16 Postharvest Physiology

In the previous chapter some of the major events between harvest and marketing were reviewed. In this chapter, the major physiological events that occur postharvest are considered.

Physiology of Horticultural Products After Harvest

Respiration

All horticultural commodities begin to senesce once harvested. After harvest, all metabolism is catabolic since the commodity no longer photosynthesizes or is attached to a photosynthesizing plant. Some compounds may be synthesized (anabolic metabolism), but only at the expense of some other compound already contained in the harvested commodity. Another way of looking at it is that the total energy status of the commodity will never be higher than it is at harvest. At harvest it is removed from its source of energy, photosynthesis.

Probably the most important physiological process occurring after harvest is respiration, the controlled release of energy within a living organism. In respiration, compounds, usually sugars, combine with O_2 in a precise, controlled manner to release energy, producing CO_2, and water. This energy released in respiration is utilized in other metabolic activities of the commodity or lost as heat. The heat given off by respiring commodities is often called vital heat and is important in estimating refrigeration requirements. Since any commodity has a specific and limited quantity of reserves in it for energy production after harvest, how rapidly this store is depleted is the major factor determining postharvest life. Postharvest life is the amount of time a product is useful to the consumer. This might be the amount of time a peach is suitable for consumption or how long a cut flower is pleasing to look at. A major focus of postharvest physiology is maximizing the useful postharvest life of a product while ensuring acceptable quality usually by effectively managing the storage environment. A long storage life is useless without quality.

In general, commodities with a high respiration rate have a low storage life and those with a low respiration rate have a long storage life. Respiration affects the levels of many of the compounds responsible for perceived quality and also affects the processes establishing physical properties determining quality such as firmness.

The negative ramification of respiration during storage is a loss of food reserves in the stored commodity. While respiration is needed to maintain a level of quality, it always leads to a loss in dry weight of the commodity. In some commodities the loss is minimal because the product is stored for only a short time, for example strawberries (*Fragaria* × *ananassa*), while in others that are often stored for a longer period, the loss can be significant, such as onions (*Allium cepa*) and potatoes (*Solanum tuberosum*). In addition to dry weight loss, quality of some commodities can suffer severely from respiratory use of sugars. A prime example of this is sweet corn (*Zea mays*).

A tremendous amount of heat is released during respiration and this heat must be removed during storage. It is extremely important to know which commodities require cold storage and to ensure that the cooling system selected is capable of removing any excess field heat as well as the heat generated during storage by respiration.

During respiration, the production of 1 mg CO_2/kg/h translates into a refrigeration requirement of 61.2 kcal/t/day or 220 BTU/t/day (Saltveit, 2004a). One BTU (British thermal unit) is the amount of energy it takes to increase the temperature of 0.454 kg of water from 3.8°C to 4.4°C (or the energy needed to raise 1 lb of water 1°F from 39 to 40°F). Refrigeration units are rated for the number of BTUs of heat they are capable of removing from a storage unit per day. This measure is often reported as tons of refrigeration per day; 1 t of refrigeration is equivalent to the amount of energy required to melt 1 t of ice at 0°C in 24 h.

Where does all the heat come from during respiration? To understand this problem, one needs to examine respiration a little more closely. The main purpose of respiration is to maintain high levels of energy-carrying molecules such as ATP and NADH in cells for cellular maintenance. The major substrate in respiration is usually glucose. The general equation for respiration utilizing glucose as the substrate is:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 686 \text{ kcal/mole}$$

One mole of glucose is equal to 180 g, coming from starch or a simple sugar such as glucose or sucrose. The energy released during the respiration of 1 mole of glucose has three different destinies. A small amount of energy (13 kcal) gets lost in entropy during the breakdown of glucose into simpler components during respiration. Approximately 281 kcal are used to produce ATP while the remaining 392 kcal (57%) is lost as heat. So much energy is lost as heat because at each step of any metabolic reaction some heat is lost. There are hundreds of individual metabolic reactions occurring during the respiration of 1 mole of glucose, thus it is easy to see why so much heat is lost in such a process.

Don't think that respiration during storage is all bad. The synthesis of lycopene in tomatoes during storage, the production of volatiles for aroma and flavor in many fruits as well as the degradation of starch into sugars all depend on the energy produced by respiration.

Ethylene

Ethylene (C_2H_4) is a very important component of postharvest physiology (Saltveit, 2004b). As indicated in Chapter 2, this volume, ethylene is a naturally occurring molecule that is a colorless gas at biological temperatures that easily diffuses through plant tissues. It can exert a biological effect at rates of parts per billion. Ethylene is biosynthesized from the amino acid methionine via *S*-adenosyl-L-methionine (SAM) which is converted into 1-aminocyclopropane-1-carboxylic acid (ACC) by ACC synthase in a highly regulated process. The final step requires ACC oxidase (and oxygen) which converts ACC into ethylene. It is an autocatalytic process meaning that the presence of ethylene above a specific threshold stimulates the production of more ethylene. In vegetative tissues, the level of ethylene is usually below this threshold, thus ethylene production is not stimulated. Similarly in non-climacteric fruits, ethylene remains below the threshold, thus ethylene production remains at a fairly constant level. In climacteric fruits ethylene levels surpass the threshold initiating autocatalytic ethylene production. This is a major problem in storing fruits and vegetables, where in general, inhibition of ethylene production is desired.

Most plant tissues generate small amounts of ethylene to regulate various aspects of growth and development. Since ethylene readily diffuses, it is normally remains at relatively low, biologically active levels in the plant tissues. Any postharvest barriers to such diffusion such as waxes or containers may lead to excessive accumulation of ethylene which could induce autocatalytic production. Ethylene is often produced by wounded tissue, thus any decaying or unsound produce can lead to premature ripening and senescence and spoil the entire lot.

Ethylene is often called the wound hormone or the ripening hormone. While it is produced in response to wounding and it does induce ripening in climacteric fruit and some non-climacteric fruit, it also has other effects (see Chapter 2). Pertinent to this discussion, ethylene stimulates the production of anthocyanins in ripening fruit while it enhances chlorophyll destruction, which is important in degreening many citrus fruit. The positive effects of ethylene on one commodity, for example degreening in citrus, may be highly undesirable in another, for example, degreening of broccoli (*Brassica oleracea* Itlaica Group).

Regulating ethylene during storage

Since ethylene has many diverse effects on different commodities, controlling its levels in storage is crucial in postharvest physiology. Increasing ethylene levels to induce autocatalytic production and the ripening process is easily accomplished using ripening chambers where ethylene gas is introduced into the atmosphere. This is an important practice for point-of-sale ripening of bananas (*Musa* spp.), avocados (*Persea americana*), and tomatoes (*Solanum lycopersicum*).

Keeping ethylene levels low during storage is usually desired to inhibit or prevent ripening. This can be accomplished by: (i) preventing ethylene generation by the product; (ii) removing excess ethylene from the atmosphere; and (iii) preventing the aberrant introduction of ethylene from external sources, particularly forklifts, into the storage facility.

Maintaining the storage facility at the lowest possible temperature without inducing chilling injury is one way of minimizing ethylene production. Separating ethylene-generating produce from sensitive commodities is another very important consideration in maintaining adequately low levels of ethylene in storage. Storage under controlled or modified atmosphere conditions can also minimize ethylene levels in storage.

Removing ethylene from the storage air with scrubbers or with small sachets inside retail containers can effectively keep ethylene levels acceptable.

One way to control ethylene in storage is to prevent ethylene synthesis using compounds such as aminoethoxyvinylglycine (AVG), aminooxyacetic acid (AOA), and silver salts. Use of these compounds is normally limited to non-food crops. Other sources of ethylene may exist in or near the storage facility, thus prevention of ethylene production by the commodity itself does not necessarily avoid a problem.

Another approach is to prevent the perception of ethylene's presence by treating produce with CO_2 or 1-methylcyclopropene (1-MCP). The inhibitor replaces ethylene at sites of molecular perception within the plant, thus the effect of ethylene is not induced because the ethylene receptor is occupied by the inhibitor rather than ethylene.

Factors Affecting Storage

Many factors affect the storage life of horticultural commodities including: (i) temperature; (ii) respiration rate; (iii) O_2 and CO_2 concentration; (iv) stage of development at harvest; and (v) postharvest pathogens (Fig. 16.1).

Temperature

Respiration and the Q_{10}

Temperature is the most important factor in postharvest physiology because temperature has a profound effect on the rates of biological processes, particularly respiration. Within the normal temperature range of most horticultural crops (0–35°C), respiration increases exponentially with temperature (Saltveit, 2004a). We often describe the sensitivity of a reaction to temperature with the Q_{10} value. The Q_{10} effectively describes the change in the rate of a reaction, in this case respiration, with a 10°C change in temperature. It is derived by dividing the rate of the reaction at the higher temperature by the rate of the reaction at the lower temperature (Saltveit, 2004a). Q_{10} values allow us to estimate respiration rates and therefore storage life at different temperatures, if we know the respiration rate at a specific temperature and Q_{10} values for the commodity. If a commodity has a storage life based on respiration rates of 10 days at 10°C and a Q_{10} value of 2 (for temperatures between 0 and 10°C) and a Q_{10} of 3 (for temperatures between 10 and 20°C), we can determine that it would store for 15 days at 5°C (10 days divided by Q_{10} of 2 = 5 extra days, 10 days + 5 days = 15 days) and 6.7 days at 20°C (10 days divided by Q_{10} of 3 = 3.3 fewer days, 10 days – 3.3 days = 6.7 days).

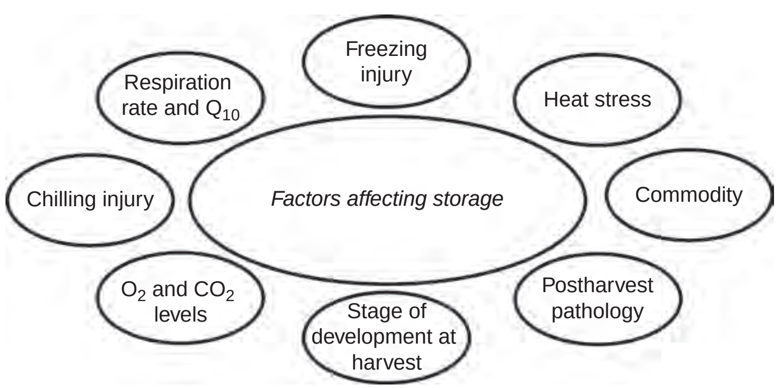

Fig. 16.1. Factors affecting storage of horticultural commodities.

Chilling injury

Temperature is also important in postharvest considerations due to the potential for chilling injury, particularly in tropical and semi-tropical commodities. The temperature at which injury occurs varies among sensitive commodities but is usually somewhere around 10 or 12°C. Some temperate commodities can suffer chilling injury but at temperatures much lower (between 0 and 5°C) (Wang, 2004a). Chilling injury is qualitative damage to the commodity that is often reflected in abnormally high respiration rates during chilling or abnormally high rates once the commodity is returned to non-chilling temperatures. The elevated respiration observed during chilling or soon thereafter is a reflection of the tissues' attempts to remove harmful toxins that accumulate during chilling and to repair damaged membranes and other cellular organelles.

Temperature and duration of exposure are important components of chilling injury. Generally when the temperature is significantly lower than the threshold, injury can occur with a much shorter exposure compared with injury that occurs closer to the threshold temperature. If the exposure is brief enough or at a temperature close to the threshold, the injury may be reversible. However, in most cases the injury becomes non-reversible very quickly. Injury is cumulative in that a number of brief exposures to unsuitable temperatures can add up quickly to extensive injury.

If the exposure to chilling temperatures is significant, a number of symptoms will appear either during chilling or after removal from storage. This is a significant component of chilling injury: the injury may not be observed until after the consumer has purchased the commodity, or the retailer has received a shipment from the wholesaler. Some of the typical symptoms include: (i) surface pitting or lesions; (ii) internal discoloration; (iii) water-soaked tissues; and (iv) failure to ripen properly. Injured commodities are also generally more susceptible to decay particularly by organisms such as *Alternaria* that do not harm healthy tissues (McColloch, 1953). Classic chilling injury symptoms for a number of commodities along with the upper threshold for injury are shown in Table 16.1 (after Wang, 2004a).

Maturity at harvest can greatly influence the extent of injury in crops such as avocado (*P. americana*), honeydew melons (*Cucumis melo*), and tomatoes (*S. lycopersicum*). There are many treatments that have been shown to lessen chilling injury in a number of different commodities. These include: (i) high or low temperature preconditioning; (ii) intermittent warming during storage; (iii) controlled atmosphere or hypobaric storage; (iv) pretreatment before storage with ethylene, abscissic acid (ABA), methyl jasmonate, or calcium; (v) waxing; and (vi) modified atmosphere packaging (MAP).

Freezing injury

Freezing injury occurs when ice crystals form in the commodity and a noted decrease in quality is observed. The freezing point of the commodity does not determine the susceptibility to freezing injury. For example parsnips (*Pastinaca sativa*) and tomatoes (*S. lycopersicum*) both have a freezing point of between −1.1 and −0.6°C yet parsnips can be frozen and thawed several times without any apparent injury while tomatoes that freeze just once are useless. The major symptoms of freezing injury are water-soaked tissue, particularly the skin, and a non-turgid, limp consistency upon thawing.

Commodities are categorized based on their susceptibility to freezing injury (Table 16.2, after Wang, 2004a). Those that are highly susceptible are likely to be injured with even a light freeze. Those that are moderately susceptible might recover from a couple of light freezes. The least susceptible commodities can be frozen and thawed a number of times without any apparent injury.

The intensity of a freezing event is coupled with its duration in determining the extent of injury for many commodities. For example, apples (*Malus domestica*) can take several days of freezing at or just below their freezing point, but would be severely injured by several hours at temperatures just several degrees colder. Another important point about freezing injury is that the organ involved does not necessarily determine the extent of injury, but rather, injury is more related to species susceptibility. For example, leaves of cabbage (*Brassica oleracea* Capitata Group) can withstand many freezes without injury while lettuce leaves (*Lactuca sativa*) are destroyed with one light-to-moderate freeze.

Bruising is a large problem if a frozen commodity is moved while frozen. It is best to let the commodity thaw before inspecting or moving it. Tissues should be thawed at a rate of 4°C/h

Table 16.1. Chilling injury symptoms for different commodities and the upper threshold temperature (°C) causing injury (after Wang, 2004a).

Commodity	Upper threshold temperature (°C)	Injury symptoms
Apples (some cultivars) (*Malus domestica*)	3	Brown core, internal flesh browning and soggy, soft scald
Asparagus (*Asparagus officinalis*)	2	Discolored, limp tips
Atemoya (*Annona* × *atemoya*)	4	Darkened skin, discolored pulp, failure to ripen
Avocado (*Persea americana*)	13	Gray-to-brown flesh discoloration
Banana (*Musa* spp.)	13	Dull skin color upon ripening
Snap beans (*Phaseolus vulgaris*)	7	Russetting and surface pitting
Cucumber (*Cucumis sativus*)	7	Skin pitting, water-soaked tissue
Eggplant (*Solanum melongena*)	7	Skin discoloration, black seeds
Ginger (*Zingiber officinale*)	7	Tissue softening and breakdown
Jicama (*Pachyrhizus erosus*)	18	Surface decay, flesh discoloration
Mango (*Mangifera indica*)	13	Gray skin, uneven ripening
Cantaloupe (*Cucumis melo*)	5	Pitting, skin decay
Honeydew (*Cucumis melo*)	10	Skin discoloration, pitting, failure to ripen
Olive (*Olea europaea*)	7	Internal browning
Orange (*Citrus* × *sinensis*)	3	Pitting, brown rind stain
Papaya (*Carica papaya*)	7	Failure to ripen, off-flavors
Pineapple (*Ananas comosus*)	10	Internal browning, skin stays green when ripe
Potato (*Solanum tuberosum*)	3	Browning, sweet flesh
Tomato (ripe) (*Solanum lycopersicum*)	10	Water soaking
Tomato (mature green)	13	Failure to develop good color when ripening

Table 16.2. Susceptibility to freezing injury of common horticultural commodities (after Wang, 2004a).

Category	Commodity
Highly susceptible	Apricots, asparagus, avocado, bananas, snap beans, most berries, cucumbers, eggplant, lemon, lettuce, limes, okra, peaches, peppers, plums, potatoes, summer squash, sweet potatoes, tomatoes
Moderately susceptible	Apples, broccoli, carrots, cauliflower, celery, cranberries, grapefruit, grapes, storage onions, oranges, parsley, pears, peas, radishes, spinach, winter squash
Slightly susceptible	Beets, Brussels sprouts, cabbage, dates, kale, kohlrabi, parsnips, rutabagas, salsify, turnips

(Lutz, 1936). Faster thawing rates cause significant injury because the membranes are not able to handle the rapid rehydration that occurs with quick thawing. Using slower rates allows more time for ice crystals to damage the cells resulting in greater observed injury once thawed. In nearly all cases, commodities that have suffered any amount of freezing injury have a shorter storage and shelf life than those that have not been frozen at all. In addition, previously frozen products often have lower quality, particularly textural quality and are more susceptible to attack by decay-causing organisms.

Heat stress

Exposure of commodities to excessively high temperatures for a brief period is often used to combat pest pressures, especially fungi. If the temperature is too high for an extended period, metabolism is severely affected. Respiration eventually ceases, enzymes are denatured, and membranes lose their integrity and function. Ultimately tissue death occurs and the commodity becomes useless.

O_2 and CO_2 concentrations

Controlling O_2 concentration in the storage facility is a method for prolonging storage life by reducing respiration of the stored commodity. The main concern is to ensure that O_2 levels are not too low since this would induce anaerobic respiration which results in off-flavors and foul odors. Most crops will store well at 2–3% O_2, however, it is wise to know the recommended level for each particular commodity. Some crops such as apples can be stored at as low as 1% O_2. The O_2 necessary to maintain aerobic conditions for respiration is coupled with temperature. As storage temperature increases, respiration rates increase and thus so does the O_2 rate required to prevent anaerobiosis.

Increased CO_2 levels are sometimes used to delay senescence and reduce decay in some commodities. High CO_2 levels coupled with low O_2 levels can, however, lead to anaerobic metabolism, thus caution is needed when altering storage gas levels.

Reducing the O_2 or raising the CO_2 concentration may suppress pathogen growth during storage. The reaction of the commodity to altered storage gas concentrations must be considered, as anaerobic respiration in stored produce is undesirable.

Stage of development at harvest

Storage life generally differs among different tissue types and stage of development at harvest. Storage organs generally have a low respiration rate while actively growing tissue such as floral or vegetative buds have a high respiration rate. Maturing tissues such as fruit have an intermediate respiration rate that generally declines as the tissue matures further. The closer to maturity a tissue is at harvest, the lower its respiration is likely to be. Once harvested, respiration slowly declines in non-climacteric tissues such as fruit and storage organs and rapidly declines in actively growing tissues. The rapid decline in actively growing tissues is usually attributed to a depletion of storage reserves. Respiration rates of climacteric fruit after harvest were discussed earlier in this chapter.

Postharvest pathology

Postharvest losses of horticultural commodities often range from 10 to 30% even with the use of modern storage facilities and technologies (Harvey, 1978). Losses can be due to biological or non-biological factors. Non-biological factors contributing to losses include rough handling and improper storage. Biological factors contributing to losses are usually infection by bacteria or fungi as well as infestation by insect pests. Postharvest diseases only occur once pathogens attack the host and cause an irreversible decline in commodity quality.

Fungi normally infect fruit while bacteria normally infect vegetables (Sholberg and Conway, 2004). Infection or infestation may occur at any point along the postharvest chain which can make this a particularly difficult problem to manage (Dennis, 1983).

Weather during production and harvest often has a marked influence on postharvest levels of pathogens by affecting both the field populations of such organisms and the susceptibility of commodities to various pathogens. Warm, wet weather often increases the population of pathogens while at the same time making commodities more susceptible to infection.

Production factors such as cultivar selection, fertility management, irrigation frequency, and pesticide applications also have a huge influence on postharvest losses. Calcium nutrition is very important in managing postharvest losses. Increased resistance to pathogens and prevention of physiological problems are associated with adequate calcium levels in apples (*M. domestica*), potatoes (*S. tuberosum*), and peaches (*Prunus persica*) (Sams, 1994). Nitrogen on the other hand tends to induce greater susceptibility to postharvest losses.

Crop maturity at harvest and postharvest handling are important. Many commodities are harvested slightly immature in order to prolong storage life. As a commodity becomes mature and begins to ripen, it becomes more susceptible to infection by pathogens (Kader, 1985). Some commodities are sprayed with a pre-harvest fungicide to reduce postharvest losses.

Postharvest handling has a major impact on losses during storage. A major concern is sanitation during harvest and packaging. Good sanitation practices should be followed by all workers involved in commodity handling and all equipment used during handling must be cleaned and sanitized regularly. In addition, culls, decayed produce, and trash must be disposed of properly to prevent build up of infectious agents. Another area for consideration to help minimize losses is chemical or biological postharvest treatment. Postharvest treatments must consider the pathogen, its location, time of treatment, commodity maturity, and storage environment. Postharvest fungicide treatment has decreased as organisms become resistant or products lose their label for use. In fact, there are a number of pathogens that are problematic in postharvest but have no registered fungicides available for their control.

Postharvest biological controls are becoming increasingly desirable as fewer chemicals are available for control and consumer demand for sustainable or organic approaches increases. Many biological control organisms are in the developmental stage and the transfer from the lab to the field is a long process. A major problem with biocontrols is that they don't always provide consistent protection. Some control, however, is better than none at all.

Both UV and gamma irradiation have been considered for postharvest control of storage diseases. There is no evidence that UV radiation reduces decay of packaged fruits or vegetables (Hardenburg *et al.*, 1986) and gamma radiation may cause undesirable side effects in some commodities and the equipment needed to provide the radiation is extremely expensive.

Low temperatures are used in commodity storage to reduce the growth rate of pathogenic organisms. The temperature is usually kept as low as possible to retard pathogen growth yet warm enough to prevent chilling injury in sensitive commodities. Exposure to high temperatures, usually by immersing the commodity in hot water, can reduce decay during storage in some commodities such as peppers (*Capsicum annuum*), tomatoes (*S. lycopersicum*), mango (*Mangifera indica*), and papaya (*Carica papaya*) (Spotts, 1984). Reduced humidity can reduce or prevent germination and growth of fungal pathogens. However, reduced humidity during storage can dehydrate a commodity and reduce its quality.

Another important component of postharvest horticulture are issues of food safety, namely, the presence of fecal coliform bacteria (Gould, 1973) and microbial toxins (Hsieh and Gruenwedel, 1990) in stored commodities. Good hygiene by harvest and postharvest workers is the key in preventing fecal coliform contamination. The appropriate management of animals and their waste products near production fields, harvest and processing stations along with the proper composting of manure used in crop production also helps avoid contamination. With some organisms, it is not the organism itself that is harmful to human health, but rather a toxin produced by the organism. Examples include: (i) botulinum toxins produced by the anaerobic bacterium *Clostridium botulinum*; (ii) aflatoxins produced by *Aspergillus* fungi; and (iii) patulin, a toxin produced by *Penicillium* and *Aspergillus* species.

The Commodities

In this section, postharvest issues for a number of horticultural commodities are reviewed (Fig. 16.2). The omission of commodities from this discussion does not reflect any opinion of importance of the commodity by the author. For more information on any listed or not-listed commodity, see Gross *et al.* (2002) or search the Internet.

Culinary herbs

Culinary herbs may be annual or perennial and include: (i) annuals such as basil (*Ocimum basilicum*), chervil (*Anthriscus cerefolium*), coriander or cilantro (*Coriandrum sativum*), dill (*Anethum graveolens*), and summer savory (*Satureja montana*); and (ii) perennials such as chives (*Allium schoenoprasum*), Chinese chives (*Allium tuberosum*), marjoram (*Origanum hortensis*), oregano (*Origanum vulgare*), peppermint (*Mentha piperita*), spearmint (*Mentha spicata*), rosemary (*Rosmarinus officinalis*), sage (*Salvia officinalis*; Fig. 16.3), tarragon (*Artemesia dracunculus*), and thyme (*Thymus vulgaris*). Leaves are most often used, however, roots and dried fruits (shizocarps) of cilantro are used as well as chive flowers.

Leaves should be harvested when green and turgid, usually before flowering and stored at 95–100% RH and just above 0°C, with the exception of basil which must not be stored any lower than 12°C or severe chilling injury in the form of blackened foliage will occur. Leaves are often bunched and tied with twine or secured with rubber bands. Packaging in clamshells or polyethylene (poly) bags help reduce dehydration. There are no standardized grades for herbs. Herbs produce little ethylene but are highly susceptible to ethylene injury exhibited as leaf yellowing and abscission (Wright, 2004a, b).

Vegetables and fruits

Root, rhizome, tuber, and bulb vegetables

BEETS Beet (*Beta vulgaris* Crass Group), also known as table beet or red beet, is a biennial producing a fleshy, edible storage root (enlarged hypocotyl). Leaves are also consumed, usually steamed or sautéed and make an excellent substitute for cooked spinach. At the seedling and young plant stage before hypocotyl enlargement, the leaves are often included raw in salad mixes. Root shape, size, color, turgidity, and smoothness

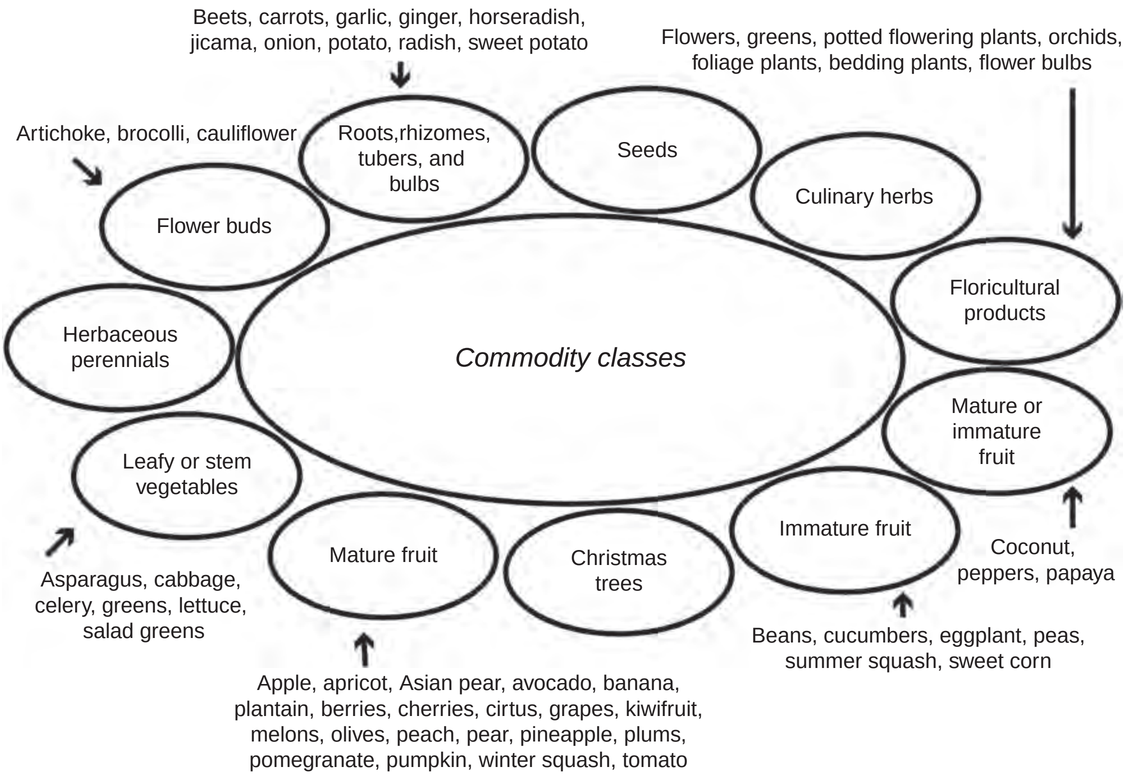

Fig. 16.2. The major horticultural commodity classes.

Fig. 16.3. Sage (*Salvia officinalis*).

(lack of rootlets) are major quality characteristics. The most important quality attribute for beet roots is a lack of zoning, or alternating dark and light concentric rings of flesh. A sharply zoning cultivar 'Chiogga' is marketed as a novelty. Leaves for salad should be small, tender, and free of blemishes.

Roots are harvested 50 days after planting or later but before full maturity is reached, especially if intended for long-term storage. Beets are often sold by the bunch with leaves attached. Beets are pre-cooled to at least 4°C. Bunched beets will keep for 10–14 days at 0°C at >98% RH. Topped beets are stored at 1 or 2°C at 98% RH and retain quality for 8–10 months (Adamicki, 2004a). Beets are not chilling sensitive, thus they should be stored as cold as possible without freezing. Topped beets can also be stored in soil trenches in areas with a sufficiently cold and consistent winter provided the temperature of the pit remains between –1 and 5°C. Beets are not stored under controlled atmospheres. Beets produce little ethylene and are not sensitive to ethylene exposure. The major problem with stored, topped beet roots is decay from gray mold (*Botrytis cinerea*) and black rot (*Phoma betae*).

CARROT Carrot (*Daucus carota*) is a biennial producing a large storage tap root, high in carbohydrates and β-carotene. High quality carrots are solid, straight from shoulder to tip, smooth and sweet with no bitterness or aftertaste. Carrots are mostly harvested when they are partially mature when the tap root is 1.8 cm or larger in diameter at the shoulder. Carrots used for fresh-cuts are harvested immature to ensure sweetness. Carrots may be bunched or top trimmed. Quick cooling to <5°C is important to maintain a crisp texture and overall freshness. Roots should be stored at 0–1°C and close to 100% RH. Under perfect storage conditions, topped carrots can be held for up to 9 months, however, most carrots are only held for 5–6 months. Bunched carrots can be held for 8–12 days and longevity is enhanced by storing them covered with flaked or shaved ice. Controlled atmosphere storage of carrots does not improve their storability, thus it is rarely used. Carrots are not chilling sensitive. They produce little ethylene, but exposure to exogenous ethylene induces the formation of isocoumarin which imparts a bitter flavor. Bitter flavors also develop when exposed to ethylene, but not in peeled roots. Thus non-peeled carrots should not be stored with other commodities producing ethylene to avoid the development of bitter flavors.

Wilting and rubberiness are indications of storage at low RH which leads to water loss. Rough handling can increase cracking and tip breakage, especially in Nantes-type carrots and other susceptible varieties (Luo *et al.*, 2004b). Topped carrots may sprout if storage temperatures are too high. Pre-harvest water stress can lead to the accumulation of terpenoids which results in off-flavors. Surface browning may develop on roots harvested immature. Roots are susceptible to a number of rots during storage including, bacterial soft rot caused by *Pectobacterium carotovora* or *Pseudomonas marginalis*, gray mold (*B. cinerea*), Rhizopus rot (*Rhizopus* spp.), watery soft rot (*Sclerotinia sclerotiorum*), and sour rot (*Geotrichum candidum*) (Snowden, 1992).

GARLIC The main edible portion of garlic (*Allium sativum*) is a bulb consisting of enlarged leaf bases called cloves that are wrapped in dried leaf sheaths attached to a basal stem plate, all surrounded by several layers of dried leaf sheaths. Flower stalks called scapes are also used. Garlic is most often sold fresh, dried and ground, or chopped and preserved in olive oil. Garlic may be harvested at almost any time during its development, but is most often harvested when mature. It is harvested mature when tops have fallen over and dried. High quality bulbs are firm, heavy for their size, have skin color appropriate to the variety and a soluble solids content (SSC) of at least 35% (Cantwell, 2004b). The necks and skins of garlic must be allowed to dry sufficiently (cure) to maximize storage. Garlic can be stored for 1–2 months at 20–30°C at <75% RH. For longer storage up to 9 months, garlic should be stored at –1–0°C at 60–70% RH. Garlic held at 5–18°C loses its dormancy and begins to sprout. Sprouting can be inhibited with a pre-harvest application of the herbicide maleic hydrazide, which is also used to prevent sprouting in onions (*A. cepa*) and potatoes (*S. tuberosum*). Garlic should be isolated during storage to prevent the odor of garlic from being transferred to other commodities. Controlled atmosphere storage at 0–5°C with high (5–15%) CO_2 retards sprouting and decay but may induce a yellow translucent color in come cultivars. Garlic is not chilling sensitive, does not produce much ethylene and is not sensitive to exogenous ethylene.

High field temperatures before harvest may lead to the storage disorder called waxy breakdown. It is characterized by light yellow areas in the clove flesh that darken. Later the clove becomes translucent, sticky and waxy but the skins remain unaffected. The most common rot of garlic in storage is caused by *Penicillium* spp. It is usually only detected after it is in the final stages of development which results in bulbs that are light in weight for their size and individual cloves that are soft and powdery with intact skins.

GINGER Though ginger (*Zingiber officinale*) is a rhizome, a creeping, underground stem, it is often called a root. It is used as a spice, a pickled vegetable, and is used medicinally. It is also dried and ground or preserved in sugar syrup, dried and sold as crystallized ginger. Ginger for pickling and crystallizing should be harvested before it is mature to avoid the fibrous texture that develops at maturity. Immature ginger is bright yellow to brown, with a high sheen and green or yellow non-sprouted buds. Mature ginger is harvested when the shoots wilt and begin to die. Rhizomes have a bright yellow-brown skin that soon loses its sheen and darkens. Rhizomes should be cooled to 12–14°C and can be stored at the same temperature at 85–90% RH for 2–3 months. Problems during storage include wilting, mold growth if condensation occurs on the rhizomes, and rot caused by *Fusarium* and *Pythium* spp. Ginger is chilling sensitive and storage at 12°C or lower leads to loss of skin color, skin pitting, and internal breakdown (Paull and Chen, 2004b). Ginger does not produce appreciable ethylene and is not sensitive to exposure to exogenous ethylene.

HORSERADISH Horseradish root (*Armoracia rusticana*) is a cruciferous perennial grown for its enlarged tap root which is normally used as a condiment for meat and fish. Long, uniform, firm, smooth roots free from hollow heart with pungent flavor are desired. Roots are harvested after frost has killed the tops, but roots for processing may be harvested earlier. Roots are extremely sensitive to wilting and should be cooled to 4 or 5°C then stored at 0°C at 98% RH, where they will keep for up to 9 months (Adamicki, 2004b). At warmer temperatures, roots loose pungency. Horseradish roots are not sensitive to chilling, produce very little ethylene, and are not sensitive to exogenous ethylene (Adamicki, 2004b). Roots infected by *Verticillium dahlia* in the field exhibit darkened vascular tissues that appear as dark spots in cross-wise sections or dark streaks in longitudinal sections of the root. This discoloration is a major cause of quality loss.

JICAMA Jicama, also called yam bean, (*Pachyrhizus erosus*) is a leguminous root crop that can be eaten raw or cooked. High quality is reflected in large, smooth, firm roots with crisp, succulent white sweetish flesh (Cantwell, 2004c). Most jicama is harvested mature after tops die. Since they are a tropical crop jicama roots are chilling sensitive. Roots exhibit injury, primarily external decay and interior discoloration and loss of crispness, after 1–3 weeks storage at 10°C. Flesh may also appear water soaked or become rubbery. To minimize chilling injury, they should be stored at 12–15°C at 80–90% RH. Under these conditions they will last 2–4 months before they begin to sprout. Once they sprout, jicama roots loose firmness and juiciness. Jicama roots produce little ethylene and are not sensitive to exogenous ethylene. Decay is the major storage problem with jicama and it can be minimized by avoiding injury to the periderm during harvest and handling. Jicama is often cured to increase periderm toughness by holding them at 20–25°C at 95–100% RH for a week.

ONION Onion (*Allium cepa* Cepa Group) is a biennial grown for its bulb of enlarged leaf bases attached to a short stem plate (Adamicki, 2004c). It is normally harvested after the first year of growth, as the bulb quickly flowers in its second year. Scallions are immature onions used for their bulbs and foliage. High quality bulbs should be firm, free from defects and have bulb size, shape, and skin color appropriate for the cultivar. Harvest maturity depends on their use. Scallions and onions for bunching can be harvested at any size. Onions for storage are harvested when 50–80% of the tops have fallen over. Bunched onions and scallions should be quickly cooled to 0°C and covered with crushed ice if possible. Onions for storage should be cooled to 0°C as quickly as possible to inhibit rooting and sprouting during storage. Slow or gradual cooling will not reduce rooting and sprouting during storage. Bunched onions can be stored for 3–4 weeks at 0°C at 95–98% RH. Mild and sweet onions are stored for up to 3 months at 3–5°C. Pungent, dry onions can be stored for up to 9 months at 0°C and 65–75% RH.

Once harvested, onion bulbs are dormant for 4–6 weeks depending on cultivar. A sprout inhibitor may be applied about 2 weeks prior to harvest if onions are to be stored for a long period. Onions for long-term storage are field dried for 2 weeks followed by room curing and drying at 25–27°C until the necks are tight and totally dry. After curing and drying, bulbs are cooled to 0°C for storage. Onions are often stored with other commodities at 3–5°C, but the length of storage is greatly reduced compared with storage at 0°C. Controlled atmospheres may be used for onion storage, particularly pungent cultivars. Low O_2 reduces respiration and prolongs storage life while elevated CO_2 reduces sprouting and root growth. Onions are not susceptible to chilling injury. Bulbs produce little ethylene and they are not particularly sensitive to exogenous ethylene, however, high levels of ethylene (>1500 μl/l) may induce sprouting. Scales may appear translucent or watery after storage due to freezing injury, delayed cold storage after curing, or late harvesting and prolonged field drying at high temperatures. Outer scales may also turn green if exposed to light. Bulbs are also susceptible to various rots during storage, so good sanitation is important for preventing losses.

POTATO The white potato (*S. tuberosum*) is an annual, cool-season crop, grown for its underground tubers that form on the ends of underground stolons as storage organs. Both skin and flesh colors vary widely among cultivars with brown russet, white, red, pink, yellow, and purple skins covering white, cream, yellow, purple, red, and striated flesh. Tubers may be long and slender or nearly round (Voss, 2004). High quality potatoes should be: (i) clean of soil or defects; (ii) appropriately sized and colored for the cultivar; and (iii) firm and free of skin greening or sprouts. While vine senescence is often used as a criterion for harvest, resistance to tuber skin abrasion (skinning) is a much better harvest index. Sugar content is often used as an additional harvest index for processing potatoes.

Potatoes destined for long-term storage must first be cured for 1–2 weeks at 20°C and 80–100% RH. Once cured, the temperature is lowered by 1 or 2°C/day until the desired storage temperature is reached. The RH should be maintained at 99% to prevent shriveling and bruising during storage. Tubers used as seed potatoes are stored at 4–5°C to minimize sprouting. The conversion of starch to sugars is a key concern for determining storage temperature. In general, starch-to-sugar conversion is greatest at low, above-freezing temperatures. Each cultivar has a characteristic starch-to-sugar conversion temperature profile, thus the cultivar must be considered along with the culinary use when determining the best storage temperature. Tubers for fresh consumption are stored at 7–10°C, to minimize starch-to-sugar conversion. Tubers for frying are stored at 10–15°C to prevent excessive sugar accumulation since many cultivars used for frying have high starch-to-sugar conversion rates at temperatures below 10°C. Cultivars used for making chips often have a high starch-to-sugar conversion rate at temperatures below 15°C, thus they should be stored between 15 and 20°C. Most cultivars will store for 2–12 months depending on temperature and whether or not they are treated with sprouting inhibitors. Controlled atmosphere storage of potatoes is minimal. Potatoes are chilling sensitive. Internal browning occurs at 1–2°C while unacceptable and non-reversible sugar accumulation occurs at 3–4°C. Potatoes produce little ethylene, except wounded tubers which will produce large amounts of ethylene. Tubers are fairly insensitive to exogenous ethylene, however, very high levels can induce sprouting.

There are a number of physiological maladies that affect potatoes during storage including black spot, blackheart, freezing injury, and greening. Black spot occurs primarily on the stem end of the tuber after a physical impact and appears as a dark, black spot at the point of impact. Blackheart is caused by low O_2 levels during storage or transportation and is induced at temperatures >30°C. High respiration rates at these temperatures leads to a lack of O_2 in the center of the tuber which causes cells to die and turn black. Freezing injury can occur at −1°C in the field or during storage. Affected tissue is easily identified as a sharply delineated water-soaked area which results in tissue deterioration after thawing. Greening occurs in tubers exposed to light. It results from a short exposure to high light levels or a longer exposure (1 or 2 weeks) to low level light and leads to chlorophyll and solanine production. Solanine is a heat-stable, toxic glycoalkaloid that is minimally degraded with cooking. Therefore, greened tubers should be discarded. Potatoes are highly susceptible to a number of rots during storage, thus sanitation to prevent infection is important.

RADISH Radish (*Raphanus sativus*) is a root crop in the family *Cruciferae*. It is quick growing and available in many colors and sizes. They are normally eaten raw, as their flesh is sweet to pungent and succulent. High quality radishes are uniform in size, firm, and crisp. Flesh should not be stringy or pithy. Roots are harvested according to size and larger ones are often pithy. They may be sold bunched or topped (Hassell, 2004).

Roots should be pre-cooled to 0–4.5°C then stored at 0°C and 90–95% RH where they will last up to 4 weeks. Bunched radishes will store for 1 or 2 weeks under these conditions. Winter black radishes will store for up to 4 months. Topping radishes helps prolong storage (Fig. 16.4). Controlled atmosphere storage at 1–2% O_2 and 2–3% CO_2 at 0–5°C slightly prolongs storage. Radishes are not sensitive to chilling injury, produce little ethylene and are not sensitive to exogenous ethylene.

SWEET POTATO The sweet potato (*Ipomea batatas*) is a perennial fleshy storage root often grown as an annual. Sweet potatoes come in a variety of colors including white, creamy white, yellow, orange, red, and purple. They may be sweet to bland and mild to strongly flavored with flesh that can range from firm to very soft. Harvest is based solely on root size as there is no specific developmental stage defining maturity: roots will continue to enlarge until they die of rot or anaerobiosis or the tops are killed by frost. Harvested roots must be cured by storing them at 29°C at 90–97% RH for 4–7 days. Storage rooms must be vented during curing. Curing helps

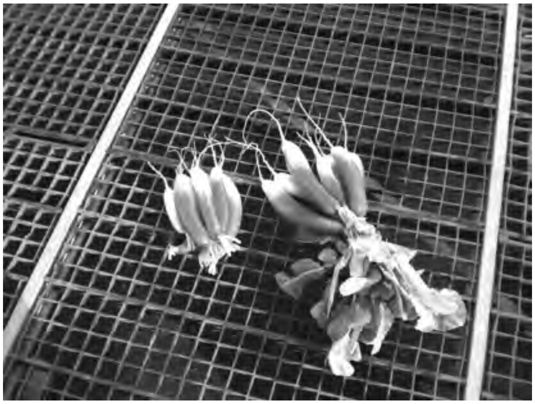

Fig. 16.4. Topped (left) and bunched (right) radishes (*Raphanus sativus*).

heal wounds caused in harvest and handling and also helps develop enzymes responsible for flavor development during cooking (Kays, 1997). As roots cure, the outer layer of parenchyma cells dehydrates while the underlying cells become suberized. A lignin-like wound periderm then develops underneath the suberized layer, and curing is complete when this layer is three to seven cells thick. After curing, roots are stored for up to a year at 14°C and 90% RH. Roots are not typically stored under controlled atmospheres. Roots are chilling sensitive at temperatures below 12°C. Symptoms include: (i) root shrivelling; (ii) surface pitting; (iii) internal browning due to the formation of chlorogenic acid and other phenols (Walter and Purcell, 1980); and (iv) hardcore formation. Hardcore formation does not become apparent until roots are cooked. Roots are sensitive to high levels of ethylene but only to levels higher than those encountered in normally ventilated storage rooms. If roots are exposed to anaerobic conditions prior to harvest (heavy rains with poor drainage), roots often decompose rapidly once in storage, emitting a distinct fermented, sour smell. Roots may also become pithy during storage. Many organisms can cause root rot during storage. Internal corking, characterized by internal necrotic lesions, is caused by a virus infecting most cultivars and may develop during storage. Sweet potato weevils (*Cylas formicarius*), fruit flies (*Drosophila* spp.), and soldier flies (*Hermetia illucens*) are serious storage pests. The sweet potato weevil enters storage on infected roots, thus roots should be examined for their presence before storage and roots discarded if weevils are present. Fruit and soldier flies often contaminate rotten or injured roots. Good sanitation during processing and storage are important for controlling many of the postharvest pests.

Leafy/stem vegetables

ASPARAGUS Asparagus (*Asparagus officinalis*) is a perennial in the family *Liliaceae* prized for its tender shoot. When harvested either white (blanched) or green, the shoot consists of a thick stem with only scale leaves at each internode. High quality asparagus spears are harvested when 10–15 cm in length and should be firm, straight, tender, and glossy with tightly closed tips. Green spears should be green their entire length as white butt ends are not desirable even though they tend to resist decay during handling as compared with spears with green butts. Asparagus continues to elongate after harvest and is one of the most perishable horticultural commodities (Luo *et al.*, 2004a) and should be cooled to 0°C as soon after harvest as possible. Spears become tough and loose flavor if they are not cooled as quickly as possible. They can be stored at 0°C and 95–99% RH for 14–21 days. Spears should be stored vertically to prevent a geotropic tip response to horizontal storage. As spears senesce, buds underlying the bracts on spears begin to grow causing the problem known as feathering. Proper storage length at the correct temperature helps reduce its appearance. Controlled atmosphere storage at CO_2 levels of 5–10% helps to slow toughening and prevent decay. Storage at O_2 levels less than 2% leads to the development of off-odors and tip discoloration. Spears are sensitive to chilling and may be injured after 10 days at 0°C. Symptoms of injury include a loss of sheen and glossiness of the entire spear, a general limp appearance as well as graying of the tips. Severe injury may lead to darkened spots or streaks near the tips. Spears produce little ethylene, however, exposure to exogenous ethylene hastens toughening.

CABBAGE Cabbage is grown for its terminal vegetative bud which may be smooth, red or green and round or pointed (*Brassica oleracea* Capitata Group), or round, green and savoyed (Prange, 2004a). Cabbage may be eaten raw, cooked or fermented. Heads should be firm and brightly colored at harvest. Maturity is based on size and head firmness or density. The head should feel heavy for its size, a sign of a nice, dense head. Immature heads are prone to decay while over-mature heads are likely to split. Cabbage should be cooled and will store at 0°C at 98–100% RH for up to 6 months. Careful temperature control is necessary as cabbage will freeze at −1°C and will senesce quickly at 1°C. Cabbage is often stored under a controlled atmosphere of 1.5–5% O_2 with 0–8% CO_2, depending on cultivar, type, and maturity. Cabbage is not sensitive to chilling injury and produces very little ethylene. It is sensitive to exogenous ethylene which can accelerate senescence.

CELERY Celery (*Apium graveloens*) is grown primarily for its succulent, thick, green-to-white petioles. The leaves are also edible and tend to be more strongly flavored than the stalk. High quality celery should have straight, well-formed, light green stalks. It is harvested based on size, usually when most of the plants in the field have reached 35–41 cm in height and outer petioles have not become pithy. Celery should be cooled quickly then stored at 0°C with >95% RH for up to 7 weeks (Luo *et al.*, 2004c). Interior petioles will continue to grow if the temperature is >0°C. Celery is not sensitive to chilling and produces little ethylene. Exposure to exogenous ethylene may cause accelerated senescence if it occurs at temperatures above 10°C. The major postharvest problem associated with celery is pithiness. Pithiness occurs when parenchyma cells in the petiole break down to form aerenchyma tissues. Pithiness is induced prior to harvest by cold stress, water stress, induction of bolting or root infection but is delayed with proper storage temperature. Blackheart is a disorder caused by calcium deficiency and water stress which causes death of cells in internal leaves which leads to brown discoloring which soon turns black. Boron deficiency leads to cracking of the petiole on the interior side.

GREENS FOR COOKING A number of vegetables are grown for their leaves which are mostly eaten cooked rather than raw. These include collards and kale (*Brassica oleraceae* Acephala Group), spinach (*Spinacia oleraceae*), rape (*Brassica napus*), mustard (*Brassica juncea*), and turnips (*Brassica rapa*) (Rushing, 2004b). Spinach may be harvested very young for use in salads but is most often harvested mid-maturity for cooking. The other greens are harvested as full-size, mature leaves that have not begun to senesce. Leaves should be uniform and free of defects, decay, and insects. Leaves should be cooled as quickly as possible after harvesting and stored at 0°C and 95–98% RH for about 2 weeks. Leafy greens are not sensitive to chilling. Leaves produce little ethylene but are very sensitive to exogenous ethylene which causes rapid yellowing and senescence.

LETTUCE There are four main types of lettuce (*Lactuca sativa*) grown for leaves used primarily in salads, soups, or as a garnish. The four types are: (i) iceberg (crisphead); (ii) butterhead (bibb, Boston); (iii) cos (romaine); and (iv) leaf (Saltveit, 2004d). Crisphead lettuce forms heavy heads of crisp, brittle leaves with prominent veins. Butterhead cultivars form open heads of softly textured, tender leaves. Cos lettuce does not form a head, but rather consists of tightly packed upright crisp leaves. Leaf lettuce does not form a head, but rather produces large, softly textured leaves with an open and spreading habit. All lettuce is extremely fragile and should be handled gently at all times. Leaves are harvested at many stages. Lettuce should be pre-cooled then stored at 0°C at 98–100% RH where it will last for up to 4 weeks. Lettuce will be freeze damaged at −0.2°C, thus extreme care must be taken when regulating the storage temperature. Lettuce produces little ethylene but senesces very rapidly if exposed to exogenous ethylene.

Controlled atmosphere storage at 1–3% O_2 and <2% CO_2 reduces some postharvest problems such as russet spot, pink rib, and brown stain. Russet spot is caused by oxidation of phenolic compounds produced in response to exposure to ethylene. It appears as brown oval spots on midribs which occasionally spread to blade tissues in severe cases. Brown stain is caused by exposure to >2.5% CO_2 and appears as large brown stains on leaf midribs. Pink rib is a pink discoloration of the midrib whose cause is unknown.

SALAD GREENS Many other leafy greens are used in salads besides lettuce (Fig. 16.5), including *Valerianella locusta, Valerianella olitoria* (corn salad, lamb's lettuce, field salad, mâche), *Taraxacum officinale* (dandelion), *Rumex scutatus* (sorrel), *Montia perfoliata* (*Claytonia perfoliata*) (claytonia), *Brassica rapa* (mizuna), and *Eruca vesicaria* (arugula). Leaves are usually harvested young and immature for best quality. Salad greens should be cooled to 0–2°C at 95–100% RH where they will store for 7–14 days. Salad greens are not chilling sensitive and they produce little ethylene. Exposure to exogenous ethylene will lead to premature

Fig. 16.5. Mixed baby salad greens.

yellowing and senescence. Leaves are extremely delicate thus must be handled gently throughout the entire production and marketing chain.

Edible flower buds

ARTICHOKE The globe artichoke (*Cynara scolymus*) is a perennial grown for its immature flower bud that resides on a fleshy central base, all enclosed by a cone of short, thick bracts (Wang, 2004b). Good artichokes will have turgid, tightly closed bracts and feel dense and heavy for their size. Buds are harvested when they reach a size appropriate for the cultivar and the intended market. Buds should be cooled to below 5°C as quickly as possible then stored at 0°C and >95% RH for up to 2 weeks. Controlled atmosphere offers no benefit compared with storage at 0°C. Artichokes are not sensitive to chilling or ethylene and produce very little ethylene. The major postharvest problems with artichoke are cosmetic issues resulting from rough handling.

BROCCOLI Broccoli (*Brassica oleracea* Italica Group) is grown for its immature inflorescence. High quality broccoli should be firm, bright green, tight with no signs of bolting (flowering) or senescence. Broccoli is stored at 0–2°C with 98–100% RH for up to 3 weeks. Icing is often used to maintain temperature and humidity around the heads, as broccoli generates considerable heat due to a high respiration rate. Storing in a controlled atmosphere of 1–2% O_2 with 5–10% CO_2 at 0–5°C can double storage life (Toivonen and Forney, 2004). Broccoli is not chilling sensitive. Broccoli generates very little ethylene but is sensitive to exogenous ethylene which causes severe floret yellowing.

CAULIFLOWER Cauliflower (*Brassica oleracea* Botrytis Group) is grown for its head of condensed and malformed flower buds known as curds. Heads should be white, firm, and compact when harvested, with no protrusion of flower parts (also known as riciness). Heads should be cooled and stored at 0°C at 95–98% RH where they will last up to 3 weeks (Forney and Toivonen, 2004). Heads should not be iced, as free-standing water on curds is not desirable and may induce decay. Cauliflower is not chilling sensitive and does not produce much ethylene. It is very sensitive to exogenous ethylene which causes curd discoloration. Boron deficiency in cauliflower may cause brownish discoloration of the curd and pith and may also cause hollow stems. Curds may also taste bitter if deficient in boron. Riciness is induced by seedling exposure to temperatures >20°C before curd initiation, or to 7°C after curd formation. Thus warm temperatures must be avoided before curd initiation and cool temperatures must be avoided after curd formation.

Immature fruits

BEANS Snap beans (yellow wax beans and green beans) (*Phaseolus vulgaris*), runner or flat beans (*Phaseoulus coccineus*), and long beans (*Vigna sesquipedalis*) are all legumes grown for their immature fruit (Cantwell, 2004a). High quality fruit should be firm, tender, without a tough vascular string and be the size and color appropriate for each type. Seeds should be tender as indicated by little or slight bulging of the pod. Beans are harvested 8–10 days after flowering, cooled rapidly to 5–7.5°C and stored at the same temperature with 95–100% RH for 8–12 days. Storage at temperatures below 5°C leads to chilling injury and some cultivars exhibit chilling injury symptoms even at the recommended storage temperature; storage at higher temperatures leads to unacceptably rapid quality loss observed as dehydration, yellowing of green-fruited cultivars, and excessive seed growth. Chilling injury symptoms include: (i) a general opaque coloring of the fruit; (ii) surface pitting; and (iii) the development of discrete brown spots on the surface which quickly become susceptible to decay. Controlled atmosphere storage at 2–5% O_2 and 3–10% CO_2 can reduce discoloration and decay. Beans produce little ethylene and exposure to exogenous ethylene hastens color loss, causes browning, and reduces storage life by up to 50%.

CUCUMBER Cucumbers (*Cucumis sativus*) are grown for their immature fruit called pepos, which are modified berries usually consisting of three united carpels (Saltveit, 2004c). Fruit are produced on indeterminate vines, although some determinate cultivars are available (the so called 'bush' form). Fruit are round or oblong and cylindrical with small warts with spines (originating as trichomes) on the skin or rind. High quality fruit are harvested immature with crisp white flesh and small or no seeds (parthenocarpic cultivars). Cucumbers are non-climacteric even though a spike in ethylene production is observed just prior to a rapid loss of chlorophyll as fruit mature and ripen. Immature fruit are highly sensitive to ethylene exposure. Fruit exposed to exogenous ethylene rapidly lose chlorophyll and become extremely susceptible to decay. Cucumbers are sensitive to chilling at temperatures less than 10°C, thus they are stored at 10–12.5°C at 95% RH for 1–2 weeks. Chilling injury is observed as surface pitting, the development of water-soaked lesions in the flesh, and loss of chlorophyll from the rind. Bruising is common in poorly handled fruit. Controlled atmosphere storage is rarely used for cucumbers.

EGGPLANT The eggplant (*Solanum melongena*) is an annual solanaceous (nightshade) crop grown for its immature fruit. Fruit may be oval, round, pear shaped or long and slender and may have skin that is white, purple, yellow, lavender, or striped. Cultivars are normally grouped into American, Japanese, Italian, Philippine, Thai, or Chinese types. High quality fruit should have a nice green calyx, firm flesh and shiny skin, and a shape and size appropriate for its type. Fruit are harvested at various stages, but become pithy and bitter with hardened seeds and tough skin as they mature. Fruit are particularly sensitive to compression bruising and should be handled gently and stored in single layers. Fruit should be cooled to 10°C as quickly as possible and stored at 10–12°C with 90–95% RH for up to 2 weeks. Fruit quality deteriorates rapidly in storage, thus they should be consumed as soon as possible after harvest. Controlled atmospheres are not used for eggplant storage. Fruit can be wrapped in plastic film to create a modified atmosphere which helps reduce weight loss and quality deterioration due to water loss (Siller-Cepeda, 2004). Eggplants readily absorb odor, especially ginger, garlic and onion, thus they must be stored separately. Surface pitting and brown surface scalding are symptoms of chilling injury caused by fruit exposure to temperatures less than 10°C. Seed and flesh browning soon follow. Eggplant have a low rate of ethylene production (0.1–0.7 μl/kg/h at 12.5°C and are moderately sensitive to exogenous ethylene >1 μl/l. Calyx abscission and tissue browning may result from exposure to high levels of ethylene.

PEA Peas (*Pisum sativum*) come in three edible types: (i) the garden or green pea where only the seeds are consumed; (ii) snow peas where undeveloped seeds and the pod are consumed; and (iii) snap peas where well-developed seeds and the thick-walled pod are consumed. All three types are produced during cool weather, usually the spring. High quality peas should be harvested at a type-appropriate stage and cooled to 0°C for storage at 95–98% RH for 1–2 weeks. Peas are not chilling sensitive but they are sensitive to exogenous ethylene even though they produce little ethylene themselves (Morris and Jobling, 2004). Exposure to ethylene results in pod yellowing and increased decay.

SUMMER SQUASH Summer squash (*Cucurbita pepo*) fruit are pepos, that are harvested immature for up to 1 week after anthesis to ensure that they are tender, firm, shiny, and flavorful (McCollum, 2004). Of the six horticultural groups of summer squash (cocozelle, crookneck, scallop, straightneck, vegetable marrow, and zucchini), zucchini is the most widely grown. High quality fruit should be young, firm, shiny, and free of defects. Dull fruits indicate senescence and overdevelopment. Fruit must be handled carefully to prevent injury to the skin, which greatly reduces their value. Squash should be cooled to 5–10°C at 95% RH where they will store for no longer than 2 weeks. Summer squash are chilling sensitive and should not be exposed to temperatures less than 5°C. Symptoms of chilling injury include surface pitting, and accelerated decay and water loss once they are transferred to non-chilling temperatures. Injury is usually not observed at chilling temperatures. Fruit produce low amounts of ethylene and yellowing of green-fruited cultivars may occur if exposed to exogenous ethylene.

SWEET CORN Sweet corn (*Zea mays*) is a member of the grass family producing ears of highly perishable kernels (Fig. 16.6). Ears are perishable in the sense that their quality declines very quickly after harvest due to changes in carbohydrate status of the kernels. The traditional sweet corn cultivars are known as 'sugary 1' (su1), containing about twice the sucrose of field corn and eight to ten times the amount of water-soluble polysaccharide, which imparts a creamy consistency to the kernels (Brecht, 2004b). More recently developed cultivars are known as 'shrunken 2' (sh2) which have twice the sugar as field corn but no water-soluble polysaccharide. The *sh2* gene inhibits starch formation which doubles the shelf life of cultivars carrying it. A third type is known as the 'sugary-enhancer' (su1/se), where the *se* gene modifies the *su1* gene so that the water-soluble polysaccharide content is not lost. These newer cultivars are collectively referred to as 'supersweet' corn.

The highest quality sweet corn has uniform size and color (white, yellow or bicolor) kernels that are sweet, plump and tender, fully filled ears covered by a tight, green husk, and all free of injury, insects, and decay. All sweet corn loses flavor during storage. The taste of su1 and su1/se cultivars becomes starchy while sh2 cultivars become watery and bland. Ears are harvested when the ears are plump and full and the silks have just turned brown and are drying. Kernels of su1 and su1/se cultivars should have a milky endosperm at maturity. The sh2 cultivars always have a watery endosperm, thus kernel consistency is not a good indicator of maturity in these cultivars.

Sweet corn must be cooled quickly after harvest to 0°C. It should be cooled in small batches, and stored in small wooden crates or baskets to minimize heat build up due to the high respiration rate during storage. Top icing crates or baskets is often used to: (i) maximize cooling during storage; (ii) remove heat of respiration; and (iii) keep the husks fresh and hydrated. In general, sweet corn can only be held in storage for a few days before quality rapidly deteriorates. Under the best conditions, sh2 cultivars may be stored for up to 2 weeks. Sweet corn is not sensitive to chilling, produces little ethylene,

Fig. 16.6. Sweet corn (*Zea mays*) nearly ready to harvest.

and is not sensitive to exogenous ethylene. The major postharvest problem with sweet corn is loss of kernel quality.

Mature fruits

APPLE The domesticated apple (*Malus domestica*) is a perennial in the family *Rosaceae* believed to have originated in south-eastern Europe. The skin of the apple contains many lenticels as well as cuticular cracks which are important in gas exchange during storage. Stage at harvest greatly affects longevity in storage. Immature fruit will have poor quality and are prone to storage disorders such as bitter pit and superficial scald. Overly mature fruit will lack firmness and flavor quality will diminish rapidly during storage. Fruit that are just about mature are usually harvested to prolong storage while maintaining the highest quality possible.

Quality is extremely important as most consumers want a blemish-free, sweet, crisp apple. Fruit size and skin color (both under color and over color) are paramount in grading. Any blemishes or defects in appearance or texture are unacceptable, even though some defects are often accepted in the organic market. Minimal flesh firmness, acidity level, and SSC vary with cultivar.

Apples are climacteric and generate varying amounts of ethylene depending on cultivar and stage of maturity. Elevated levels of ethylene are associated with ripening. Early-season cultivars generally have high ethylene production rates, ripen quickly, and have a short storage life while later-season cultivars produce little ethylene until the climacteric, ripen slowly, and have a longer storage life. Monitoring and adjustment of storage ethylene levels is crucial in postharvest apple management. This is accomplished most often via low temperature storage and controlled atmosphere storage. The compound 1-MCP which is structurally related to ethylene is applied at low levels to interfere with ethylene action by preventing the attachment of ethylene molecules to receptors in plant tissues. Best results are obtained when fruit is treated soon after harvest and before it has progressed along the maturity/ripening chain. Besides delaying ripening while maintaining SSC and firmness during storage, 1-MCP prevents scald, a serious postharvest disorder of apples characterized by irregular, patchy, brown or gray skin discoloration.

Most apples are stored in 1 bushel boxes; 1 bushel of apples weighs approximately 18.2 kg. The number of apples per bushel is usually indicated on the box. Most apples are stored in controlled atmospheres at 1–4°C at 90–95% RH depending on the cultivar. Postharvest physiological maladies afflicting apple are separated into three classes: (i) those that develop only while fruit are on the tree; (ii) those that develop on the tree or in storage; and (iii) those that develop only in storage.

Watercore is a physiological condition that develops while the fruit is still on the tree. Intercellular air spaces within the fruit flesh become filled with sorbitol and appear water soaked. It develops on the tree as the fruit matures and nights are cool. In 'Delicious' strains, watercore is a serious problem as it leads to breakdown during storage while watercore in 'Fuji' strains is desirable for the sweetness it imparts to the fruit.

Bitter pit is an example of a malady that develops on the tree or in storage. It is characterized by the development of pits in the flesh either near the surface or deep within the fruit, caused by low levels of calcium in the fruit. The pits eventually turn brown. Cultivars vary in their susceptibility to bitter pit, and in those that are susceptible, the more immature the fruit is at harvest, the more likely it is to suffer from bitter pit. Excessive pruning, high temperature, or drought often exacerbates the problem of bitter pit. Postharvest treatment with calcium may reduce the development of bitter pit in storage.

The disorders that only develop during storage include senescent breakdown, chilling injury, and injury caused by an inappropriate storage atmosphere. Senescent breakdown develops in fruit that are harvested at an overly mature stage. It is characterized by a general loss of flavor quality and tissue softening.

Storage disorders associated with temperature include low temperature breakdown, brown core, and internal browning. Susceptibility depends on cultivar and problems are exacerbated with a cold, wet growing season. Low temperature breakdown leads to brown discoloration of vascular tissues and the flesh with the maintenance of a ring of unaffected tissue just below the skin. Brown core, also known as coreflush, begins with browning of flesh near the core, which proceeds to affect the entire fruit. Internal browning is only observed once the fruit is cut and appears as graying of the flesh. Both coreflush and internal browning are often associated with high levels of CO_2 in storage.

Superficial scald appears as an irregular discoloration on the skin after long-term storage. It can be reduced with a postharvest treatment of fruit with diphenylamine (DPA), however, DPA is not universally allowed as a postharvest treatment. Scald can be reduced with low O_2 and low ethylene storage.

Soft scald appears as irregular, sharply defined areas of soft, light brown tissue on the skin that may penetrate the flesh. Harvest maturity and storage temperature must be closely regulated for susceptible cultivars.

If O_2 levels are too low during storage, a loss of flavor and an increase in fermentation odors develop over time. Additionally, a purplish brown color may develop on the skin of red cultivars and brown soft patches resembling soft scald may occur. Fruit may also soften unexpectedly. Excess CO_2 may lead to wrinkled, depressed patches of skin on the greener side of fruit. Internal symptoms may include tissue browning or cavity formation in the flesh (Watkins *et al.*, 2004).

APRICOT The apricot (*Prunus armeniaca*), native to China, is highly prized for its sweet, flavorful fruit that can be eaten fresh or dried. Once harvested, fruit softens quickly and is susceptible to bruising and has a short shelf life. In general, the highest quality apricots have an SSC of >10%, titratable acidity (TA) of 0.7–1.0%, and flesh firmness of 8.9–13.3 N/cm^2.

Fruit are hand-harvested firm mature when the under color changes from green to yellowish, the exact nuances of harvest color varying with cultivar and shipping distance. Depending on market destination, fruit may be bulk packed in 10 kg containers or tray packed in single- or double-layer containers. Fruit are stored for 1 or 2 weeks at –0.5–0°C at 90–95% RH. Fruit may be shipped in a controlled atmosphere of 2–3% O_2 and 2–3% CO_2. Low O_2 (<1%) may lead to off-flavors and high CO_2 (>5% for >2 weeks) may lead to flesh browning and loss of flavor. Ethylene induces ripening in apricot and may also encourage fungal growth on fruit.

Apricots are susceptible to chilling injury if stored at temperatures >0 and <5°C, which appears as loss of flavor, flesh browning or gel breakdown. Gel breakdown develops at temperatures between 2.2 and 7.2°C when fruit are stored for a long time. Flesh begins to look water soaked and later may become spongy or gel-like and finally brown. Pit burn develops in fruit exposed to temperatures above 38°C before harvest. Flesh around the pit softens and turns brown (Crisosto and Kader, 2004e).

ASIAN PEAR Asian pears (also called Chinese pears, Japanese pears, Oriental pears, sand apples, salad pears, and apple pears) are a group of pome fruits derived primarily from *Pyrus ussuriensis* and *Pyrus serotina* with a flavor reminiscent of a European pear and the texture of a crisp apple, even when ripe.

Asian pears are very sensitive to bruising and skin abrasions and are often wrapped in foam nets and boxed in single layers to prevent injury during storage and transit. Fruit remain quite firm even when ripe, are juicy and high in SSC. Fruit are harvested primarily based on a change in ground color from green to yellow or brown, depending on cultivar. Fruit should not be pre-cooled before storage as this tends to induce a malady called fresh spot decay especially in large or overly mature fruit. Fruit are stored at 0°C at >90% RH. Fruit are quite sensitive to ethylene, thus ethylene must be controlled in storage.

Fresh spot decay is internal and appears as spots of brown tissue or cavities in the flesh, particularly near vascular tissues towards the stem end of the fruit. The disorder may appear while the fruit is still on the tree, but becomes more pronounced after 2–6 weeks of storage. The cause remains unknown.

Another internal postharvest problem with Asian pears is internal browning and core breakdown where brown, water-soaked areas in the core or flesh develop during storage. Fruit that remain on the tree for more than 180 days are most likely to develop this problem, thus fruit are usually harvested when nearly all the fruit on a tree are still green.

Low O_2 in storage (level varies with cultivar) leads to discolored surface skin depressions while high CO_2 levels (>5%) lead to core or flesh browning. Fruit are also susceptible to watercore and scalding, much like that described for apples (Crisosto, 2004).

AVOCADO Avocados (*Persea americana*), native to Central America and Southern Mexico, are classified into three races: (i) West Indian; (ii) Mexican; and (iii) Guatemalan. West Indian avocados are tropical with large fruit and relatively low oil content. The Mexican race is subtropical with smaller, thin-skinned fruit of higher oil content.

Guatemalan avocados are subtropical with round, thin-skinned fruit with intermediate oil content. Many commercial cultivars are hybrids of these three races (Bergh and Lahav, 1996).

High quality avocados at harvest should be of the appropriate size for its race, and have good skin color free from skin defects including spray residues. Ripe fruit should be free of postharvest defects including bruising and flesh graying. Avocados have significant oil content, sometimes as high as 30% by fresh weight. The oil quality is similar to olive oil, being approximately 75% monounsaturated, 15% saturated, and 10% polyunsaturated omega 6, and is considered a type of healthy oil.

The percentage dry matter of an avocado is closely related to its oil content, and is therefore widely used as a maturity index. Optimum percentage dry matter at harvest varies with cultivar and ranges from 17 to 25%. Fruit are harvested mature, but not ripe. Fruit can hang on the tree for months as they will not ripen until removed from the tree. The longer fruit remains on the tree, the faster it ripens once harvested. Once harvested, fruit are rapidly cooled to delay ripening to store at a temperature of 5–12°C, depending on cultivar, at 85–95% RH.

Controlled atmosphere storage is often employed, particularly when shipping fruit long distances. The atmosphere used varies with cultivar but is generally 2–5% O_2 and 3–10% CO_2. These levels reduce ethylene generation, respiration, ripening, and softening. Low O_2 injury may occur if O_2 levels fall below 2% and results in irregular brown patches on the skin and flesh browning as well. Elevated CO_2 levels (>10%) can lead to skin discoloration and the development of off-flavors. The use of 1-MCP for delaying ripening is still in its experimental stage. Step-down storage temperatures are often used when storing avocados by decreasing the storage temperature by a degree or two each week until the fruit reach a minimum of 4°C. The storage starting temperature varies with cultivar.

The main postharvest problem limiting long-term storage of avocados is chilling injury, internal and external, which are caused by very different storage conditions. Internal injury appears as grayish brown flesh near the base of the fruit and particularly around the seed. Vascular browning also appears; it begins at the base of the fruit and progresses towards the stem end as the problem develops. Softening of the flesh also occurs. Internal injury often begins to appear after 4 or more weeks in storage at 6°C and is exacerbated by ethylene exposure.

External chilling injury appears as irregular black patches on the skin and occurs after fruit exposure to temperatures <3°C. It often becomes more pronounced after removal from storage. Fruit that are more mature are less susceptible to external chilling injury.

Mature avocados produce little ethylene, however, once fruit begins to ripen ethylene production accelerates dramatically. Ethylene from ripening fruit can initiate ethylene production in mature, non-ripe fruit which are extremely sensitive to ethylene. Many retail outlets expose avocados to ethylene before displaying them for sale to induce rapid ripening (Woolf *et al*., 2004).

BANANA AND PLANTAIN Bananas and plantains are derived from *Musa acuminata* and *Musa bavisiana* and are fruits eaten for their fleshy pulp which is covered by the ovary wall or peel (Kerbel, 2004). The pulp is derived from the innermost layers of the ovary wall and is consumed either raw or cooked. Plantain pulp is much starchier than that of bananas and is usually consumed cooked, even when ripe. Both plantains and bananas are seedless. Both must be harvested mature, but not ripe, as pulp texture is often unacceptable if harvested ripe. Fruit are ripened after shipping either under controlled conditions or naturally. The main harvest index used for both is the time from the emergence of the bunch from the pseudostem and the individual fruit length and diameter. Bananas are shipped and stored at 13–14°C while plantains are shipped and stored at 9–12°C, both at 90–95% RH. Controlled atmosphere storage is often used during shipment of both bananas and plantains and MAP using poly bags is beneficial for prolonging storage life and delaying ripening and senescence. Neither fruit are pre-cooled, as both are susceptible to chilling injury at temperatures below 13°C which is observed as brown or black streaks on the peel or as a grayish color on ripe fruit. In severe cases, the flesh may turn brown or black and may develop an off-flavor. Both fruits are sensitive to exogenous ethylene depending on fruit maturity, temperature, ethylene concentration and length of exposure. Exogenous ethylene even at very low levels will induce ripening. Controlled ripening is nearly always used with bananas while plantains may be ripened under controlled conditions or allowed to ripen naturally. Fruit are ripened by exposing them to 10–1000 μl/l ethylene in sealed chambers for 24–48 h at 14–18°C. The concentration used varies with ripening facility, but the higher concentrations are normally used to ensure uniform ripening. Rooms must be vented immediately after ethylene treatment to prevent CO_2 build up which can inhibit ethylene-induced ripening. Peel color on a scale from 1 to 7 is used as an indicator of ripeness, with 1 indicating dark green, 6 indicating fully yellow, and 7 indicating brown flecking of yellowed fruit. Fruit are usually marketed at stage 3–4.

A disorder called 'maturity bronzing/maturity stain' sometimes develops 20–30 days before harvest if the crop experiences water deficits along with hot, humid weather during bunch emergence. Eating quality is not affected since the disorder is primarily a discoloration of the skin. Stained fruit are not marketable. If fruit are exposed to temperatures above 30°C, ripening can be irreversibly inhibited.

BLACKBERRY Blackberries (*Rubus* spp.) are grown for their soft, sweet, juicy succulent fruits in many areas of the world. While their root systems are perennial, their fruit-bearing shoots are either annual (primocane fruiting cultivars) or biennial (floricane fruiting cultivars). Blackberry-raspberry hybrids include tayberry, loganberry, youngberry, and boysenberry. Fruits are composed of numerous drupelets attached to a common receptacle which remains as a harvested part of the fruit. High quality fruit are fully black in color, regularly shaped, firm, and free of sunscald. Sunscald can appear as individually whitish-pink discolored drupelets on an otherwise normally colored fruit. Fruit should be harvested as ripe as possible to maximize blackberry flavor and sweetness. The best maturity indices are fruit color and fruit-removal force. Fruit should be harvested when they are a dull black color (as opposed to shiny) and are able to be released from the plant with gentle force. Shiny, non-ripe fruit are often extremely acidic and unpalatable. Fruit are fragile, thus they should be harvested into containers from which they will be sold (generally 1 or 0.5 pint containers, equivalent to 473 ml and 237 ml, respectively) and cooled to <5°C as quickly as possible. Fruit can be stored for 2 days to 2 weeks, depending on ripeness at harvest, at −0.5–0°C at >90% RH (Perkins-Veazie, 2004a). Decay and fruit softening can be reduced with controlled atmosphere storage at 10–20% CO_2 with 5–10% O_2. Fruit are not sensitive to chilling. Ethylene production varies with cultivar and ripeness. Elevated ethylene levels can stimulate the growth of gray mold (*B. cinerea*).

BLUEBERRY Blueberries (*Vaccinium* spp.) are perennials grown for their blue-skinned fruit which encloses a creamy-white to green colored, juicy flesh. A waxy bloom gives the fruit their light blue color. The three major types of blueberries are: (i) lowbush (*Vaccinium angustifolium*); (ii) highbush (*Vaccinium corymbosum*); and (iii) rabbiteye (*Vaccinium ashei*). Lowbush blueberries are small (<1 g per fruit), grow in native stands, and are highly prized for processed products. Highbush blueberries are grown in the mid-latitudes while rabbiteyes are grown in lower latitudes due to their lack of winter hardiness. Rabbiteye fruit often have a gritty mouth feel from seeds and stone cells, but have more anthocyanins than highbush or lowbush and a much longer shelf life than either of them (Perkins-Veazie, 2004b). High quality fruit are harvested when the entire fruit is a uniform blue color. It should be firm with little or no red coloration at the stem end and free of defects. Fruit should be rapidly cooled to <5°C and stored at −0.5–0°C with >90% RH, where they will last for 2 weeks (lowbush and highbush) or 4 weeks (rabbiteye). Fruit deterioration can be delayed and storage life increased to up to 6 weeks with controlled atmospheres of 10–15% CO_2 plus 1–10% O_2 at <5°C. Blueberries are not chilling sensitive. Ethylene production varies with cultivar and gray mold (*B. cinerea*) growth can be accelerated with high levels of ethylene. The main problems encountered postharvest include water loss with fruit shriveling and rot.

CHERRY (SWEET) Sweet cherry (*Prunus avium*) is a rosaceous tree fruit grown for its small, sweet fruit. The fruit is a drupe and the edible portion is the ripened exocarp (skin) and mesocarp (flesh) of the ovary wall which surrounds the inedible endocarp (pit) which contains the seed. Cherries are dark red ('Bing'), light red ('Sweetheart') or yellow with a red blush ('Rainier'). High quality fruit is harvested mature and ripening and harvest index is primarily based on skin color (Mattheis and Fellman, 2004). Fruit must be cooled quickly and stored at −1–0°C at >95% RH where they will last from 2 to 4 weeks. Both controlled atmosphere and modified atmospheres can prolong storage life when applied to fruit that is not too mature. Fruit is stored at 1–5% O_2 at 5–20% CO_2 in controlled atmospheres and 5–10% O_2 with 5–15% CO_2 with MAP. Maintaining a temperature of 0–5°C is critical for MAP to prevent anaerobiosis. Cherries are not sensitive to chilling and produce little ethylene. However, exposure to exogenous ethylene leads to increased respiration and rapid quality loss. Cherries are prone to a number of postharvest disorders including pitting, bruising, and brown stem. Pitting of fruit is caused by tissue deterioration just below the skin. Bruising results from rough handling and brown stems develop from pedicels scraped during handling. All three maladies may not develop or may not be noticed until fruit reaches the consumer. Gentle handling and proper temperature and humidity control after harvest helps to minimize these problems. Cherries are extremely susceptible to postharvest decay, often by organisms that infect the fruit early in its development. Various pathogens are involved in cherry decay and may include one or more of the following organisms: blue mold (*Penicillium expansum*), gray mold (*B. cinerea*), *Alternaria* sp., brown rot (*Monilinia fructicola*), Rhizopus rot (*Rhizopus stolonifer*), *Cladosporium* sp., and *Aspergillus niger*. Fruit may split as they ripen, making them prone to infection just prior to harvest as well.

CITRUS (GRAPEFRUIT, LEMON, LIME, ORANGE) The fruit of *Citrus* species is a hesperidium, a modified berry that has a leathery, inedible rind that surrounds the edible segments that are filled with juice vesicles (Burns, 2004a, b). All citrus produce little ethylene and are non-climacteric with no postharvest ripening stage.

Grapefruit (*Citrus* × *paradisi*) are available in white and red cultivars. High quality fruit should be turgid with a smooth, blemish-free peel and a pleasant balance of SSC and acidity. When production regions experience warm night temperatures, grapefruit are exposed to 1–5 µl/l ethylene for 12 h to 3 days at 20–29°C depending on production region, to induce the destruction of chlorophyll in the peel. This process is called degreening. Degreening must take place under high RH (90–95%) and air exchange in the degreening room must ensure that CO_2 does not build up. After harvest and any necessary degreening, fruit should be stored at 5–8°C at 95% RH to minimize water loss and peel pitting around the oil glands. Under these conditions fruit will last up to 6 weeks with no decrease in quality. Waxes may be applied to fruit to minimize water loss. Controlled atmosphere storage of grapefruit is not common. Grapefruit exhibit chilling injury symptoms when exposed to temperatures lower than 5°C. Peel pitting not targeted around the oil glands is a classic symptom of chilling injury. Coating grapefruit with high-shine water wax can reduce chilling injury. Intermittent warming or stepwise lowering of the storage temperature can also reduce chilling injury. Granulation, drying of grapefruit segments, is common in late-harvested, larger fruit, especially those stored for long periods. If large fruit are harvested early in the season, granulation is less likely. Oleocellosis is a rind injury caused by rough-handling-induced disruption of oil glands. In particular, excessive force used during harvest or harvesting when fruit is particularly turgid (early in the morning or at high RH), can cause this problem. Symptoms often appear during storage as greenish or brown, firm irregular patches on the rind that soon darken and become sunken. Losses in storage caused by decay can be extensive. Decay may come from infection of fruits by organisms prior to harvest, for example anthracnose (*Colletotrichum gloeosporioides*) or brown rot (*Phytopthora citrophthora*), or by infection of wounds incurred during harvest and handling, such as green and blue mold (*Penicillium digitatum* and *Penicillium italicum*, respectively) and sour rot (*G. candidum*).

Lemons (*Citrus limon*) are grown for their tart, refreshing fruit that are used to enhance the flavor of many foods and to make refreshing beverages. High quality lemons should be uniformly well-colored, smooth, firm, with no defects and have a pleasant citrus aroma. Lemons are harvested when they have a juice content of 28–30% by volume (Gross and Smilanick, 2004). Lemons harvested green have a much longer storage life than those harvested yellow. Lemons should be stored at 7–12°C at between 85 and 95% RH with ventilation and away from products with strong odors, as lemons easily absorb them. Storage life varies with maturity at harvest, season, production area and specific storage conditions but can be up to 6 months. Controlled atmosphere storage is rarely used for lemons. Lemons are sensitive to chilling and should not be held at temperatures less than 10°C, although 3–4 weeks at 3–5°C during marketing is not harmful. Symptoms of chilling injury include skin pitting, interior discoloration, red blotch (a superficial browning of the rind), and loss of juice. Lemons produce little ethylene and exposure to exogenous ethylene can lead to accelerated quality deterioration during storage. Lemons harvested green are degreened by exposing fruit to 1–10 μl/l ethylene for 1–3 days at 20–25°C. Exposure of lemons to ethylene for degreening also accelerates quality loss.

Some postharvest physiological problems observed in lemons include oleocellosis (see grapefruit discussion), peteca, and membrane stain. Peteca is a pitting of the rind which begins in the white portion and develops into sunken, brown pits on the surface of the rind. Peteca appears to be caused by an imbalance of calcium and potassium in the rind. Membrane stain is a brown discoloration of the membranes between fruit segments and can be avoided by never storing fruit of susceptible cultivars below 13°C. Lemons are susceptible to the same decay-causing organisms as grapefruit.

Limes are divided into Persian limes (*Citrus latifolia*) and key limes (*Citrus aurantifolia*), with Persion limes being nearly seedless and key limes containing numerous seeds (Burns, 2004b). High quality limes should be turgid, appropriately sized, and colored a deep green (Persian limes) or greenish yellow (key limes) with at least 42% juice by volume. Limes are stored at 10°C and 95% RH for up to 8 weeks. Controlled atmospheres are not used for lime storage. Fruit produce little ethylene but are sensitive to exogenous ethylene showing loss of green color and accelerated quality decline. Fruit are susceptible to chilling injury exhibiting peel pitting. Oleocellosis can occur if fruit are harvested when fruit are very turgid. A major postharvest problem with limes is stylar-end breakdown, a general deterioration of fruit tissue integrity at the stylar end, often aggravated by high field heat or rough handling and often observed in larger fruit. Fruit are also susceptible to postharvest decay as described for grapefruit. Stem end rots may occur in both key limes (caused by *Diplodia natalensis*) and Persian limes (caused by *D. natalensis, Phomopsis citri*, and *Alternaria citri*).

Sweet oranges (*Citrus sinensis*) come in a wide variety of shape, sizes, and colors (Ritenour, 2004). Fruit may be spherical or oblong, seedless or seeded, green or light to dark orange in color. There are four generally recognized groups of sweet orange cultivars: (i) round; (ii) navel; (iii) blood; and (iv) acidless. High quality fruit should be mature, with a good, uniform color, smooth, and free of defects and decay. Maturity indices vary with region of production but generally include percentage color, SSC, TA, and sugar:acid ratio. Some indices also include a percentage juice by volume. While most commercial operations do not rapidly cool harvested oranges, doing so would improve fruit quality at the market. Most oranges are stored 'on the tree' and harvested as needed for the market. Fruit can be stored at 0–8°C at 85–95% RH for up to 12 weeks after harvest. Specific storage conditions and length of storage vary, depending on maturity at harvest, growing region, and cultivar.

Controlled atmosphere storage can prolong the maintenance of quality in oranges but is not often used because it does not reduce losses due to decay, the number one postharvest problem in oranges. Chilling injury may or may not be a problem depending on production region. For example, oranges produced in Florida or Texas rarely show chilling injury symptoms, while those grown in California or Arizona develop symptoms below 0–5°C. Symptoms include peel pitting, brown staining (external brown patches on the rind), and watery breakdown. Watery breakdown causes the fruit to look like it has been frozen then thawed and may develop several days after removal from storage. Oranges may be degreened by exposure to 5 μl/l ethylene gas for 1–3 days at 20–28°C.

Creasing of oranges is a postharvest deterioration of the white part of the rind (albedo) with the collapse of the overlying colored portion of the rind (flavedo) which leads to the appearance of creases on the skin of the fruit. Creases may split allowing decay organisms to enter the fruit. Thin-skinned, mature fruit are susceptible to this condition. Granulation, pitting, and oleocellosis (see grapefruit) are also major problems in orange. Physiologically over-mature fruit are subject to rind staining, the development of brown blemishes from abrasions on the skin. Stem-end rind breakdown appears as the breakdown of tissues at the stem end and is characterized by a small ring of unaffected tissue immediately surrounding the stem scar. Water loss from the fruit between harvest and storage or processing appears to cause this problem, thus rapid movement through packing or processing helps to alleviate this condition. Oranges are susceptible to postharvest decay by a number of organisms, making it the number one postharvest problem. Problems include green mold (*Penicillium digitatum*), blue mold (*Penicillium italicum*), Diplodia stem-end rot (*Diplodia natalensis*), Phomopsis stem-end rot (*Phomopsis citri*), brown rot (*Phytophthora citrophthora*), sour rot (*G. candidum*), and anthracnose (*C. gloeosporioides*).

CRANBERRY The cranberry (*Vaccinium macrocarpon*) is a perennial, woody, creeping evergreen related to the blueberry. Native to eastern North America, it produces a tart-flavored red fruit often processed into a beverage, dried to mimic raisins (craisins), or canned as a jellied condiment. Ninety-eight percent of the world's cranberries are produced in North America. High quality fruit are harvested as red as possible without over-maturity since only fruit with 75% red color are considered acceptable (Prange, 2004b). Cranberries are stored at 2–5°C at 90–95% RH for up to 4 months. Red color can be enhanced by holding fruit at 7–10°C for a few weeks before cooling. Controlled atmospheres are not normally used for cranberry storage. Cranberries are sensitive to chilling as storage at temperatures near 0°C leads to a rubbery texture and a dull appearance with increased decay. If fruit must be held at lower temperatures, intermittent warming to 21°C for a day every 30 days helps to alleviate some of the chilling injury. Cranberries produce little ethylene. Exposure to exogenous ethylene increases anthocyanin content, especially if fruit are exposed to light during exposure. Physiological breakdown of cranberries can occur in over-mature or senescing berries and is observed as a loss of sheen on the fruit, development of a rubbery texture, and diffusion of anthocyanin throughout the berry tissue.

CURRANT, GOOSEBERRY, AND ELDERBERRY Currants and gooseberries (*Ribes* spp.; gooseberries are sometimes identified as a separate genus, *Grossularia*) are closely related deciduous bushes bearing small berries that are mostly used for processing (Prange, 2004c). Currants may be red, white or pink (*Ribes sativum*) or black (*Ribes nigrum*). Gooseberries are greenish yellow to pink to very dark, nearly black, depending on cultivar and ripeness at harvest. Elderberries (*Sambucus canadensis* L.) are mostly harvested from wild stands with only limited commercial production. The small, bluish-black berries are processed since uncooked fruit is quite astringent and inedible. Currants and elderberries are produced in clusters and high quality fruit should be harvested as ripe (determined by color), large, uniform clusters, free of decay or injury. Black currants may be harvested as individual berries since the cluster does not ripen uniformly. Gooseberries are harvested as single berries either immature (very firm and tart) or ripe (soft and often very sweet), depending on final use. Elderberries ripen over time and must be harvested over a 2 week period in late summer. Fruit should be quickly cooled after harvest and stored at –0.5–0°C at 95% RH for 1.5, 2.5, and 3 weeks for black currant, red currant, and gooseberry, respectively. All three berries are not chilling sensitive. Red currants and gooseberries can be stored under controlled atmospheres of 10–20% CO_2 and 1.5–2% O_2 (depending on species and cultivar) at 1°C to prolong shelf life up to 8–14 weeks. Black currant does not respond to controlled atmosphere storage and no information is available for elderberry.

GRAPES (TABLE AND AMERICAN) The table grape (*Vitus vinifera*) is grown for berries that are harvested in clusters when a minimum SSC is reached and acceptable cultivar-dependent color has developed (Crisosto and Smilanick, 2004). 'Thompson Seedless' is probably the most well-known table grape cultivar. The American grape (*Vitis labrusca*) is grown in regions where *V. vinifera* grapes will not survive low winter temperatures (Perkins-Veazie, 2004d). 'Concord' is a well-known cultivar, along with 'Catawba', 'Delaware', 'Niagara', 'Venus', 'Himrod', and 'Reliance'.

Table grape berries should be firm and clusters well filled with a minimal, cultivar- and market-dependent SSC. Fruit should be cooled as quickly as possible to –1–0°C and SO_2 (100 µl/l for 1 h to control gray mold during storage) applied. Pads soaked in sodium metabisulfite are often used in packing flats to generate additional SO_2 during storage and shipping. Fruit should be stored with moderate airflow (20–40 ft^3/min/t of grapes) at 90–95% RH. Well-handled fruit can be stored for 1 to several months. Controlled atmospheres are not used for storing table grapes, they are not chilling sensitive, produce little ethylene, and are not sensitive to exogenous ethylene.

A major postharvest problem of table grapes is berry shattering, or abscission of individual berries from the cluster. Many table grapes are treated with gibberellic acid at fruit set which weakens the pedicel-berry bond, making the cluster more susceptible to shattering. Rough handling during harvest, packing and shipping increases the incidence of shattering.

Another postharvest disorder of table grapes is called waterberry. It develops soon after verasion (color change of the berries during ripening) as small dark spots on the cluster stem. Berries soon become watery and soft. Waterberry seems to be related to excessive nitrogen fertilization, canopy shading or cool weather during ripening.

GRAPE (MUSCADINE) Muscadine grapes (*Vitis rotundifolia*) are grown in the south-eastern USA and differ from table and American grapes in that they grow singly or in small clusters and are harvested as individual berries, have larger berries, and are uniquely flavored. Berries are harvested when they readily detach from the stem and have an SSC of 14–18% (Perkins-Veazie, 2004e). Fruit are either bronze colored or black. Fruit are cooled as quickly as possible and stored at –0.5–0°C at >90% RH for 1–4 weeks. Muscadines are not chilling sensitive, produce little ethylene, and are not affected by exogenous ethylene. Gray mold (*B. cinerea*) growth may be stimulated by ethylene.

KIWIFRUIT There are a number of edible kiwifruit species worldwide, but by far the most common edible species is *Actinidia deliciosa* (Rushing, 2004c). This is the common egg-sized, fuzzy brown-skinned, green-fleshed kiwifruit. The fruit is a berry with hundreds of dark black seeds embedded in the bright green flesh. A yellow-fleshed fruit of *A. chinensis* is becoming popular as well. High quality kiwifruit at harvest should be firm, free of defects and have a minimum of 6.5% SSC. After harvest, many kiwifruit are cured for up to 48 h at ambient temperatures to allow the stem scar to dry in an attempt to minimize decay in storage. Once cured, fruit are stored at 0°C at 90–95% RH for up to 5 months. Chilling injury has been reported at temperatures near 0°C. Symptoms include a zone of water-soaked tissue in the outer pericarp at the stylar end of the fruit, skin pitting, and scalding. Curing fruit before storage seems to alleviate the occurrence of chilling injury. Kiwifruit are well suited for controlled atmosphere storage at 1–2% O_2 plus 3–5% CO_2 at 0°C which prolongs storage life to 6 months without the fruit softening often experienced with cold storage in air. Mature, non-ripe kiwifruit produce very little ethylene, however, fruit are extremely sensitive to exogenous ethylene at levels as low as 5 parts per billion. This low level of ethylene can induce softening without ripening. Higher levels of ethylene induces ripening, thus storage facilities must be kept free of any ethylene gas. Kiwifruit suffers from a postharvest disorder called hard core, which occurs when the flesh softens rapidly and appears water soaked during storage but the core remains hard and tough. Hard core may be caused by high levels of CO_2 coupled with exposure to ethylene. Ethylene in controlled atmosphere storage can induce distinct white patches in core tissues that are very obvious in ripe fruit. This problem may develop as soon as 3 weeks after harvest. Kiwifruit are susceptible to gray mold (*B. cineria*), blue mold (*Penicillium expansum*), and Phompsis rot (*Phomopsis actinidiae*).

MELONS

WINTER MELONS Winter melons (*Cucumis melo* Inodorus Group) include honey dew, casaba, crenshaw, and canary melons grown for their sweet, melting or crisp, white, light green or pink flesh. All melon types should be firm, well sized and shaped, and free from defects when harvested (Lester and Shellie, 2004). Honey dew melons should be harvested when fruit have a waxy appearance and is whitish to very light green in color. Standard honey dew melons do not slip (abscise with gentle force) when ripe and are cut from the vine when mature, but not necessarily ripe. Hybrid honey dews will slip from the vine and are mostly harvested when ripe. Casaba melons are harvested when fruit are very furrowed and yellow and the blossom end yields to slight pressure. Crenshaw melons are ripe when half of the dark-green skin has turned yellow, the blossom end yields with light pressure and a pleasant aroma is released at room temperature. Fully yellow-skinned crenshaw melons are overripe and not pleasant to eat. Canary melons are ripe when the skin is bright yellow and the blossom end yields to slight pressure. The flesh is crisp and fragrant when ripe.

Honey dew melons cut from the vine and all other mature, but not ripe, melons in this group are not cooled after harvest and are stored at 10°C at 90–95% RH for up to 3 weeks. Honey dews that are harvested full slip, those harvested cut from the vine and induced to ripen with ethylene, and all other ripe melons can be held at 7°C at 95% RH for 7–10 days. All mature, but not ripe, melons produce little ethylene, but benefit from a treatment with ethylene after harvest to induce ripening and promote higher quality. Mature, but not ripe, melons are susceptible to chilling injury at 7°C and sensitivity decreases as fruit ripens. Chilling injury appears as pitting or elongated lesions on the rind. All melons are susceptible to bruising and compression injury, thus they should not be bulk stored, but rather packed in smaller, suitable containers.

NETTED MELONS Muskmelons (*Cucumis melo* Reticulatus Group) are grown for their orange, melting, fragrant sweet flesh that is surrounded by a rind with a raised netted epidermis. Cantaloupes (*Cucumis melo* Cantaloupensis Group) are non-netted and much less common than muskmelons (Shellie and Lester, 2004). Muskmelons are often categorized as Western shipper melons, grown primarily in the south-western USA, and Eastern Choice melons, grown for local consumption, generally in the eastern USA. Eastern Choice melons are highly sutured while Western shipper melons are not. French Charentais melons are small, round, gray-green skinned, slightly netted melons with prominent dark-green longitudinal stripes. Galia melons have a very fine uniform netting and green flesh. Ananas melons have sparse cracked netting with white, very sweet flesh. Persian melons are very similar to Western shipper melons, but are much larger and have an orange-pink flesh.

All melons in this group must be harvested sufficiently mature to ensure ripening after harvest. Maturity is judged by skin under color and stem slipping. Most of these melons are harvested when half of the stem attaching the melon to the vine has separated from the melon. This is called the half-slip stage. These melons are never cut-harvested as they will not soften or develop sufficient aroma and sweetness if harvested before half slip. Netted melons are cooled after harvest and stored at 2–7°C at 95% RH for 10–14 days. Chilling injury may develop in mature unripe fruit at <2°C. Symptoms include rind pitting and a failure to ripen properly when moved to room temperature. Sensitivity to chilling injury decreases as fruit ripen. Netted melons are climacteric and begin producing elevated levels of ethylene around 4 days prior to stem slip continuing up until about 10 days after harvest. Exposure to exogenous ethylene should be avoided as it reduces storage life. Melons harvested prematurely cannot be induced to ripen with ethylene. Melons are susceptible to sunburn which can cause a bronze coloration of rind under color and net discoloration. Melons are also susceptible to bruising and compression injury.

WATERMELON Watermelon (*Citrullus lanatus*) is a cucurbit producing fruit which come in a wide variety of shapes, sizes, and flesh colors. Fruit may be small and round to large and oblong with light green to almost black skin that may or may not be marbled or striped. Flesh colors may be dark red, pink, yellow and orange and fruit may be seeded or seedless. The fruit consists of a thin rind with a white-fleshed inner rind that is about 2 cm thick, all enclosing the edible flesh which should be crisp, sweet, highly flavored and juicy (Rushing, 2004a). Watermelons should be harvested ripe. Indices for harvest include: (i) a change in the ground color from white to yellow; (ii) drying of the tendril(s) opposite the fruit; and (iii) a change in the rind appearance from glossy to dull. Ripe melons also produce a dull, hollow sound when thumped compared with a brighter, more metallic ring of unripe fruit. In general, watermelons are not pre-cooled and are stored at 10–15°C at 90% RH for 2–3 weeks. Chilling injury of watermelons can occur at temperatures <10°C and appear as rind staining, rind pitting, loss of flesh color and flavor, and increased decay once returned to non-chilling temperatures. Watermelons produce very little ethylene and are extremely sensitive to exogenous ethylene. As little as 5 ppm ethylene can induce rind softening, rind thinning, flesh color fading, and mealiness.

OLIVE Olives (*Olea europa*) are grown for their small, oily drupe, of which the fleshy mesocarp is consumed or pressed to extract the oil (Crisosto and Kader, 2004d). Fruit may be harvested mature green or ripe (purple turning black) for processing as fermented olives or oil extraction. Ripe olives generally have an oil content of 12–25% depending on the cultivar. Green fruit are harvested when they achieve a uniform color with very few white lenticels showing and they extrude a white juice when squeezed. Ripe olives are harvested based on skin color and removal force generally 3–4 months after green olives are harvested. Over-ripe fruit bruise easily and are subject to decay. Fruit sunburn easily and should be protected after harvest. Ripe fruit should be processed immediately. Fruit can be stored for a short time at 5–7.5°C with 90–95% RH. Storage in a controlled atmosphere consisting of 2–3% O_2 with 0–1% CO_2 can prolong storage of fresh green olives up to 12 weeks. Green olives are subject to chilling injury at <5°C. Injury symptoms appear as a brownish discoloration near the pit which becomes more intense with time and progresses through the rest of the flesh until the fruit eventually looks like it has been cooked. Both green and ripe olives produce little ethylene. Both are susceptible to injury from exogenous ethylene which is manifest as a loss of green color in green olives and a loss of flesh firmness in either type. Nailhead is a postharvest disorder caused by storage of fruit at 10°C for >6 weeks or at 7.5°C for >12 weeks. It appears as surface pitting and spotting.

PEACH AND NECTARINE Peaches (*Prunus persica*), native to China and Persia, are one of the 'summer fruits' prized for their sweet, tender flesh with a bright, fresh flavor. Nectarines (*Prunus persica*) were probably derived from peaches and are grown nearly anywhere peaches are grown (Crisosto and Kader, 2004a, b). The best peaches and nectarines have a high sugar content (at least 11% SSC) with slight acidity (less that 0.7% TA) (Crisosto and Kader, 2004a, b). Nectarines have slightly higher TA than peaches. Since they are rather delicate when ripe, fruit are harvested mature and allowed to fully ripen off the tree. Harvest is based on a change in skin ground color from green to yellowish. Fruit firmness is also a measure used to determine 'firm mature' fruit ready for harvest (27–36 N/cm^2) or 'tree ripe' fruit (9–14 N/cm^2) and varies considerably among cultivars. Fruit should be cooled as quickly after harvest as possible and cooled to −1–0°C with 90–95% RH with good ventilation where they will store for 2–4 weeks with minimal loss in quality. Color retention and fruit firmness can be enhanced with controlled atmosphere storage of 6% O_2 plus 17% CO_2 at 0°C. Peaches are climacteric, thus ethylene evolution depends on ripening stage. Fruit are sensitive to exogenous ethylene, as it will induce ripening in mature fruit.

Peaches are susceptible to chilling injury at all recommended storage temperatures, but especially if stored at 2.2–7.6°C, thus they should be marketed as quickly as possible. Chilling injury appears as internal breakdown of the flesh. Internal breakdown seems to affect nectarines less than peaches, however, it is still a major postharvest problem. Internal breakdown is characterized as dry, mealy or woolly flesh or translucent flesh radiating from the pit. Flesh may alternately be hard textured. Intensely red-colored flesh radiating away from the pit ('bleeding') is another symptom. Flavor is often compromised before any symptoms are visible. Another postharvest problem called 'inking' is a superficial skin discoloration caused by abrasions and heavy metal contamination (iron, copper, aluminum) of cooling or wash water which appears 24–48 h after harvest. Peaches are susceptible to postharvest rots, particularly brown rot, caused by *M. fructicola*. Infection begins during flowering and rot may occur anytime thereafter. Fruit are also susceptible to gray mold (*B. cinerea*) and Rhizopus rot (*R. stolonifer*).

PEAR (EUROPEAN) The European pear (*Pyrus communis*) is a member of the family *Rosaceae*. The edible portion of the fruit is the enlarged, fused bases of the calyx, corolla, and stamens. Pears are harvested mature and must be exposed to 2–8 weeks of cold storage at −1°C to induce ripening upon removal to 20°C. The length of cold storage needed to induce ripening at 20°C varies with cultivar and ripening will occur in 4–7 days at 21°C. Fruit that is harvested before they are mature are susceptible to superficial scald, water loss, and skin discoloration due to rubbing against other fruit or the storage container. Superficial scald does not appear in storage, but rather is a patchy discoloration of the skin which occurs after removal from storage for ripening. Eating quality is not affected, however, the fruit are visually unappealing. Fruit harvested 'over-mature' tend to develop core breakdown and CO_2 injury. Fruit firmness is the best indicator of maturity (Chen, 2004). Heat unit accumulation during 9 weeks following bloom provides a good estimate of harvest date. Fruit are extremely sensitive to storage temperature with fruit stored at −1°C lasting 30–40% longer in storage than those stored at 0°C. Fruit should be stored at >90% RH to prevent dehydration. Controlled atmosphere storage at 2–2.5% O_2 with 0.8–1% CO_2 can prolong storage life. Once appropriately chilled pears are brought to ripening temperatures, autocatalytic ethylene production commences and ripening occurs. If fruit are not chilled correctly, ethylene production will not commence and fruit will fail to ripen. Inadequately chilled fruit may be induced to ripen if exposed to exogenous ethylene.

Pithy brown core is a postharvest malady affecting 'd'Anjou' pears exposed to elevated CO_2 levels. Pithy, brown areas develop near the core of the fruit and may extend into the surrounding flesh. The tissues are dry and pithy, not soft and watery like that which develops from core breakdown. Core breakdown is characterized by softening and tissue breakdown near the core. Initially the tissue is soft and watery but eventually turns brown. Low O_2 levels in controlled atmosphere storage can lead to brown speck in 'd'Anjou' pears. It appears as brown specks on the skin. Senescent scald may affect any pear cultivar. It develops in cultivars that senesce during storage which leads to an inability to ripen once removed from storage. Additionally, yellow, then brown discoloration of the skin occurs, the fruit are inedible, will not ripen, and the skin easily slips off the fruit. To prevent senescent scald, fruit must be removed from storage before it begins to develop.

PINEAPPLE The pineapple (*Ananas comosus*) is a tropical, multiple, aggregate fruit. High quality fruit should have flat eyes (the individual fruitlets), and fresh, green crown leaves. Fruit is harvested based on eye flatness and SSC which should be at least 12% (Paull and Chen, 2004a). Consumers also look for nicely colored fruit (yellow ground color with slight green over color) and rich, fruity aroma. Fruit do not ripen once harvested. Fruit are susceptible to chilling injury below about 7°C and are generally stored between 7 and 12°C at 85–95% RH for 7–10 days. A major symptom of chilling injury is internal browning. Fruit are susceptible to sunburn in the field and to bruising at any point during handling. Fruit produce little ethylene and are generally insensitive to exogenous ethylene exposure.

PLUM AND FRESH PRUNE Japanese plums (*Prunus salicina*) are usually eaten fresh or as jam or jelly while European plums (*Prunus domestica*) may be eaten fresh but are most often dried whole into prunes (Crisosto and Kader, 2004c). High quality fruit of either type of plum has a high SSC, acceptable TA, and minimal astringency. Plums are often harvested based on skin color changes, increases in SSC and a decrease in flesh firmness. Plums should be cooled to −1–0°C and stored at 90–95% RH under well-ventilated conditions where they will last for 4–6 weeks. Controlled atmosphere storage at 1–2% O_2 and 3–5% CO_2 helps prevent flesh softening and undesirable changes in ground color. Most plums are susceptible to chilling injury when stored at 5°C but not when stored at 0°C (Crisosto and Kader, 2004c). Chilling injury symptoms usually appear when fruit is moved to warmer temperatures for ripening and appears as translucent flesh which soon browns. Lack of juiciness may also develop in late-season cultivars. Flesh translucency is also called gel breakdown. Ethylene gas production depends on the stage of ripeness and exogenous ethylene will induce ripening in all plums. Internal browning not associated with chilling injury is caused by high temperatures during fruit maturation and delayed harvest. Plums are susceptible to postharvest rots such as brown rot (*M. fructicola*), gray mold (*B. cinerea*), and Rhizopus rot (*R. stolonifer*).

POMEGRANATE The pomegranate (*Punica granatum*), also called the Chinese apple, requires a long, hot summer for production. It is very tolerant of cold, drought and salt stress (Pekmezci and Erkan, 2004). The fruit is round with a prominent calyx and a hard, leathery skin. A bright red pulp (aril) surrounding the edible seed is consumed directly or processed into juice. The white, leathery membrane separating layers of seeds is not edible and may be somewhat bitter and astringent. High quality fruit must have a blemish-free, nicely colored skin and juicy arils surrounding small seeds. All pomegranates are harvested fully ripe. The acid:sugar ratio of the juice must meet market requirements and varies with cultivar. Pomegranates are 45–65% juice and the skin contains up to 30% tannins which can be used in medical or dye industries. TA varies with cultivar: (i) <1% in sweet cultivars; (ii) between 1 and 2% in sweet-sour cultivars; and (iii) >2% in sour cultivars. SSC ranges from 8 to 20% depending on cultivar. Pomegranates are susceptible to chilling injury below 5°C and most cultivars are stored at around 6°C at 90–98% RH to prevent dehydration. Chilling injury is observed as pitting and brown discoloration of the rind, brown discoloration of the membrane separating arils, and pale-colored arils. A controlled atmosphere of 3% O_2 with 6% CO_2 reduces loss of TA and vitamin C. Fruit can be stored for up to 6 months. Fruit produce little ethylene and are not sensitive to exogenous ethylene.

PUMPKIN AND WINTER SQUASH There are three species in the family *Cucurbitaceae* that are grown for their fruit which is harvested physiologically mature: (i) *Cucurbita pepo* (pumpkin and acorn squash); (ii) *Cucurbita maxima* (winter squash and giant pumpkin); and (iii) *Cucurbita moschata* (butternut squash, crookneck squash, and calabaza) (Brecht, 2004a). Fruit are harvested physiologically mature in the fall and many can be stored for many months with no loss in quality. Fruit are harvested when the rind has become hard and has lost is sheen, the fruit has just begun to abscise from the plant, the ground spot of the fruit has become yellow, and tendrils nearest the fruit on the vine have turned brown. Fruit should be harvested when mature, based on these characteristics and not based on vine death. Quality improves more in storage than on the vine once fruit is mature.

Fruit are stored for several months at 10–13°C at 50–70% RH with good ventilation. Chilling injury can occur at temperatures <10°C and appears as skin pitting and a loss of flavor as well as accelerated development of rots when returned to non-chilling temperatures. Fruit produce little ethylene. Exposure to exogenous ethylene may lead to yellowing of green fruit and stem abscission. While curing of pumpkins and winter squash at 24–27°C for 10–20 days before storage to harden the rind is often recommended by some authorities, it is not beneficial and may actually reduce eating quality of some cultivars (Brecht, 2004a).

RASPBERRY Raspberries (*Rubus ideaus*) are soft, sweet, juicy succulent fruits that are grown in many areas of the world. While their root systems are perennial, their fruit-bearing shoots are either annual (primocane fruiting cultivars) or biennial (floricane fruiting cultivars). Raspberries are available in red, yellow, black, and purple cultivars. Red and yellow raspberries are divided into two subspecies, *Rubus ideaus* subsp. *vulgatus*, the European red raspberry, and *Rubus ideaus* subsp. *strigosis*, the American red raspberry. Black raspberry cultivars may be *Rubus occidentalis* (North American black raspberry) or *Rubus glaucus* (a South American tetraploid black raspberry). Purple raspberries (*Rubus neglectus*) are hybrids of red and black raspberries (Perkins-Veazie, 2004c). Fruits are composed of numerous drupelets attached to a common receptacle which remains on the plant when fruit is harvested. Harvested fruit is thimble-shaped with a hollow center, making it extremely delicate.

High quality fruit are fully colored, regularly shaped, firm and free of defects and decay. Sunscald (individual whitish drupelets) caused by excessive UV radiation can be a problem in raspberries. Fruit are harvested ripe and are easily removed from the plant with little force when ready to pick. Fruit should be cooled rapidly and are stored for no more than 2–5 days at –0.5–0°C at >90% RH. Raspberry deterioration is reduced under controlled atmosphere storage in 10–20% CO_2 with 5–10% O_2. Levels of CO_2 greater than 20% can induce softening, discoloration, and development of off-flavors. Raspberries are not chilling sensitive. Ethylene production varies with cultivar and exposure to exogenous ethylene can stimulate gray mold (*B. cinerea*) growth and cause darkening of red raspberries.

STRAWBERRY The strawberry (*Fragaria × ananassa*) is a perennial that is often grown as an annual for its fruit which consists of many achenes (the botanical fruit, often called seeds) on a common swollen receptacle that becomes sweet and turns red when ripe (Fig. 16.7). Fruit should be harvested as ripe as possible since fruit does not ripen after harvest (Mitcham, 2004). Harvest of strawberry is solely based on color. Fruit should be firm, well colored, sized and shaped for the cultivar, with the calyx attached at harvest. Fruit must be cooled immediately upon harvest to 0°C and stored at 90–95% RH for up to 7 days. Modified atmospheres of 10–15% CO_2 are often used during shipping to reduce decay and fruit respiration, with whole pallets of fruit covered and treated. Strawberries are not chilling sensitive, produce very little ethylene, and are not sensitive to exogenous ethylene. Reduction in storage-room ethylene may reduce decay by reducing *Botrytis* growth. If >15% CO_2 is used during MAP, skin may take on a bluish caste, fruit flesh may turn white, and off-flavors may develop.

TOMATO The tomato (*Solanum lycopersicum*) is grown worldwide for its fruit (a berry) which is eaten fresh or cooked in various ways. Tomatoes come in many colors (red, yellow, ivory, purple) and shapes (cherry, plum, grape, mini-pear, slicing, and beefsteak). Tomatoes are harvested at any stage from physiologically mature to fully ripe, and should be firm, turgid, uniform in color, and shiny with no defects. Mature fruit can be ripened off the vine. Most tomatoes are field grown, however, significant greenhouse production occurs in Canada, Holland, Spain, and Israel.

It is often difficult to determine the physiological maturity of tomato (Sargent and Moretti, 2004), but it is often based on the color of seeds, amount of gel in the seed locule, and the color of any gel in the seed locule. Only tomatoes that are harvested when all locules contain gel and the seeds are pushed aside when sliced through the equatorial

Fig. 16.7. Strawberries (*Fragaria* × *ananassa*).

plane will ripen to the highest quality. Fruit that are less mature than this stage will not ripen to very good quality. Ripeness stages are often defined by skin-color transformation from totally green to fully red.

Tomatoes should be cooled to 12°C for storage or 20°C for ripening, both at 90–95% RH. Controlled atmosphere storage is feasible with 3% O_2 plus 2% CO_2. Exact storage conditions often depend on cultivar and stage of maturity and ripeness at harvest. Prolonged storage may lead to the production of off-flavors. Fruit are sensitive to chilling at temperatures less than 10°C, depending on the cultivar and the stage of ripeness. Symptoms of chilling injury include surface pitting, non-uniform ripening, and increased storage rots. Tomatoes produce significant amounts of ethylene and are also sensitive to exogenous ethylene, which will induce ripening of mature fruit. Fruit are often ripened with ethylene gas at the marketing stage.

Tomato fruit are susceptible to a number of physiological problems. Blotchy ripening is the development of green and yellow patches on the surface of red tomatoes. Sunburn results from elevated fruit temperatures during development caused by excessive fruit exposure to light during fruit development. This disrupts lycopene synthesis and leads to the development of yellow areas in affected skin and fleshy tissues which remain even after ripening. Blossom end rot results from poor calcium uptake of insufficient translocation into developing fruit. This leads to the development of dry, dark-brown discolored patch at the stylar end of green fruit which eventually is colonized by decay-causing organisms. Graywall is observed as necrotic vascular tissue in the pericarp wall. The problem starts in green fruit and seems to result from trying to grow tomatoes under marginal conditions or to be a response to tobacco mosaic virus or a bacterial infection. Internal bruising caused by rough handling of green fruit is observed as impaired ripening in locular gel and leads to a reduction in vitamin C content, a reduction in acidity, and a reduction in total carotenoids, and an unacceptable consistency with the development of off-flavors. Tomatoes are susceptible to many bacterial and fungal rots that may begin in the field or greenhouse and carry through into storage, thus good sanitation at every stage of processing must be practiced.

Mature or immature fruits

COCONUT The coconut (*Cocos nucifera*) is consumed at two different stages of development. Immature coconuts (6–9 months after flowering) are harvested for their liquid endosperm (coconut water) and jelly-like meat while mature coconuts (12 months after flowering) are harvested for their water as well as their hardened, white endosperm (Paull and Ketsa, 2004). Well-developed nuts are harvested at the appropriate stage for their use. Immature fruit are harvested when the short stem that held the male flower on top of the coconut (called the rachillae or rat's tail) is half browned and the coconut skin around the calyx is creamy white or yellowish. Mature fruit are characterized by a totally brown rat's tail and skin that is turned brown. Both immature and mature coconuts are husked to varying degrees after harvest. The immature nut is partially husked while the entire husk is removed from mature nuts. Mature coconuts with husks intact can be stored at ambient temperatures for 3–5 months before the liquid endosperm has evaporated, the shell has cracked, or the nut has sprouted. Young, husked and wrapped coconuts are held at 3–6°C at 90–95% RH for 3–4 weeks. Unwrapped nuts displayed at ambient temperatures will last 1–2 days. Treatment with sodium metabisulfite reduces browning of young, husked coconuts and may prolong shelf life by several days. Immature coconuts are chilling sensitive, with their green skins turning brown after 7 days at 0°C. Other quality attributes are unaffected by chilling. Coconuts produce very little ethylene and are not sensitive to exposure to exogenous ethylene. Mechanical damage, water loss, and mold growth are the most common postharvest problems associated with both immature and mature coconuts.

PAPAYA Papaya (*Carica papaya*) is a tropical fruit that can be eaten either green or ripe. High quality fruit should be appropriately sized for a given cultivar, with a smooth skin free from blemishes (Zhou *et al*., 2004). Fruit destined for Western countries should not have the heavy, musky aroma associated with some South-east Asian cultivars. For fresh consumption as a sweet fruit, papayas should be harvested after ripening has commenced and the fruit has at least 11.5% SSC and some skin has yellowed. After harvest, fruit should be cooled and stored at 7–13°C at 90–95% RH. Chilling injury may occur at 7–10°C while fruit continue slow ripening at 10–13°C. Fruit that have just begun to ripen can be stored at 7°C for up to 14 days without chilling injury. Ripe fruit can be held at 1–3°C for a week or so. The more immature the fruit, the greater is its susceptibility to chilling injury, which is manifest as skin scald, water soaking of flesh, and the development of lumps around the vascular tissue in the flesh. Controlled atmosphere storage is not utilized in papaya production. Papayas produce some ethylene as they ripen from the inside out. Exogenous ethylene is not recommended to induce ripening as it causes ripening from the outside inwards, which leads to undesirable excessive fruit softening. Fruit may develop green, slightly sunken areas when ripe that result from abrasion injury to the fruit when green. Small brown, raised skin freckles may develop on sun-exposed fruit after a period of cool, rainy weather. The fruit skin may also show scald if exposed to sun either before or after harvest. Premature ripening may occur in fruit with low calcium levels.

PEPPER Peppers (*Capsicum annuum*) are generally known as bell peppers and chili peppers (González-Aguilar, 2004). Bell peppers are harvested either immature or allowed to mature and ripen turning red, yellow, orange, gold, brown, or purple. Ripe fruit are generally sweeter than immature fruit and often have a less intense characteristic pepper flavor of immature fruit. Chili peppers are varied in shape, size, and color and may be mild to very hot. They are harvested ripe and may be consumed fresh or dried. After harvest, peppers can be stored at 7–13°C at 90–95% RH for 2–3 weeks. Chilling injury occurs at <7°C and appears as surface pitting, seed-cavity discoloration and water soaking of flesh. Ripe peppers are less sensitive to chilling than green peppers. Peppers are non-climacteric and produce little ethylene. Exposure to exogenous ethylene causes flesh softening and increased respiration but not color change. Peppers are susceptible to blossom end rot, similar to that observed in tomatoes, which is caused by a calcium deficiency in the developing fruit.

Floricultural products

Fresh-cut flowers and greens

Many different species are harvest for cut flowers and the greens that often accompany them (Fig. 16.8). Species include ferns and lycopods, angiosperms and gymnosperms (Reid, 2004). Postharvest quality of these products is 100% visual and the harvested commodity often consists of more than one plant organ. For example, a long-stem rose consists of a stem, leaves, and a flower bud, each contributing to the quality of the commodity. Imperfections in one or more of these organs greatly detract from its value. The main characteristics that result in reduced quality of cut flowers and greens include: (i) senescence of flowers and leaves; (ii) wilting; (iii) tropic responses; and (iv) shattering or loss of petals and leaves.

Wilting is a major cause of reduced quality. Wilting usually is caused by the obstruction of the vascular tissue after harvest by bacteria, dirt, or an air embolism. Most cut commodities should be stored at >95% RH at low temperatures to minimize water loss during storage. Sugars released into the vase water from cut stems provide an ideal growing environment for bacteria, yeast, and other fungi. Metabolic products from these organisms or the organisms themselves can plug the xylem of the commodity, effectively preventing uptake of the vase solution, causing wilting. In order to prevent growth of such organisms, care must be taken along the supply chain to prevent contamination of the commodity with these organisms and to prevent the establishment of a favorable environment for their growth and development. Clean water should always be used in making storage solutions and a biocide should be part of the solution recipe. All containers and utensils should be routinely disinfected.

Dissolved minerals in water often make the storage solution alkaline which greatly reduces water uptake by most commodities. Either water free

Fig. 16.8. Sunflowers (*Helianthus annuus*) ready for harvest.

from dissolved minerals or acidified water should be used to ensure that the storage solution is acidic. Citric acid is often used to acidify cut flower solutions. Certain chemicals often found in tap water are often toxic to many cut ornamentals. Sodium, which is often found at high levels in 'softened' water, is toxic to carnations and roses while fluoride, often found in drinking water, is toxic to gaillardia, gerbera, gladiolus, roses, and freesia.

An air embolism is a small bubble of air that becomes trapped in a xylem vessel, preventing water movement. They often occur at the time of cutting. These obstructions can be removed by: (i) cutting stems under water; (ii) ensuring that the storage or vase solution is acidic (pH 3–4); (iii) heating the solution to 40°C or cooling it to 0°C; (iv) placing stems in >20cm of water; or (v) briefly immersing stems (10 min) in a 0.02% (v/v) detergent solution.

Flower and leaf senescence is another major cause of reduced vase life. Leaf yellowing and senescence is also detrimental to quality, especially in crops such as *Alstroemeria, Chrysanthemum*, and marguerite daisy (*Argyranthemum frutescens*) where leaves are an important part of the floral display (Reid, 2004). Shattering of flower petals, leaves, and even branchlets leads to reduced product quality. It is often caused by exposure to ethylene.

One of the main physiological considerations in determining the vase life of cut flowers and greens is their food supply after harvest. Sugars and starch stored in the various commodity parts supply the food needed for continued development (usually flower opening) and metabolic maintenance. Many floricultural crops are harvested early in the day to allow for postharvest processing. This is unfortunate since food reserves are often at their lowest early in the day. To compensate for this, many cut flowers are fed a sugar solution at low temperatures for as long as 24 h immediately after harvest. Leaf yellowing is probably related to a reduced carbohydrate status in the cut commodity.

Spike-type flowers such as gladioli and snapdragon are particularly susceptible to reduced quality from geotropism. To prevent unwanted geotropic bending of flower spikes, always store spikes upright whenever possible. Spikes will bend upwards if stored horizontally.

As with all other horticultural commodities, cut flowers and greens have harvest indices for maximizing storage life. Many cut flowers are harvested in the bud stage, but at a point where the buds are developed enough so that they will fully open upon display. Some are harvested when buds are just starting to open (*Rosa, Gladiolus*) while others are harvested when flowers are nearly fully open

(*Chrysanthemum, Dianthus*). Cut foliage is harvested when the youngest leaf is fully expanded.

Flowers are often graded based on the weight of a given stem length or simply stem length of the cutting. Weight of a given stem length is often positively related to the quality of flower(s) the stem holds. Stem straightness and freedom of the cutting from any defects are also used in grading schemes. Most flowers are sold in bunches of five, ten, 12 or 25 stems. Specialty flowers such as members of the family *Orchidaceae*, and *Zingiber, Strelitzia, Anthurium*, and *Helianthus* are often sold singularly or in smaller bunches.

All cut flowers except those that are chilling sensitive (*Anthurium, Zingiber*, tropical orchids, *Strelitzia*) should be cooled as quickly as possible after harvest and stored at 0–1°C. Chilling-sensitive species should be cooled and held at 10°C. Chilling injury may be observed as darkened leaves and petals or water-soaked petals. Most flowers should be stored at 95–99% RH.

Most cut flowers are sensitive to ethylene gas. Exposure to even small amounts of ethylene often hastens senescence. Some flowers produce ethylene as they age and senesce (*Dianthus*) while others produce very little ethylene themselves (*Antirrhinum*) yet are very sensitive to exogenous ethylene and shatter quickly upon exposure to even very low levels of ethylene. Many cut flowers are treated with anionic silver thiosulfate or 1-MCP to inhibit ethylene's effects. Storage at the proper temperature minimizes ethylene production and sensitivity to ethylene.

Controlled atmosphere storage is not normally employed in the cut flower industry (Reid, 2004).

Potted flowering, foliage, and bedding plants

POTTED FLOWERING PLANTS Flowering potted plants are an important commodity in horticulture. Specimens are often greenhouse-grown then shipped to their point of sale, often hundreds, even thousands of miles away from the site of production. Only the highest quality plants should be shipped as they will often have to endure low light, poor ventilation, harmful gases, and excessive vibrations during transit.

Quality of flowering potted plants is based on flower longevity and leaf quality. Maintaining vibrant flowers and green foliage at the same time for an extended period is not an easy task when plants are subject to the stresses of shipping mentioned above. Additionally some species are cold tolerant while others are chilling sensitive. Sensitivity to ethylene also varies considerably among species.

Production practices may greatly influence flower longevity and leaf color. Excessive fertility leads to poor flower longevity. For example, *Chrysanthemum* fertilization is halted 3 weeks prior to marketing with a concomitant increase in flower longevity of 7–11 days (Nell, 2004a). Excessive watering during the final 2 weeks of potted rose (*Rosa* spp.) production leads to significant losses during shipment due to damage to the root system.

During shipping losses can occur due to: (i) disease; (ii) incorrect temperature; (iii) exposure to ethylene; and (iv) extended shipping period. Appropriate temperature management during shipping is the single most important factor during shipping determining quality retention. All potted flowering plants should be shipped at the lowest species-appropriate temperature possible. This leads to decreased respiration, ethylene production and consumption of food storage reserves by the plants. Chilling-sensitive plants are shipped at 10–12°C while chilling-insensitive plants are shipped at 2°C.

Exposure to ethylene is also a potential problem. Open flowers are usually more sensitive to ethylene than buds and ethylene sensitivity of the whole plant increases with temperature. Injury symptoms include premature flower senescence, bud drop, and leaf yellowing. Several anti-ethylene chemicals such as 1-MCP and silver thiosulfate can be used to minimize damage, especially in chilling-sensitive species that must be shipped at higher temperatures.

ORCHID *Phalaenopsis* and *Dendrobium* orchids have become enormously popular as flowering potted plants. The major problem associated with the supply chain and handling of orchids is their extreme sensitivity to ethylene (Wang, Y.T., 2004). Pollination and emasculation trigger ethylene evolution which causes rapid wilting and water soaking of flower petals within 3 days, greatly reducing flower longevity. Some success has been achieved in greatly reducing ethylene sensitivity of orchid flowers using treatments with silver thiosulfate and 1-MCP. Protection from ethylene injury can last up to 7 days.

Tropical orchids are also extremely susceptible to chilling injury at temperatures as high as 15°C. Preconditioning plants for 10 days at 25°C followed by 10 days at 20°C may reduce the amount of injury. Light is important during storage and retailing for maintaining flowering and flower quality in orchids.

FOLIAGE PLANTS A number of different species are grown as potted plants specifically for their foliage (Nell, 2004b). Many of the same problems encountered with potted flowering plants are encountered when shipping potted foliage plants. Plants are shipped in darkness which is not conducive to maintaining healthy foliage. Temperature control during shipping is critical for maintaining healthy, high quality plants. Most foliage plants are shipped at 15–18°C at 85–90% RH. Lower shipping temperatures may lead to chilling injury, especially if transit time is long. Foliage plants should not be shipped with products that emit ethylene (flowers, fruits, and vegetables). Foliage plants are particularly susceptible to ethylene injury during shipping since they are shipped at relatively high temperatures where even extremely low levels of ethylene can induce damage.

Many growers acclimate their plants for shipping by reducing fertilizer and water application, decreasing light levels and temperature for 2–4 weeks before shipping. Acclimatized plants suffer fewer problems during shipping and marketing and have a longer shelf life than non-acclimatized plants.

BEDDING PLANTS Many vegetable transplants and flowering bedding plant transplants must be transported or stored for brief periods. Proper transport and storage are required to prevent problems both to the plant at the transplant stage and to the commodity once it is planted (Kim *et al.*, 2004). Transplant death is an obvious problem. Premature or delayed flowering is a major problem observed following improper handling during transport and storage. Some vegetable transplants such as onions (*A. cepa*) may bulb prematurely if handled improperly. Plugs are smaller than transplants and are usually more sensitive to environmental conditions during shipping and storage. However, their small size often makes them easier to handle during shipping and storage.

Storage temperature and irradiance are the two factors that determine the length plug plants can be stored without damage. Light during storage or transport reduces damage especially when storage temperatures are higher and length of storage is longer. Shipping and storage temperature are species dependent. Many plugs benefit from cooling prior to shipping if shipped over long distances. Plug water status should be closely monitored during storage and care must be taken not to overwater plugs as this is likely to cause problems with *Botrytis*, a major problem of plug plants during storage. Lower cooler RH reduces the incidence of *Botrytis* but may increase the frequency of watering needed.

Flower bulbs

Many species that are geophytes (plants with underground storage organs) are important horticultural crops. The storage of their bulbs (a term often used to include bulbs, corms, tubers, rhizomes, tuberous roots, and enlarged hypocotyls; De Hertogh and Le Nard, 2004) is an important part of the production cycle. While there are over 60 taxa grown commercially, six of them account for 90% of the world production of flower bulbs: *Tulipa* (39%), *Narcissus* (20%), *Lilium* (19%), *Gladiolus* (8.5%), *Hyacinthus* (4%), and *Iris* (3%) (De Hertogh and Le Nard, 2004).

Pre-production storage of these propagules is species, sometimes cultivar, specific and local authorities should be consulted for recommendations. This section will consider general storage and pre-production (postharvest) practices and problems.

Flower bulbs are divided into two categories: (i) those that will be used for propagation (planting stock); and (ii) those that will be used for commercial production of cut flowers, flowering potted plants, or planted directly into the landscape (commercial bulbs) (De Hertogh and Le Nard, 2004). For both categories, optimizing pre-production storage and growing conditions combine to achieve a number of objectives:

- to control flowering from floral initiation to anthesis;
- to control disease and insects; and
- to prevent physiological disorders.

An important physiological characteristic to know for each bulb species in question is when does floral initiation occur and what factor(s) influence it. Some bulbs initiate flowers before harvest and placement in storage (hardy *Narcissus*), while others initiate flowers during postharvest storage (*Tulipa* and *Hyacinthus*) or in the production field or greenhouse (Easter lily, *Lilium*). In addition, it is important to know how long floral development from initiation to anthesis takes. This process may be as short as a few weeks or it may take months. The species temperature sensitivity with respect to flowering is also important information for success. As with other horticultural commodities, it is also important to know the species sensitivity to ethylene, RH requirements during storage, and any other particular storage requirements for a species.

Temperature is undoubtedly the most important factor that must be regulated during the preplanting phase of production as floral production is precisely controlled by a specific temperature and duration and these values vary considerably among species, from –2 to 34°C for days to weeks (Hartsema, 1961).

Ventilation is important for regulating O_2, CO_2, ethylene, and RH and varies with species and storage temperature. Moisture, and in particular RH, must be monitored and regulated to prevent desiccation but at the same time prevent the growth of disease-causing organisms. Some bulbs are stored in moist peat moss or other material to prevent desiccation. All bulbs except Dutch iris are sensitive to ethylene of 0.1 ppm and higher. Exposure to even extremely low levels of ethylene can cause floral abortion rendering the bulb useless. It is often wise to monitor storage rooms for ethylene, especially ultra-sensitive species such as tulips. Modified atmospheres have been used to a limited extent for bulb storage.

Since storage requirements and subsequent problems associated with improper handling of bulbs during the postharvest/pre-production period are very particular for each species, a general discussion for only the six major genera will follow.

***GLADIOLUS* (GLADIOLI)** Gladioli plants are propagated via corms, short, swollen, vertical underground stems. Flower formation occurs after planting and is dependent on soil temperature (13°C optimal). Corms used for either planting stock or commercial production are treated similarly. After harvest, corms are cleaned and graded then stored for 2–3 weeks at 15–23°C. Corms are then stored at 2°C under highly ventilated conditions for 8–10 weeks to break dormancy. Corms held for long-term storage should be held at 2°C. Prior to planting, corms are stored at 20–30°C for 4–8 weeks to promote sprouting.

***HYACINTHUS* (HYACINTHS)** Hyacinths are propagated via bulbs, short stems with swollen fleshy leaves or leaf bases. Flower development requires at least 10–14 weeks of temperatures between 5 and 9°C after planting. Depending on intended use, hyacinth bulbs are treated differently after harvest.

For production bulbs, bulbs are harvested in June (The Netherlands), cleaned and graded then stored at 30°C under highly ventilated conditions until 1 September. Bulbs are then stored for at 38°C for 2 weeks followed by 44°C for 3 days, then at 25.5°C until planting. Large bulbs used for scooping and scoring are stored at 25.5°C from harvest through to planting. Scooping and scoring are techniques that can be used when propagating bulbs. Scoring consists of making two shallow perpendicular cuts into the basal plate of a bulb to induce callus formation, from which bulblets (baby bulbs) will form. Scooping involves removing most of the basal plate with a spoon or similar instrument, leaving the rim of the basal plate intact. Callus tissue soon forms, followed by bulblets.

Bulbs used for flowering are available in two forms: (i) prepared bulbs; and (ii) regular bulbs. Prepared bulbs are used for very early forcing. After harvest in June, bulbs are stored under dry, highly ventilated conditions at 30°C for 2 weeks, followed by 25.5°C for 3 weeks, then 23°C until the uppermost floret on the inflorescence reaches a particular floral stage called stage A_2. Stage A_2 is when the second whorl of stamens is visible in the developing floret. Bulbs are then stored at 17°C until planting. (Note that floral *initiation* occurs during this warm storage, each temperature promoting a particular aspect of floral initiation and differentiation, but complete floral *development* requires exposure to much lower temperatures after planting.) After planting prepared bulbs require a minimum of 10 weeks at 5–9°C for floral development. Regular bulbs which are used for later forcing are stored at 25.5°C. Four weeks before forcing, bulbs are stored at 17°C for 4 weeks. After planting, regular bulbs require a minimum of 13 weeks at 5–9°C for floral development. Bulbs used in the landscape are harvested then stored at 25.5°C. They are shipped and then subsequently stored at 17°C. The extra care given to prepared bulbs in moving them from 30°C to 25.5°C to 23°C then to 17°C allows them to flower up to 1 month earlier than bulbs that are not prepared.

***IRIS* × *HOLLANDICA* (DUTCH IRIS)** There are many species of iris, however, the Dutch iris (*Iris × hollandica*) is the one used extensively for forcing. These iris are propagated via bulbs and should be handled very carefully to prevent mechanical injury which often leads to infection by *Fusarium* and *Penicillium*.

Production bulbs (bulbs for propagation) for planting are handled very carefully to minimize flower formation and produce round commercial-sized bulbs. Bulbs that are in the 7/8 cm size category are extremely sensitive to temperature with respect to flower formation. Larger bulbs readily flower and smaller ones do not and neither are affected to any great degree by temperature during storage after harvest with regards to flowering. The 7/8 cm size bulbs should be stored at 23°C from harvest in early summer until 1 September then at 30–35°C for 2 weeks followed by 5–9°C until planting. Smaller bulbs are stored at 18–20°C. Larger bulbs would not be used for propagation since they will readily flower after planting. Bulbs should be stored at 50–60% RH. Higher humidity will encourage the growth of *Penicillium*.

Commercial bulbs for forcing are handled in a number of different ways. After harvest, bulbs for very early forcing are stored at 30°C for a few days then exposed to 500 ppm ethylene for 24 h to stimulate floral initiation, especially in small bulbs or bulbs not exposed to high (>30°C) field temperatures. These bulbs should be planted for forcing as soon after ethylene treatment as possible. For later forcing, bulbs are stored at 30°C after harvest. Depending on cultivar, bulbs are stored at 5–9°C for 6–11 weeks prior to planting to stimulate flower development.

***LILIUM* (LILIES)** There are two basic types of lilies grown commercially: (i) the Easter lily (*Lilium longiflorum*); and (ii) *Lilium* species and hybrids. Easter lilies are usually forced in a greenhouse and grown as a potted flowering plant for the Easter holiday.

Production bulbs of Easter lilies are immediately replanted after harvest in late September. Commercial bulbs for potted plants are packed in moist peat moss after harvest. Bulbs can be handled in two different ways: (i) planted immediately and allowed to grow for 3 weeks at 15–16°C followed by 6 weeks at 2–7°C; or (ii) packed in moist peat moss and 'case cooled' at 2–7°C for 6 weeks then potted and grown in the greenhouse at 15–16°C. Once bulbs/plants have been chilled by either method, growth in the greenhouse is carefully monitored and flower development is regulated with temperature, light, water, fertility and chemical growth regulators so that blooming will coincide with the Easter holiday.

Hybrid and species lilies are used as fresh cut flowers, potted plants, or landscape specimens. Commercial bulbs are harvested, graded, cleaned and packed in moist peat moss. They are then wrapped in polyethylene for storage and shipping. Bulbs are cooled at 2°C for 6–8 weeks and then either planted for forcing or stored at between –1 and –2°C until needed for year-round forcing. Production bulbs are stored in moist peat moss at 2°C until planted.

***NARCISSUS* (HARDY DAFFODILS AND 'PAPERWHITES')** Two groups of *Narcissus* are used commercially: (i) hardy daffodils; and (ii) 'Paperwhite' *Narcissus*.

Production bulbs of daffodils are harvested, graded and then stored at 17–20°C until planting. For commercial production, bulbs are harvested, cleaned and graded. Bulbs for early forcing are given 1 week at 1.1°C followed by 17°C until planting. Bulbs for regular use are stored at 17–21°C.

'Paperwhites' are harvested, cleaned and graded and both production and commercial bulbs are then stored at 25–30°C under highly ventilated conditions until planting. If shoots emerge prior to planting, bulbs should be placed at 2°C to retard growth until desired for forcing. Prior to planting, bulbs need 2 weeks at a temperature between 9 and 17°C to ensure complete floral development.

***TULIPA* (TULIPS)** Tulips are the largest taxa of flowering bulbs grown worldwide, used as forced cut flowers, potted flowering plants, and landscape specimens. Bulbs are particularly sensitive to ethylene, so care in the entire harvest and storage chain must be taken to ensure that bulbs will not be exposed to it. Tulips are also susceptible to *Fusarium* and often acquire it in the field, thus routine inspections during storage are needed to remove infected bulbs. Additionally, decaying bulbs emit considerable ethylene which can lead to flower abortion and flowering abnormalities.

Production bulbs are harvested, cleaned and graded then stored at 23–25°C for 3–4 weeks. They are then stored at progressively lower temperatures

(23–20°C, then 17–15°C) until planting which enhances the production of large bulbs during propagation.

Commercial bulbs for forcing are given a 1 week exposure to 34°C immediately after harvest. They are then moved to a well-ventilated storage facility at 17–20°C. Once bulbs reach stage G (pistil formation) of floral development, they are moved to 5–9°C. If bulbs are moved before this stage is reached, flower abortion may occur. For later forcing, bulbs are stored at 17–23°C. Depending on the style of forcing, bulbs are given at least 8–10 weeks at 5°C prior to planting. When grown in temperate landscapes, bulbs that have been stored at 20–23°C are shipped and stored at 17°C until they are planted in the fall. They then receive their cold treatment naturally.

Herbaceous perennials

Herbaceous perennials often require storage at some point during their production chain. Most often, storage is between propagation and planting. The list of herbaceous perennials covers plants that are stored as dormant crowns with attached roots with no green leafy tissues attached (bare-roots) to those that are stored with fairly succulent leaves (greentops). In general, the less leafy material stored, the longer the storage life. There has been a considerable shift from storage of herbaceous plant material as overwintering bare-roots and greentops to storage as plugs. Plugs are small plants growing in plastic 30 cm × 60 cm trays that have from 32 to 516 cells.

Bare-roots and greentops

The biggest problems encountered during storage are desiccation, rot, and the growth of fragile buds once dormancy has broken. Desiccation can be prevented by storing propagules in poly bags. The polyethylene allows O_2 exchange while preventing moisture loss. Plants should be checked regularly to ensure that they are not drying out. Rots develop when propagules are not cleaned and appropriately dried before storage or when they enter storage infected with a rot-causing organism. Wood fibers or shredded newspaper added inside the poly bag absorbs excess moisture and condensation. Bud growth often occurs during shipping or retail storage. Every effort should be employed to maintain storage at –2°C until planting.

Propagules should be dormant before harvest. Species that do not have a dormant period should be harvested as late in the fall as possible. Mature plants or a late harvest help to ensure that the plants have maximum food reserves to survive storage. The major consequence of harvesting too early is a greatly reduced storage life.

After harvest propagules should be cooled to 0°C as quickly as possible to minimize respiration, which is often substantially increased due to wounding during harvest. As plants are processed for storage (cleaning, grading, washing, and packing) great care should be taken to avoid further injury, cool the product and to prevent anaerobiosis from occurring by maintaining adequate ventilation. Most propagules are stored at –2°C with shredded newspaper or some other dry filler inside unsealed poly bags which are placed in cardboard boxes (Cameron, 2004). Boxes should be appropriately sized to prevent overcrowding.

Some species such as *Gaillardia* and *Coreopsis* must be overwintered as potted plants rather than bare-root plants. The potted plants are placed inside poly liners to prevent desiccation, and then placed in cardboard boxes for storage. Some herbaceous perennials such as *Hibiscus, Alcea* and *Sidalcea* are chilling sensitive and can therefore only be stored at warm temperatures for a short time.

Plug plants

Plug production is the most widely utilized method of propagating herbaceous perennials. Either seeds or cuttings are planted in plugs of varying sizes and are ready for transplanting within 6–12 weeks. These plug trays are then sold to growers for transplanting into production containers for retail or wholesale markets. Plug plants are normally purchased and containerized in the fall and sold the following spring or summer.

Most herbaceous perennials require exposure to low temperatures to overcome dormancy to achieve acceptable regrowth in the spring. Containerized plants developed from plugs are often overwintered in minimally heated greenhouses to accumulate chilling. It is increasingly popular to supply a cold treatment to plants in the plug stage before planting. This reduces space requirements for chilling and provides more control over the exposure to the chilling temperature. Plugs can be stored at low temperatures to orchestrate production schedules with consumer demand. Plugs can be stored at 5°C and held for 3 months with little damage as long as light levels high enough for maintenance photosynthesis is provided; the level of light required varies with species. Plugs stored in the dark for a long period do not normally survive transplanting.

Seeds

All seeds of commercially important horticultural crops must be stored for some quantity of time after harvest for food or as propagules for production (Walters and Towill, 2004). The major factor determining the storage life of viable seeds is moisture content and tolerance to desiccation. Three categories of seeds based on their desiccation tolerance are: (i) orthodox; (ii) recalcitrant; and (iii) intermediate.

Orthodox seeds are produced by most annual or biennial crops. They are extremely tolerant of nearly complete desiccation and are easily stored under cool, dry conditions for many years. Recalcitrant seeds are produced from herbaceous plants from aquatic habitats, tropical perennials, and some deciduous, temperate perennials. They are much less tolerant of desiccation and can be stored for a year or less at 92–98% RH. Tropical recalcitrant seeds are usually chilling sensitive and must be stored at >15°C. They can usually be stored from 2 weeks to 3 months. Temperate recalcitrant seeds are not chilling sensitive and are stored at 2–5°C and will survive storage for 6 months to 2 years. With all recalcitrant seeds, storage at high RH may lead to microbial contamination. High RH during storage often causes recalcitrant seeds to germinate. As soon as they do, they must be treated as seedlings and stored or planted appropriately. Intermediate seeds are produced by tropical and subtropical perennials and some nut species and can usually be stored for several years without a loss in viability. They are stored at 40–60% RH at 5°C and remain viable for 2–5 years under these conditions.

Seed maturity describes a stage of seed development where desiccation tolerance has been triggered in the seed and has fully developed. Immature seeds will not store well since the desiccation tolerance process has not been triggered or completed, thus any seed intended for storage should be mature at harvest. This is true for all three types of seeds. It is important to harvest orthodox seeds as soon as the seed is mature since exposure to high RH promotes seed deterioration.

High O_2 concentration in the storage atmosphere greatly reduces seed viability but the converse has not been demonstrated. Exposure to even low levels of light also decreases seed longevity therefore seed should always be dried and stored in the dark at 0°C. Storage at higher temperatures will reduce seed longevity by 50% for every 5°C increase in storage temperature.

Christmas trees

Cut Christmas trees are an important horticultural commodity in many parts of the world and their useful life is very dependent on postharvest practices (Hinesley and Chastagner, 2004). Cut trees may be shipped long distances and therefore must be stored for up to 1 month. Tree moisture greatly impacts longevity.

Once cut, Christmas trees begin to lose moisture. The moisture content of a tree is measured as water potential (symbolized as ψ) and is measured using a pressure bomb. A pressure bomb consists of a chamber in which a twig is inserted with just the cut surface protruding from the chamber. Pressure is applied to the chamber until moisture is observed at the cut. The force required to make moisture visible on the cut surface is reported as bars and the water potential is the negative value of this force. For example, if a sample requires 2 MPa (megapascals) of pressure to cause moisture to be visible at the cut surface, the water potential of that sample was –2, or ψ = –2 MPa (1 MPa is about –10 bars = –10 atmospheres). Drier samples require more pressure to produce moisture at the cut, indicating a lower (more negative) water potential.

If water potential is measured over time from when the tree is cut, two inflections can be observed in the time × pressure graph generated from the data. The first inflection point, V1, is observed soon after the tree first begins to dry out and varies with species and is normally –18 to –28 MPa. Once the tree reaches this first inflection point, the rate of drying slows down considerably. After a while, the tree begins to dry out more quickly and another inflection point is observed, V2. It appears that V2 corresponds to the moisture content where damage is first observed, such as needle dropping, discoloration, failure to rehydrate if placed in water. V2 ranges from –30 bars in eastern white pine (*Pinus strobus*) to –40 for Douglas fir (*Pseudotsuga menziesii*) and Fraser fir (*Abies fraseri*). During shipping and storage, the objective is to keep the water potential above V2 to minimize damage upon display of the tree. Measuring V1 and V2 are valuable research tools, but are not routinely used by Christmas tree growers, brokers of the average consumer.

The main idea with all species is to never let the moisture content of a tree to reach a limit so low that it won't rehydrate if re-cut and placed in water. Since trees cannot be shipped in water, minimizing moisture loss between harvest and display are crucial. Once displayed, different species maintain and loose water at different rates. For example, noble fir (*Abies procera*) and Fraser fir (*A. fraseri*) maintain high moisture content for 4 weeks while eastern red cedar (*Juniperus virginiana*) and Atlantic white cedar (*Chamaecyparis thyoides*) only maintain high moisture content for 1 week before drying out, even when displayed in water.

A reasonable generalization is that a cut Christmas tree uses about 1 l of water/2.54 cm of trunk diameter/day, thus a moderate-sized tree will use 1 l/day. Many consumers do not use a large enough reservoir and allow the tree to dry out between watering. Once the tree has dried, it may not rehydrate very well, even if re-cut. Even though many additives have been suggested for prolonging tree longevity, the best solution to use for tree watering is plain water (Hinesley and Chastagner, 2004). Spray-on anti-transpirants do not extend tree longevity. The use of flame retardants is not recommended as they can injure needles. Maintain fire retardancy by keeping the tree moisture level as high as possible.

Trees that acclimate or become cold hardy last longer when cut compared with non-hardened trees for some unknown reason. The sugar raffinose increases in many trees during hardening but whether or not this influences tree longevity is not clear. Acclimated trees are also able to withstand exposure to cold between harvest and display, for example in the Christmas tree lot before it is sold. Non-acclimated trees that are exposed to cold after harvest suffer severe needle loss upon display, even if adequate water is supplied. Thus not only is species important when selecting a tree for longevity, but so is the environment from which it came.