INVOLVED IN DETERIORATION

RESPIRATION

Respiration is the process by which stored organic materials (carbohydrates, proteins, fats) are broken down into simple end products with a release of energy. Oxygen (O_2) is used in this process, and carbon dioxide (CO_2) is produced. The loss of stored food reserves in the commodity during respiration means the hastening of senescence as the reserves that provide energy to maintain the commodity's living status are exhausted; reduced food value (energy value) for the consumer; loss of flavor quality, especially sweetness; and loss of salable dry weight, which is especially important for commodities destined for dehydration. The energy released as heat, known as vital heat, affects postharvest technology considerations, such as estimations of refrigeration and ventilation requirements.

The rate of deterioration (perishability) of harvested commodities is generally proportional to the respiration rate. Horticultural commodities are classified according to their respiration rates in table 4.1. Based on their respiration and ethylene (C_2H_4) production patterns during maturation and ripening, fruits are either climacteric or nonclimacteric (table 4.2). Climacteric fruits show a large increase in CO_2 and C_2H_4 production rates coincident with ripening, while nonclimacteric fruits show no change in their generally low CO_2 and C_2H_4 production rates during ripening.

ETHYLENE PRODUCTION

Ethylene (C_2H_4), the simplest of the organic compounds affecting the physiological processes of plants, is a natural product of plant

Table 4.1. Horticultural commodities classified according to respiration rates

Class	Range at 5°C (41°F) ($mg\ CO_2/kg\text{-}hr$)*	Commodities
Very low	<5	Dates, dried fruits and vegetables, nuts
Low	5–10	Apple, beet, celery, citrus fruits, cranberry, garlic, grape, honeydew melon, kiwifruit, onion, papaya, persimmon, pineapple, pomegranate, potato (mature), pumpkin, sweet potato, watermelon, winter squash
Moderate	10–20	Apricot, banana, blueberry, cabbage, cantaloupe, carrot (topped), celeriac, cherry, cucumber, fig, gooseberry, lettuce (head), mango, nectarine, olive, peach, pear, plum, potato (immature), radish (topped), summer squash, tomato
High	20–40	Avocado, blackberry, carrot (with tops), cauliflower, leek, lettuce (leaf), lima bean, radish (with tops), raspberry, strawberry
Very high	40–60	Artichoke, bean sprouts, broccoli, Brussels sprouts, cherimoya, cut flowers, endive, green onions, kale, okra, passion fruit, snap bean, watercress
Extremely high	>60	Asparagus, mushroom, parsley, peas, spinach, sweet corn

Note: *Vital heat (Btu/ton/24 hrs) = mg CO_2/kg-hr × 220.
Vital heat (kcal/1,000 kg/24 hrs) = mg CO_2/kg-hr × 61.2.

metabolism and is produced by all tissues of higher plants and by some microorganisms. As a plant hormone, C_2H_4 regulates many aspects of growth, development, and senescence and is physiologically active in trace amounts (less than 0.1 ppm). It also plays a major role in the abscission of plant organs.

The amino acid methionine is converted to *S*-adenosylmethionine (SAM), which is the precursor of 1-aminocyclopropane-1-carboxylic acid (ACC), the immediate precursor of C_2H_4. ACC synthase, which converts SAM to ACC, is the main site of control of ethylene biosynthesis. The conversion of ACC into ethylene is mediated by ACC oxidase. The synthesis and activities of ACC synthase and ACC oxidase are influenced by genetic factors and environmental conditions, including temperature and concentrations of oxygen and carbon dioxide.

Horticultural commodities are classified according to their C_2H_4 production rates in table 4.3. There is no consistent relationship between the C_2H_4 production capacity of a given commodity and its perishability; however, exposure of most commodities to C_2H_4 accelerates their senescence.

Generally, C_2H_4 production rates increase with maturity at harvest and with physical injuries, disease incidence, increased temperatures up to 30°C (86°F), and water stress. On the other hand, C_2H_4 production rates by fresh horticultural crops are reduced by storage at low temperature, by reduced O_2 levels (less than 8%), and elevated CO_2 levels (more than 2%) around the commodity.

COMPOSITIONAL CHANGES

Many changes in pigments take place during development and maturation of the commodity on the plant; some may continue after harvest and can be desirable or undesirable:

- Loss of chlorophyll (green color) is desirable in fruits but not in vegetables.
- Development of carotenoids (yellow and orange colors) is desirable in fruits such as apricots, peaches, and citrus. Red color development in tomatoes and pink grapefruit is due to a specific carotenoid (lycopene); beta-carotene is provitamin A and thus is important in nutritional quality.
- Development of anthocyanins (red and blue colors) is desirable in fruits such as apples (red cultivars), cherries, strawberries, cane berries, and red-flesh oranges. These water-soluble pigments are much less stable than carotenoids.
- Changes in anthocyanins and other phenolic compounds may result in tissue browning, which is undesirable for appearance quality. On the other hand, these constituents contribute to the total antioxidant capacity of the commodity, which is beneficial to human health.

Changes in carbohydrates include starch-to-sugar conversion (undesirable in potatoes, desirable in apple, banana, and other fruits); sugar-to-starch conversion (undesirable in peas and sweet corn; desirable in potatoes); and conversion of starch and sugars to CO_2 and water through respiration. Breakdown of pectins and other polysaccharides results in softening of fruits and a consequent increase in susceptibility to mechanical injuries. Increased lignin content is responsible for toughening of asparagus spears and root vegetables.

Changes in organic acids, proteins, amino acids, and lipids can influence flavor quality of the commodity. Loss in vitamin content, especially ascorbic acid (vitamin C) is detrimental to nutritional quality. Production of flavor volatiles associated with ripening of fruits is very important to their eating quality.

GROWTH AND DEVELOPMENT

Sprouting of potatoes, onions, garlic, and root crops greatly reduces their food value and accelerates deterioration. Rooting of onions and root crops is also undesirable. Asparagus spears continue to grow after harvest; elongation and curvature (if the spears are held horizontally) are accompanied by increased toughness and decreased palatability. Similar geotropic responses occur in cut gladiolus and snapdragon flowers stored horizontally. Seed germination inside fruits such as tomatoes, peppers, and lemons is an undesirable change.

Table 4.2. Fruits classified according to respiratory behavior during ripening

Climacteric fruits		Nonclimacteric fruits	
Apple	Muskmelon	Blackberry	Lychee
Apricot	Nectarine	Cacao	Okra
Avocado	Papaya	Carambola	Olive
Banana	Passion fruit	Cashew apple	Orange
Biriba	Peach	Cherry	Pea
Blueberry	Pear	Cranberry	Pepper
Breadfruit	Persimmon	Cucumber	Pineapple
Cherimoya	Plantain	Date	Pomegranate
Durian	Plum	Eggplant	Prickly pear
Feijoa	Quince	Grape	Raspberry
Fig	Rambutan	Grapefruit	Strawberry
Guava	Sapodilla	Jujube	Summer squash
Jackfruit	Sapote	Lemon	Tamarillo
Kiwifruit	Soursop	Lime	Tangerine and mandarin
Mango	Sweetsop	Longan	
Mangosteen	Tomato	Loquat	Watermelon

Table 4.3. Classification of horticultural commodities according to ethylene (C_2H_4) production rates

Class	Range at 20°C (68°F) ($\mu L\ C_2H_4$/kg-hr)	Commodities
Very low	Less than 0.1	Artichoke, asparagus, cauliflower, cherry, citrus fruits, grape, jujube, strawberry, pomegranate, leafy vegetables, root vegetables, potato, most cut flowers
Low	0.1–1.0	Blackberry, blueberry, casaba melon, cranberry, cucumber, eggplant, okra, olive, pepper (sweet and chili), persimmon, pineapple, pumpkin, raspberry, tamarillo, watermelon
Moderate	1.0–10.0	Banana, fig, guava, honeydew melon, lychee, mango, plantain, tomato
High	10.0–100.0	Apple, apricot, avocado, cantaloupe, feijoa, kiwifruit (ripe), nectarine, papaya, peach, pear, plum
Very high	More than 100.0	Cherimoya, mammee apple, passion fruit, sapote

TRANSPIRATION OR WATER LOSS

Water loss is a main cause of deterioration because it results not only in direct quantitative losses (loss of salable weight), but also in losses in appearance (wilting and shriveling), textural quality (softening, flaccidity, limpness, loss of crispness and juiciness), and nutritional quality.

The commodity's dermal system (outer protective coverings) governs the regulation of water loss. It includes the cuticle, epidermal cells, stomata, lenticles, and trichomes (hairs). The cuticle is composed of surface waxes, cutin embedded in wax, and a layer of mixtures of cutin, wax, and carbohydrate polymers. The thickness, structure, and chemical composition of the cuticle vary greatly among commodities and among developmental stages of a given commodity.

The transpiration rate (evaporation of water from the plant tissues) is influenced by internal, or commodity, factors (morphological and anatomical characteristics, surface-to-volume ratio, surface injuries, and maturity stage) and by external, or environmental, factors (temperature, relative humidity [RH], air movement, and atmospheric pressure). Transpiration is a physical process that can be controlled by applying treatments to the commodity (e.g., waxes and other surface coatings or wrapping with plastic films) or by manipulating the environment (e.g., maintaining high RH and controlling air circulation).

PHYSIOLOGICAL BREAKDOWN

Exposure of the commodity to undesirable temperatures can result in physiological disorders:

- Freezing injury results when commodities are held below their freezing temperatures. The disruption caused by freezing usually results in immediate collapse of the tissues and total loss of the commodity.

- Chilling injury occurs in some commodities (mainly those of tropical and subtropical origin) held at temperatures above their freezing point and below 5° to 15°C (41° to 59°F), depending on the commodity. Chilling injury symptoms become more noticeable upon transfer to higher (nonchilling) temperatures. The most common symptoms are surface and internal discoloration (browning), pitting, watersoaked areas, uneven ripening or failure to ripen, off-flavor development, and accelerated incidence of surface molds and decay (especially the incidence of organisms not usually found growing on healthy tissue).
- Heat injury is induced by exposure to direct sunlight or excessively high temperatures. Its symptoms include bleaching, surface burning or scalding, uneven ripening, excessive softening, and desiccation.

Certain types of physiological disorders originate from preharvest nutritional imbalances. For example, blossom end rot of tomatoes and bitter pit of apples result from calcium deficiency. Increasing calcium content by preharvest or postharvest treatments can reduce the susceptibility to physiological disorders. Calcium content also influences the textural quality and senescence rate of fruits and vegetables; increased calcium content has been associated with improved firmness retention, reduced CO_2 and C_2H_4 production rates, and decreased decay incidence.

Very low O_2(<1%) and high CO_2 (>20%) atmospheres can cause physiological breakdown of most fresh horticultural commodities, and C_2H_4 can induce physiological disorders in certain commodities. The interactions among O_2, CO_2, and C_2H_4 concentrations, temperature, and duration of storage influence the incidence and severity of physiological disorders related to atmospheric composition.

PHYSICAL DAMAGE

Various types of physical damage (surface injuries, impact bruising, vibration bruising, and so on) are major contributors to deterioration. Browning of damaged tissues results from membrane disruption, which exposes phenolic compounds to the polyphenol oxidase enzyme. Mechanical injuries not only are unsightly but also accelerate water loss, provide sites for fungal infection, and stimulate CO_2 and C_2H_4 production by the commodity.

PATHOLOGICAL BREAKDOWN

One of the most common and obvious symptoms of deterioration results from the activity of bacteria and fungi. Attack by most organisms follows physical injury or physiological breakdown of the commodity. In a few cases, pathogens can infect apparently healthy tissues and become the primary cause of deterioration. In general, fruits and vegetables exhibit considerable resistance to potential pathogens during most of their postharvest life. The onset of ripening in fruits, and senescence in all commodities, renders them susceptible to infection by pathogens. Stresses such as mechanical injuries, chilling, and sunscald lower the resistance to pathogens.

ENVIRONMENTAL FACTORS INFLUENCING DETERIORATION

Temperature. Temperature is the environmental factor that most influences the deterioration rate of harvested commodities. For each increase of 10°C (18°F) above optimum, the rate of deterioration increases by two- to threefold (table 4.4). Exposure to undesirable temperatures results in many physiological disorders, as mentioned above. Temperature also influences the effect of C_2H_4, reduced O_2, and elevated CO_2. The spore germination and growth rate of pathogens are greatly influenced by temperature; for instance, cooling commodities below 5°C (41°F) immediately after harvest can greatly reduce the incidence of Rhizopus rot. Temperature effects on postharvest responses of chilling-sensitive and nonchilling-sensitive horticultural crops are compared in table 4.5.

Relative humidity. The rate of water loss from fruits and vegetables depends on the vapor pressure deficit between the commodity and the surrounding ambient air, which is influenced by temperature and RH. At a given temperature and rate of air movement, the rate of water loss from the commodity depends on the RH. At a given RH, water loss increases with the increase in temperature.

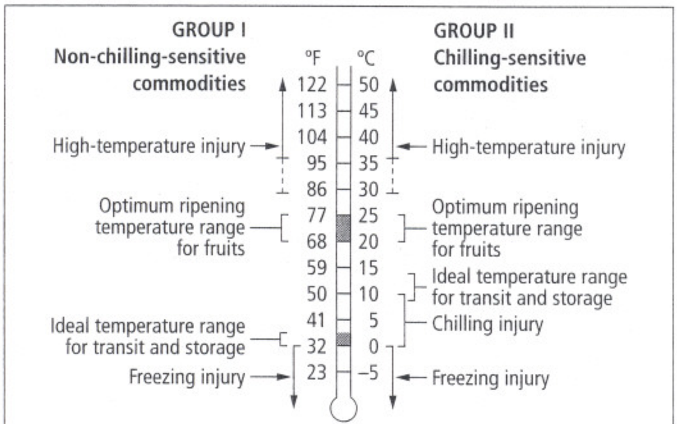
Atmospheric composition. Reduction of O_2 and elevation of CO_2, whether intentional

Table 4.4. Effect of temperature on deterioration rate of a non-chilling-sensitive commodity

Temperature (°F)	Temperature (°C)	Assumed Q_{10}*	Relative velocity of deterioration	Relative shelf life	Loss per day (%)
32	0	—	1.0	100	1
50	10	3.0	3.0	33	3
68	20	2.5	7.5	13	8
86	30	2.0	15.0	7	14
104	40	1.5	22.5	4	25

Note: $^*Q_{10} = \dfrac{\text{Rate of deterioration at temperature (T)} + 10°\text{C}}{\text{Rate of deterioration at T}}$

Table 4.5. Fruits and vegetables classified according to sensitivity to chilling injury



GROUP I Fruits	GROUP I Vegetables	GROUP II Fruits	GROUP II Vegetables
Apple*	Artichoke	Avocado	Beans, snap
Apricot	Asparagus	Banana	Cassava
Blackberry	Beans, lima	Breadfruit	Cucumber
Blueberry	Beet	Carambola	Eggplant
Cherry	Broccoli	Cherimoya	Ginger
Currant	Brussels sprouts	Citrus	Muskmelon
Date	Cabbage	Cranberry	Okra
Fig	Carrot	Durian	Peppers
Grape	Cauliflower	Feijoa	Potato
Kiwifruit	Celery	Guava	Pumpkin
Loquat	Corn, sweet	Jackfruit	Squash
Nectarine*	Endive	Jujube	Sweet potato
Peach*	Garlic	Longan	Taro
Pear	Lettuce	Lychee	Tomato
Persimmon*	Mushrooms	Mango	Watermelon
Plum*	Onion	Mangosteen	Yam
Prune	Parsley	Olive	
Raspberry	Parsnip	Papaya	
Strawberry	Peas	Passion fruit	
	Radish	Pepino	
	Spinach	Pineapple	
	Turnip	Plantain	
		Pomegranate	
		Prickly pear	
		Rambutan	
		Sapodilla	
		Sapote	
		Tamarillo	

Note: *Some cultivars are chilling sensitive.

(modified or controlled atmosphere storage) or unintentional (restricted ventilation within a shipping container or transport vehicle), can either delay or accelerate the deterioration of fresh horticultural crops. The magnitude of these effects depends on the commodity, cultivar, physiological age, O_2 and CO_2 levels, temperature, and duration of holding.

Ethylene. Because the effects of C_2H_4 on harvested horticultural commodities can be desirable or undesirable, C_2H_4 is of major concern to all produce handlers. Ethylene can be used to promote faster and more uniform ripening of fruits picked at the mature-green stage. On the other hand, exposure to C_2H_4 can be detrimental to the quality of most nonfruit vegetables and ornamentals.

Light. Exposure of potatoes to light should be avoided because it results in greening due to formation of chlorophyll and solanine (toxic to humans). Light-induced greening of Belgian endive is also undesirable.

Other factors. Various kinds of chemicals (e.g., fungicides, growth regulators) may be applied to the commodity to affect one or more of the biological deterioration factors.

POSTHARVEST TECHNOLOGY PROCEDURES

TEMPERATURE MANAGEMENT PROCEDURES

Temperature management is the most effective tool for extending the shelf life of fresh horticultural commodities. It begins with the rapid removal of field heat by using one of the following cooling methods: hydrocooling, in-package icing, top-icing, evaporative cooling, room cooling, forced-air cooling, serpentine forced-air cooling, vacuum cooling, or hydro-vacuum cooling.

Cold storage facilities should be well-engineered and adequately equipped. They should have good construction and insulation, including a complete vapor barrier on the warm side of the insulation; strong floors; adequate and well-positioned doors for loading and unloading; effective distribution of refrigerated air; sensitive and properly located controls; enough refrigerated coil surface to minimize the difference between the coil and air temperatures; and adequate capacity for expected needs. Commodities should be stacked in the cold room with air spaces between pallets and room walls to ensure good air circulation. Storage rooms should not be loaded beyond their limit for proper cooling. In monitoring temperatures, commodity temperature rather than air temperature should be measured.

Transit vehicles must be cooled before loading the commodity. Delays between cooling after harvest and loading into transit vehicles should be avoided. Proper temperature maintenance should be ensured throughout the handling system.

CONTROL OF RELATIVE HUMIDITY

Relative humidity can influence water loss, decay development, incidence of some physiological disorders, and uniformity of fruit ripening. Condensation of moisture on the commodity (sweating) over long periods of time is probably more important in enhancing decay than is the RH of ambient air. Proper relative humidity is 85 to 95% for fruits and 90 to 98% for vegetables except dry onions and pumpkins (70 to 75%). Some root vegetables can best be held at 95 to 100% RH.

Relative humidity can be controlled by one or more of the following procedures:

- adding moisture (water mist or spray, steam) to air by humidifiers
- regulating air movement and ventilation in relation to the produce load in the cold storage room
- maintaining the refrigeration coils within about 1°C (2°F) of the air temperature
- providing moisture barriers that insulate storage room and transit vehicle walls; adding polyethylene liners in containers and plastic films for packaging
- wetting floors in storage rooms
- adding crushed ice in shipping containers or in retail displays for commodities that are not injured by the practice
- sprinkling produce with water during retail marketing (use on leafy vegetables, cool-season root vegetables, and immature fruit vegetables such as snap beans, peas, sweet corn, summer squash

SUPPLEMENT TEMPERATURE MANAGEMENT

Many technological procedures are used commercially as supplements to temperature management. None of these procedures, alone or in their various combinations, can substitute for maintenance of optimal temperature and RH, but they can help extend the shelf life of harvested produce beyond what is possible using refrigeration alone (table 4.6).

Treatments applied to commodities include

- curing of certain root, bulb, and tuber vegetables
- cleaning followed by removal of excess surface moisture
- sorting to eliminate defects
- waxing and other surface coatings, including film wrapping
- heat treatments (hot water or air, vapor heat)
- treatment with postharvest fungicides
- sprout inhibitors
- special chemical treatments (scald inhibitors, calcium, growth regulators, anti-ethylene chemicals for ornamentals)
- fumigation for insect control
- ethylene treatment (de-greening, ripening)

Treatments to manipulate the environment include

- packaging
- control of air movement and circulation
- control of air exchange or ventilation
- exclusion or removal of C_2H_4
- controlled or modified atmospheres (CA or MA)
- sanitation

RECENT TRENDS IN PERISHABLES HANDLING

SELECTION OF CULTIVARS

For many commodities, producers are using cultivars with superior quality and/or long postharvest life, such as "super-sweet" sweet corn, long-shelf-life tomatoes, and sweeter melons. Plant geneticists in public and private institutions are using molecular biology methods along with plant breeding procedures to produce new genotypes that taste better, maintain firmness better, are more disease resistant, have less browning potential, and have other desirable characteristics.

PACKING AND PACKAGING

The produce industry is increasingly using plastic containers that can be reused and recycled in order to reduce waste disposal problems. For example, standard-sized (48 by 40 in., about 120 by 100 cm) stacking (returnable) pallets are becoming more widely used. There is continued increase in use of modified atmosphere and controlled atmosphere packaging (MAP and CAP) systems at the pallet, shipping container (fiberboard box liner), and consumer package levels. Also, the use of absorbers of C_2H_4, CO_2, O_2, and/or water vapor as part of MAP and CAP is increasing.

COOLING AND STORAGE

The current trend is towards increased precision in temperature and relative humidity (RH) management to provide the optimal environment for fresh fruits and vegetables during cooling and storage. Precision temperature management (PTM) tools are becoming more common in cooling and storage facilities. Forced-air cooling continues to be the predominant cooling method for horticultural perishables. Operators can ensure that all produce shipments leave the cooling facility within 0.5°C (about 1°F) of the optimal storage temperature. Periodic ventilation of storage facilities is effective in maintaining C_2H_4 concentrations below 1 ppm, which permits mixing of temperature-compatible, ethylene-producing, and ethylene-sensitive commodities.

Table 4.6. Fresh horticultural crops classified according to relative perishability and potential storage life in air at near-optimal temperature and RH

Relative perishability	Potential storage life (weeks)	Commodities
Very high	<2	Apricot, blackberry, blueberry, cherry, fig, raspberry, strawberry; asparagus, bean sprouts, broccoli, cauliflower, cantaloupe, green onion, leaf lettuce, mushroom, pea, spinach, sweet corn, tomato (ripe); most cut flowers and foliage; fresh-cut (minimally processed) fruits and vegetables
High	2–4	Avocado, banana, grape (without SO_2 treatment), guava, loquat, mandarin, mango, melons (honeydew, crenshaw, Persian), nectarine, papaya, peach, pepino, plum; artichoke, green beans, Brussels sprouts, cabbage, celery, eggplant, head lettuce, okra, pepper, summer squash, tomato (partially ripe)
Moderate	4–8	Apple and pear (some cultivars), grape (SO_4-treated), orange, grapefruit, lime, kiwifruit, persimmon, pomegranate, pummelo; table beet, carrot, radish, potato (immature)
Low	8–16	Apple and pear (some cultivars), lemon, potato (mature), dry onion, garlic, pumpkin, winter squash, sweet potato, taro, yam; bulbs and other propagules of ornamental plants
Very low	>16	Tree nuts, dried fruits and vegetables

POSTHARVEST INTEGRATED PEST MANAGEMENT (IPM)

Controlled atmosphere (CA) conditions delay senescence, including fruit ripening, and consequently reduce the susceptibility of fruits to pathogens. On the other hand, CA conditions unfavorable to a given commodity can induce physiological breakdown and render it more susceptible to pathogens. Calcium treatments have been shown to reduce decay incidence and severity; wound healing following physical injury has been observed in some fruits and has reduced their susceptibility to decay. Biological control agents are being used alone or in combination with reduced concentrations of postharvest fungicides, heat treatments, and/or fungistatic CA for control of postharvest diseases.

Chemical fumigants, especially methyl bromide, are still the primary method used for insect control in harvested fruits when such treatment is required by quarantine authorities in importing countries. Many studies are under way to develop alternative methods of insect control that are effective, not phytotoxic to the fruits, and present no health hazard to the consumer. These alternatives include cold treatments, hot water or air treatments, ionizing radiation (0.15–0.30 kilogray) and exposure to reduced (less than 0.5%) O_2 and/or elevated CO_2 (40–60%) atmospheres. This is a high-priority research and development area because of the possible loss of methyl bromide as an option for insect control.

USE OF CONTROLLED AND MODIFIED ATMOSPHERES

The use of CA during transport and/or storage of fresh fruits and vegetables (marketed intact or lightly processed) continues to expand because of improvements in nitrogen-generation equipment and in instruments for monitoring and maintaining desired concentrations of oxygen and carbon dioxide. Controlled atmosphere is a useful supplement to the proper maintenance of optimal temperature and RH during transport and storage of many fresh fruits and vegetables. It allows use of marine transport instead of air transport of some commodities.

Several refinements in CA storage have been made in recent years to improve quality maintenance. These include creating nitrogen by separation from compressed air using molecular sieve beds or membrane systems; low O_2 (1.0–1.5%) storage; low ethylene CA storage; rapid CA (rapid establishment of the optimal levels of O_2 and CO_2); and programmed (or sequential) CA storage (e.g., storage in 1% O_2 for 2 to 6 weeks followed by storage in 2 to 3% O_2 for the remainder of the storage period). Other developments, which may expand use of MA during transport and distribution, include using edible coatings or polymeric films with appropriate gas permeabilities to create a desired MA around and within the commodity. Modified atmosphere packaging is widely used in marketing fresh-cut fruits and vegetables.

Successful application of atmospheric modification depends on the commodity, cultivar, maturity stage at harvest, and a positive return on investment (benefit-cost ratio). Commercial use of CA storage is greatest worldwide on apples and pears; less on kiwifruits, avocados, persimmons, pomegranates, nuts, and dried fruits and vegetables. Atmospheric modification during long-distance transport is used on apples, asparagus, avocados, bananas, broccoli, cane berries, cherries, figs, kiwifruits, mangoes, melons, nectarines, peaches, pears, plums, and strawberries. Continued technological developments in the future to provide CA during transport and storage at a reasonable cost are essential to greater CA applications on fresh fruits and vegetables.

TRANSPORTATION

Improvements are continually being made in attaining and maintaining the optimal environmental conditions (temperature, RH, and concentrations of O_2, CO_2, and C_2H_4) in transport vehicles. Produce is commonly cooled before loading and is loaded with an air space between the palletized produce and the walls of the transport vehicles to improve temperature maintenance. In some cases, vehicle and produce temperature data are transmitted by satellite to a control center, allowing all shipments to be continuously monitored. Some new trucks have air ride suspension, which can eliminate transport vibration damage. As the industry realizes the value of air ride, its popularity will increase.

HANDLING AT WHOLESALE AND RETAIL

Wholesale and retail markets have been increasingly using automated ripening, in which the gas composition of the ripening atmosphere, the room temperature, and fruit color are continuously monitored and modulated to meet desired ripening characteristics. Improved ripening systems will lead to greater use of ripening technology to deliver products that are ripened to the ideal eating stage. Better-refrigerated display units, with improved temperature and RH monitoring and control systems, are being used in retail markets, especially for fresh-cut fruit and vegetable products. Many retail and food service operators are using Hazard Analysis Critical Control Points (HACCP) Programs to assure consumers that food products are safe.

FOOD SAFETY ASSURANCE

During the past few years, food safety became and continues to be the number-one concern of the fresh produce industry. U.S. trade organizations such as the International Fresh-Cut Produce Association (IFPA), Produce Marketing Association (PMA), United Fresh Fruit and Vegetable Association (UFFVA), and Western Growers Association (WGA) have taken an active role in developing voluntary food safety guidelines for producers and handlers of fresh fruits and vegetables. The U.S. Food and Drug Administration (FDA) published in October 1998 the *Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables*. This guide should be used by all handlers of fresh produce to develop the most appropriate agricultural and management practices for their operations.

The FDA guide is based on the following basic principles and practices associated with minimizing microbial food safety hazards from the field through distribution of fresh fruits and vegetables.

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 of fresh produce is associated with human or animal feces.

Principle 4. Whenever water comes in contact with produce, the quality of the water 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.

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