15 From Harvest to Market

Employing the finest methodologies in horticultural production are meaningless if commodities are not harvested at the appropriate time and handled in a manner to maximize their longevity during transit and storage. Quantitative and qualitative losses occur from harvest to consumption. Quantitative losses are easy to assess but losses in quality are much more difficult to evaluate, particularly since quality is such a subjective characteristic. In general, a reasonable estimate of total crop loss from harvest to human consumption is about 33% (Kader and Rolle, 2004).

To minimize losses and to maximize both nutritional and economic value of horticultural commodities, it is essential to know characteristics for each product under consideration. In this chapter we will explore the many facets of harvesting and handling that have a significant impact on the postharvest life of horticultural products. In the following chapter (Chapter 16) we will consider the biology of postharvest physiology.

Quality, Maturity, and Ripeness

Quality is a subjective issue. Even though there are a number of attributes we consider that help to describe the quality of a commodity (Fig. 15.1), the end determination of whether or not a sample is good or poor quality is a matter of opinion. While every individual has his or her own idea of quality, an educated consumer is the best evaluator of quality. If the consumer does not like the product, it really doesn't matter what a physiologist says about the quality attributes observed.

Since quality is so subjective, quality standards have been adopted by many countries around the world to help maintain consumer confidence in the quality of horticultural commodities that they purchase. It is far beyond the scope of this book to examine these standards, however, a basic understanding of the parameters that go into setting up these guidelines makes understanding them less difficult.

Quality

The main components of quality include appearance (for all commodities), and texture and flavor for fruits, vegetables, herbs, and spices. The relative importance of each quality attribute depends on the individual assessing quality. A grower is often interested in the quantity and overall appearance of the commodity at harvest. A shipper or broker may be more concerned with firmness or stage of maturity that might affect longevity in storage or transit. The consumer is often most interested in taste and longevity after purchase. Even though everyone has their opinion of quality, in the long run, it is the consumer who ultimately determines the quality of an item since their assessment determines whether or not the item will be purchased again on their next visit to the market.

Appearance

Appearance can be broken down into size, shape, color, gloss, and freedom from defects and decay. Size, shape, color, and gloss are often determined by cultivar and management practices. Defects and decay may come from poor management decisions or pest problems but may also be an inherent physiological problem of the commodity. For example, russetting in Golden Delicious apple (*Malus domestica*) cultivars is an inherent defect in this strain of apple. On the other hand, bitter pit in apple is a visual defect that may be inherent to certain apple strains, but may be controlled with appropriate calcium management.

Texture

Texture includes such attributes such as firmness, crispness, juiciness, mealiness or toughness depending on the commodity. Texture is important in both

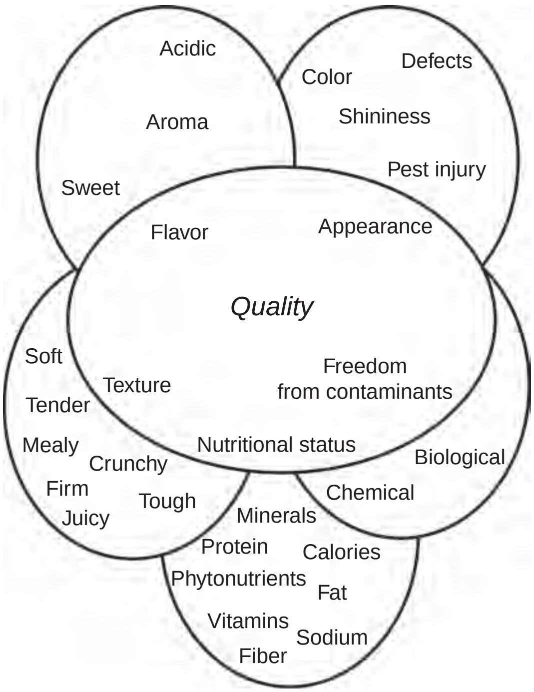

Fig. 15.1. Components of quality.

eating and shipping quality. Soft-textured commodities do not ship well and are often harvested at less than ideal maturity or ripeness in an effort to increase firmness and improve shipping ability at the expense of flavor.

Texture is not a single well-defined attribute, but rather a collection of intrinsic characteristics that help define quality that determines the acceptability of fruits and vegetables to the consumer (Abbott and Harker, 2004). Texture is often described as hard, soft, crisp, limp, mealy, melting, woolly, tough, leathery, gritty, stringy, dry, and juicy and is extremely subjective. Of these, only the firmness or lack thereof of the flesh is relatively easily measured and quantified. Firmness is often measured via the Magness-Taylor pressure test and the force needed to push a stainless steel tip of specified diameter a prescribed depth into the flesh of a fruit is reported as a value expressed in Newtons per square centimeter. Other tests such as a shear test (force required to cut tissues) or a compression test (force required to rupture cells in tissues) are used in research but not much in the produce industry.

Another reason it is often difficult to quantify texture is that each individual in a population of fruit varies, sometimes considerably, in texture due to the inherent nature of the quality. Almost constant changes at the cellular level make texture a changing attribute that is only a useful description at the time of evaluation and not for some time in the future during or after storage.

It is important to understand the nature of the commodity under evaluation in order to develop a good assessment of texture. Most commodities are composed of parenchyma cells which by nature are relatively soft and non-lignified. Cell walls (rich in cellulose) are joined together by the middle lamella, (rich in pectins and hemicellulose), which undergo varying degrees of decomposition and softening as a commodity matures, ripens, and senesces. The combination of cell wall strength, middle lamella composition and cellular turgidity all contribute to the perceived texture of the tissue in question. Some tissues have little intercellular air space, for example carrots (*Daucus carota*), while other tissues may have up to 25% air space, for example apples (*M. domestica*). Greater air space often leads to the perception of softer tissue. The hydration level of cell walls may affect the perceived juiciness of tissue. The perception of wooliness in apple and peach (*Prunus persica*) flesh may be due to cells separating at the middle lamella rather than cells rupturing during chewing, as occurs in crisp flesh (Harker *et al.*, 1997).

Cooking often, but not always, softens tissue by degradation of pectin polymers combined with loss of turgor due to thermally induced membrane disruption. Some tissues, such as water chestnut (*Eleocharis dulcis*) or sugarbeets (*Beta vulgaris*), do not soften appreciably during cooking due to cell wall structure or due the presence of substances which enhance thermal textural stability (for example ferulic acid in water chestnuts) (Waldron *et al.*, 1997).

Other factors also contribute to texture. For example different tissue zones in specific commodities such as: (i) the periderm, pericycle, and phloem parenchyma in carrots; (ii) the outer and inner pericarp and core in kiwifruit (*Actinidia deliciosa*); and (iii) the locules and gel of a tomato (*Solanum lycopersicum*). The different tissues differ in strength and must be taken into account when assessing texture. The epidermis of many fruits and vegetables is often thickened and may be covered in cutin which alters the texture. In addition the presence of collenchyma cells, for example in celery stalks (*Apium graveolens*) and pear flesh (*Pyrus* spp.), can have a profound effect on texture. Tough fibers in the vascular tissue can cause stringiness in some commodities, for example pineapple (*Ananas comosus*) and asparagus (*Asparagus officinalis*).

Flavor

Flavor includes components such as sweetness, acidity, astringency, bitterness, aroma, and off-flavors. Flavor is an extremely subjective characteristic as human taste-bud sensitivity varies among individuals. Even though objective measurements are made on components of flavor, particularly sweetness (brix) and acidity (pH), evaluation by taste panels helps to define levels for measured components that produce acceptable flavor.

Flavor is governed mostly by sweetness and sourness that is perceived on the tongue in the parts per hundred range and is the component that receives the most attention. Aroma is a key component produced by volatiles that contributes to the perceived flavor and is often very difficult to separate from the other flavor components (Baldwin, 2004). Aroma is perceived in the nose at parts per billion levels. Other flavor components include bitterness, saltiness, and astringency. Sweetness is often the most important component of flavor for most produce. The brain takes the information gathered by the nose and tongue and synthesizes a perceived flavor that may change instantaneously. This makes flavor extremely subjective even though we can readily measure all of the components that are integrated into the flavor profile.

The sugars that play a key role in sweetness are: (i) fructose (sweetest); (ii) sucrose (less sweet); and (iii) glucose (least sweet). Soluble solids content (SSC) is easily measured using a refractometer, however, the perceived sweetness is not always linearly related to SSC and may also be affected by the levels of the different sugars in the sample. Citric, tartaric and malic acids are some of the key organic acids that impart sourness to products. Some commodities such as banana (*Musa* spp.) and melons (*Cucumis melo*) have little acidity. Acidity is often assessed by titration (titratable acidity, TA) or by simply measuring pH. The perceived sourness is usually best reflected by a ratio of SSC to TA or pH, rather than TA or pH measurements alone.

Aromatic compounds are usually released during cell disruption during eating or food preparation when enzymes and substrates that were previously compartmentalized are allowed to interact (Buttery, 1993). Further release of volatiles often accompanies cooking. Measuring specific compounds is difficult and time consuming and measured levels may not necessarily relate in a consistent fashion to a perceived flavor or aroma profile.

Often taste test panels can provide a better quality rating than measuring flavor or aroma components. Flavor of horticultural products is often evaluated using trained test panels to select promising new cultivars followed by consumer taste tests to determine acceptance of previous selections. Other quality attributes are usually evaluated along with flavor. Often a simple three-point scale with the options of ‘like’, ‘no opinion’ and ‘dislike’ for each quality attribute is sufficient to identify acceptable or preferred samples.

Genetics is the most crucial element in determining flavor (Baldwin *et al*., 1992) with other factors such as pre-harvest environment, cultural practices, harvest maturity, and postharvest handling having less of a role. Thus cultivar selection is crucial in flavor considerations as the genetics of the cultivar provide the base which production factors may act on to modify flavor quality.

Nutritional status

An increasingly important component to quality of edible horticultural products is their positive contribution to human health. Fruits, nuts, and vegetables provide vitamins C, A, thiamine (B1), niacin (B3), pyroxidine (B6), folacin (folic acid or folate) (B9), and E, as well as minerals and dietary fiber. Most commodities are low in fat and cholesterol and have a reasonable caloric value. Estimates of significant plant contributions of vitamins and minerals to the average US diet are 91% of vitamin C, 48% of vitamin A, 30% of folacin, 27% of vitamin B6, 17% of thiamine, 15% of niacin, 16% of magnesium, and 19% of iron (Kader *et al*., 2004). Legume vegetables, potatoes (*Solanum tuberosum*), and nuts contribute close to 5% of the protein consumed in the average US diet. Nuts are also rich in essential fatty acids. Many commodities supply antioxidants, and compounds that are anti-carcinogenic, and that help alleviate problems caused by diabetes and heart disease.

While genetics plays a major role in which beneficial compounds are produced by specific plants, temperatures favor sugar and vitamin C synthesis while β-carotene (vitamin A) synthesis is promoted by more moderate temperatures (15–21°C). Warm-season crops produce more B vitamins at warmer temperatures (27–30°C) while cool-season crops produce more B vitamins at lower temperatures (10–15°C). The production of B vitamins is not affected by light levels while vitamin C increases and vitamin A decreases under high light levels (Gross, 1991).

The nutritional contribution of horticultural products often decreases after harvest but the rate of loss can be minimized with proper postharvest handling with each commodity (Lee and Kader, 2000). Water-soluble nutrients are often lost when cooking water is discarded rather than consumed while fat-soluble nutrients may be stabilized or their levels may be enhanced with cooking. The human health benefits of horticultural products are discussed in depth in Chapter 17, this volume.

Freedom from contaminants

Another important quality attribute of many horticultural commodities is freedom from chemical or biological contaminants. Chemical contaminants can include natural compounds such as glycoalkaloids in potatoes (*S. tuberosum*) or fungal and bacterial toxins as well as heavy metal contaminants. Pesticide residues are also an important contaminant often found on commodities and it is often the most important concern for many consumers (Kader and Rolle, 2004) even though microbial contamination especially by *Salmonella, Listeria, Escherichia coli* and others is considered more harmful by many authorities.

BIOLOGICAL CONTAMINANTS One of the major biological hazards for humans consuming fresh produce is contamination from microorganisms including bacteria, parasites, and viruses. While many microorganisms are beneficial to humans (they give us bread, wine, cheese, and sauerkraut), the wrong organism in the wrong place at the wrong time can cause serious, sometimes fatal food-borne illnesses. Either the organism itself or toxic metabolites can cause harm.

Some bacteria such as *Clostridium botulinum, Bacillus cereus* and *Listeria monocytogenes* are found in the soil and can easily contaminate produce. Other bacteria such as *Salmonella, Shigella*, pathogenic *E. coli*, and *Campylobacter* live in human and animal intestines and can contaminate produce through: (i) infiltration of sewage into production fields; (ii) irrigation with contaminated water; (iii) animals wandering in production fields; or (iv) using incompletely composted animal manure on production fields. Handling of produce by contaminated individuals can introduce pathogens at any stage along the production path (Beuchat, 1998). In some cases, more than a million cells of the pathogen per gram of food are required to cause illness and in others, such as with *Shigella*, only ten cells per gram are needed to cause illness. The bottom line is that all steps must be taken to prevent bacterial contamination of produce and to prevent growth of contaminants that might already be present through handling and storage under proper conditions. This is especially important since much of the produce consumed by humans is consumed raw.

Parasites such as *Cryptosporidium, Cyclospora, Giardia, Entamoeba, Toxoplasma, Sarcocystis, Isospora*, and nematodes can be transmitted in infected produce after contamination by an infected individual, water contaminated with fecal material, or animals wandering in the production field. These parasites can cause severe gastrointestinal distress and even death. Viruses including hepatitis A virus, Norwalk virus, rotaviruses, astroviruses, enteroviruses (polioviruses, echoviruses, and coxsackie viruses), parvoviruses, adenoviruses, and coronaviruses, can be transmitted through infected produce.

Control strategies for minimizing contamination include general good agricultural practices like: (i) irrigating with clean water; (ii) using only properly composted manure; and (iii) ensuring worker hygiene and proper sanitation during handling and storage. The most important control strategy is maintaining worker hygiene (Beuchat, 1998).

CHEMICAL CONTAMINANTS Chemical contamination of produce may occur naturally or may arise from contamination along the production chain. Some common potential contaminants include polychlorinated biphenyls (PCBs), lubricants, cleaners, pesticides, fertilizers, sanitizers, antibiotics, lead from packaging materials, and heavy metals from contaminated soil. Some naturally occurring chemical contaminants might include mycotoxins like aflatoxin, mushroom toxins, alkaloids, and phytohemagglutinin, a toxin produced in kidney beans (*Phaseolus vulgaris*). Chemical contaminants may cause acute or chronic illness.

PHYSICAL CONTAMINANTS Many physical contaminants could find their way into fresh produce and pose a serious hazard. Some examples of common foreign materials found in fresh produce include glass fragments, wood shards, stones, plastic packaging material, staples, jewelry, and hair clips. Most incidents of contamination with foreign objects are accidental and hard to prevent. Thorough inspection of produce during packaging helps reduce this type of contamination.

Harvesting

Harvesting is the removal of the commodity from the parent plant or the removal of the entire plant from the production field if it is the economic commodity. Many products can be harvested at various stages of development. However, in general there are standards for harvesting most commodities based on size and/or stage of development. A major stage of development, particularly in fruit is maturity.

Maturity is a term often associated with commodities in which the harvested portion is a botanical fruit. The fruit is mature if it has reached the stage of development just prior to ripening and would continue development if removed from the plant. Immature fruit will not continue to develop. Fruit is often divided into two groups: (i) those that will not ripen once removed from the plant; and (ii) those that will ripen if harvested mature. A ripe fruit is ready to eat. Fruit that will not ripen once harvested include cane berries (*Rubus* spp., *Ribes* spp.), cherry (*Prunus* spp.), citrus fruits (*Citrus* spp.), grape (*Vitis* spp.), lychee (*Litchi chinensis*), pineapple (*Ananas comosus*), pomegranate (*Punica granatum*), strawberry (*Fragaria* × *ananassa*), and tamarillo (*Solanum betaceum*). Fruit that can ripen if harvested mature and exposed to the proper environment include apple (*M. domestica*), apricot (*Prunus armeniaca*), avocado (*Persea americana*), banana (*Musa* spp.), cherimoya (*Annona cherimola*), guava (*Psidium* spp.), kiwifruit (*A. deliciosa*), mango (*Mangifera indica*), nectarine (*P. persica*), papaya (*Carica papaya*), passion fruit (*Passiflora edulis*), pear (*Pyrus* spp.), peach (*P. persica*), persimmon (*Diospyros* spp.), plum (*Prunus* spp.), quince (*Cydonia oblonga*), sapodilla (*Manilkara zapota*), tomato (*S. lycopersicum*), cantaloupe (*C. melo*), and watermelon (*Citrullus lanatus*). Immature fruit will not ripen once harvested. Most fruit attain best eating quality if allowed to ripen on the plant. However, to enable long-distance shipping, many commodities are harvested mature but not ripe.

Fruit are often categorized as climacteric or non-climacteric. Climacteric fruit are those fruit that can be harvested mature and will ripen after harvest (the second group from above). Non-climacteric fruit (the first group) will not ripen once harvested. Non-climacteric fruit have a low, relatively constant rate of ethylene production as it proceeds from maturity through ripeness and senescence. In addition, the rate of CO_2 is relatively constant through the ripening process. Climacteric fruit are characterized by a rapid (sometimes 1000-fold) increase in ethylene production as ripening is initiated. This rapid increase in ethylene is closely followed by a sharp increase in CO_2 production. Ethylene production is an autocatalytic process: ethylene induces ethylene production. Regulation of ethylene production especially in climacteric species is a focal point of postharvest physiology (see Chapter 16, this volume). Climacteric fruit can be induced to ripen by exposing them to ethylene.

Many vegetables are harvested immature. This includes leafy vegetables and vegetables where the harvested portion is immature fruit. For example cucumbers (*Cucumis sativus*), sweet corn (*Zea mays*), green beans (*Phaseolus vulgaris*), peas (*Pisum sativum*), and okra (*Abelmoschus esculentus*). Most of these vegetables reach optimum eating quality prior to maturity. Delayed harvest of many vegetables leads to inferior quality.

Maturity indices

Maturity or harvest indices are visual, physical, and chemical attributes that allow the grower to determine the best time to harvest a particular commodity (Fig. 15.2). These indices are a compromise between a stage that is best for eating and a stage that is best for marketing. Maturity indices have been developed for leafy vegetables, root vegetables, 'fruit' vegetables, and fruit crops. In many instances several maturity indices are combined when evaluating a crop and its suitability for harvesting.

Physical attributes

The most common harvest index for many commodities is size. The worldwide produce industry has established a standard size for each commodity at harvest. This may include a minimum and maximum size as well as different grading categories for different sizes. Size is usually length or diameter or a combination of the two. Some commodities such as

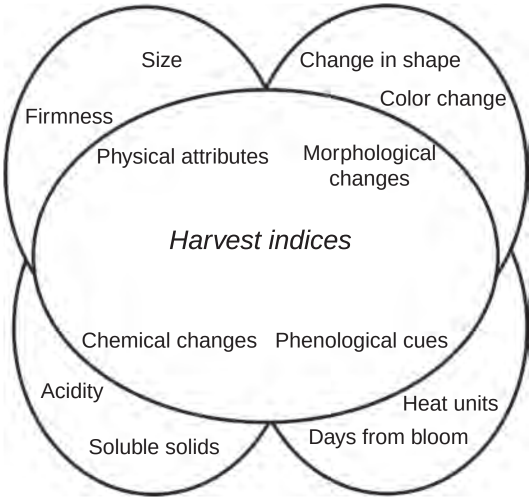

Fig. 15.2. General harvest indices for horticultural commodities.

banana (*Musa* spp.) and cucumber (*C. sativus*) change from angular to nearly round as they reach maturity and this can be used as a signal to harvest.

Fruit firmness is another harvest index, easily measured with a penetrometer. A penetrometer is a small, usually hand-held device that consists of a gauge to which a slender compression cylinder is attached. Different diameter tips are available that are attached to the compression cylinder according to the crop under consideration. The tip of the cylinder is marked so that the operator knows the depth to which the tip should be inserted into the flesh. Normally the skin of the fruit is removed and the tip of the compression cylinder is forced into the flesh to the line on the tip. The force needed to insert the tip registers on the gauge and is recorded as values expressed in Newtons·per square centimeter. The old method of reporting pressure in kilograms per square centimeter is no longer acceptable. A consistent methodology should be developed so that the tip is pressed into the flesh in a similar manner among the fruit being tested. Several readings on opposite sides of the fruit are often taken to better estimate firmness.

Morphological changes

Morphological changes are often used as maturity indices. These include the development of an abscission zone at the point of fruit attachment to the vine in muskmelons (*C. melo*) and curling and drying of the tendril adjacent to the point of fruit attachment to the vine in watermelon (*C. lanatus*). The development of a waxy layer on the epidermis of plums (*Prunus* spp.), grapes (*Vitis* spp.), and honeydew melons (*C. melo*) can be used to determine time of harvest. Netting develops on muskmelons as they approach maturity. Gel-like material forms around tomato (*S. lycopersicum*) seeds as the fruit begins to mature.

Internal or external fruit color is used as a maturity index for some fruits such as apricot (*P. armeniaca*), nectarine (*P. persica*), persimmon (*Diospyros* spp.), strawberry (*Fragaria × ananassa*), peach (*P. persica*), plum (*Prunus* spp.), and raspberry (*Rubus* spp.). Color is a fine index of visual quality but has little to do with flavor quality. The percentage juice by volume is a maturity index for lemon (*Citrus × limon*). Again, this single attribute confers nothing concerning the flavor quality of the juice. Fruit tenderness is used to determine optimum harvest for peas (*P. sativum*). Solidity or firmness of developing heads is used to determine when to harvest head lettuce (*Lactuca sativa*) and cabbage (*Brassica oleracea* Capitata Group).

Chemical changes

SSC (soluble solids content) is another index of maturity associated with the sugar content of produce and is reported as a percentage or as degrees brix (°BX). Some crops must reach a minimal level of SSC before they can be harvested for sale. In many cases higher SSC is associated with higher quality. Acidity is often measured as well as pH or TA (titratable acidity) and a ratio of SSC to pH or TA can provide a reasonable estimate of flavor quality. Persimmons (*Diospyros* spp.) are evaluated for astringency as a harvest index.

Some crops such as apples (*M. domestica*) utilize a starch-iodine test to reflect the amount of starch contained in the product that potentially will be converted to sugars as the product matures and ripens. A solution of tincture of iodine is applied to the cut surface of the produce. Any starch in the tissue will stain black and the relative amount of starch in the tissue can be ascertained by comparing the degree of staining of the sample to standardized stain color charts.

Phenological development

Days from blossom or days from seeding are often used to estimate harvest date. In general, this method will provide a reasonable estimate of when the crop should be harvested. A better estimate can be obtained if temperature data is available to calculate heat units and the number of heat units required for crop development and maturation is available from references.

Harvest

Harvesting is a critical stage in any horticultural production chain. Once produce is harvested, quality does not improve, it can only be maintained. Every effort must be made to: (i) harvest during the right time of the day to maintain quality; (ii) harvest at the appropriate stage of development; and (iii) harvest only produce that has the potential to hold up during storage, shipping, and sale. Once harvested, the commodity must be handled to maximize shelf life. A properly trained, skilled, hygienic harvest team is a worthwhile investment for any grower as commodity handling from harvest through to consumption is critical for maintaining quality. Pickers and supervisors who know what they are doing and why they are doing it go a long way to ensure success.

Most commodities should be harvested during the coolest part of the day, usually early morning. In some regions this may present a problem since produce may be wet from dew. Many commodities should not be harvested wet to minimize the chances of contamination and decay during storage. Harvesting when it is cool is tied to the product's respiration rate.

Respiration uses substrates from the commodity to provide the energy required for metabolic maintenance. Once harvested, the commodity is no longer manufacturing substrates, so any that are used postharvest are from those stored in the commodity. The faster that stored substrates are used, the faster the product deteriorates. By harvesting when the temperature is cool, respiration is minimized as much as possible. In addition, the amount of field heat that must be removed before storage is decreased.

Most produce is harvested based on harvest indices specific to each crop. Besides knowing when to harvest, it is important to know how to harvest. One major rule of thumb is to be as gentle as possible with produce during the entire harvesting, sorting, cleaning, packing, storing, shipping, and selling chain of events to minimize mechanical damage to the product. Damage immediately decreases the quality and therefore value of the product and renders it more susceptible to disease-causing organisms and physiological decay due to the sound-induced ethylene produced. All harvesting tools and containers should be disinfected daily with either a chlorine- or hydrogen-dioxide-based solution and thoroughly rinsed. Cutting tools should be sharp and disinfected and workers should be trained in their proper use. Vehicles and work areas should be kept clean of crop debris and trash. Produce should be kept as cool as possible and placed in cold storage (when appropriate) as soon as possible.

Grading and culling should start in the field at harvest with only high quality marketable produce selected and harvested. Minimal culling should be required at the packing area. Many products are field packed as they are harvested, minimizing the number of times the product is handled. Each handling costs time and money and presents the opportunity for mechanical damage and bruising. All workers assisting in harvesting and packaging must follow good hygiene and sanitation practices. Field containers should not come in contact with soil and should be free of dirt and other contaminants. Field sanitation is especially important for crops that are not washed before storage, such as grapes (*Vitis* spp.) and strawberries (*Fragaria* × *ananassa*).

Field heat removal

One of the most important things to do at harvest to maximize storage life and quality is to remove as much field heat as possible from the commodity as quickly as possible. Cooling to remove field heat may occur in mobile field units or at the packing or storage facility. Removing field heat helps prolong storage life and quality by: (i) reducing respiration and the production of ethylene; (ii) reducing water loss from the product (which can be substantial during storage); and (iii) reducing the growth of harmful pathogens in or on the product.

Heat is removed from produce by two mechanisms: (i) conduction; and (ii) convection. Conduction removes heat from a commodity by transferring heat from within a product to its coldest surface. With convection, heat is removed by carrying it away in a medium such as air or water. There are several methods of removing field heat from produce and all must minimize opportunities for produce contamination. The major concern is contamination by microorganisms. Heat is usually removed by air either by storing produce in a cold room or by forced air cooling, or with water via hydrocooling or icing of produce.

The simplest heat removal is accomplished by placing produce in a cold room. Cooling occurs very slowly and may be unacceptably slow for some commodities. Cooling can be hastened by forcing cooled air over the product and through the storage containers. The source region for the air used in forced air cooling must be clean and free of possible contaminants and filters should be checked and cleaned regularly. Using water (hydrocooling) or ice as the cooling medium rather than air hastens cooling significantly, however, the chances of contamination also increase. Water used for cooling must be replaced at least daily and ice must be made from contaminant-free, chlorinated, potable water and stored in sanitary conditions.

Another method of cooling certain produce, such as root crops, broccoli, and Brussels sprouts, is by placing ice or 'liquid ice' (60% ice, 40% water) in direct contact with the produce. Regular ice contains large amounts of air which reduces direct produce-to-ice contact and results in slower, less efficient cooling. Liquid ice creates much better contact with greater rates of cooling.

Vacuum cooling is accomplished by placing the produce in an airtight steel container and applying a vacuum to it. The vacuum causes water in the produce to vaporize and thereby cool the produce. Faster cooling is achieved with increased exposure of produce surfaces, allowing more water to vaporize more quickly. Produce usually cooled this way includes iceberg lettuce (*L. sativa*), celery (*A. graveolens*), cauliflower (*B. oleracea* Botrytis Group), sweet corn (*Z. mays*), carrots (*D. carota*), and sweet peppers (*Capsicum annuum*). The major disadvantage of this method is that 1% of the produce weight is lost during cooling as water is removed by vaporization for each 5°C drop in produce temperature (Holdsworth, 1985). Hydro-vacuum cooling is a modification that showers the produce with water during the cooling process to reduce the water lost from produce during cooling.

Postharvest water quality

Water is used for many postharvest operations including: (i) quick washes to remove field dirt; (ii) to minimize bruising in dump tanks; (iii) to remove field heat; (iv) to prepare waxes or fungicide dips; and (v) for heat treatments to remove insect pests. No matter what its use, water must be clean, potable and kept that way during the process in which it is used. Keep in mind that clean, potable water can quickly become contaminated by contaminated produce placed in it. Even produce that appears to be clean can harbor considerable contaminants, especially in warm wet weather.

Chlorine is often added as a sanitizer to water used for postharvest processing. It is most often added as sodium hypochlorite, calcium hypochlorite, or liquid chlorine. As chlorine reacts with organic matter from the produce during postharvest processing, it loses its effectiveness. Therefore the free chlorine level of the water must be regularly monitored (at least hourly) and maintained at a level of at least 200 ppm. The water must be replaced on a daily basis even with chlorine treatment and local environmental guidelines must be followed regarding disposal of the wastewater.

One important consideration when using water during postharvest processing is that in some commodities, water and any microbial or chemical contaminant can be actively absorbed into the product during processing, especially if the produce temperature is much higher than the water temperature. When warm apples (*M. domestica*), celery (*A. graveolens*), mangoes (*M. indica*) or tomatoes (*S. lycopersicum*) are placed into cold water, a water pressure differential develops that creates a suction effect that leads to infiltration of water into the produce. Any contaminant that may be in the water is drawn into the produce, away from any possible effect of sanitizers added later. This stresses the importance of water monitoring for effective sanitizer concentration during processing to reduce the possibility of contamination (Sargent *et al*., 2007). To avoid this potential problem, the temperature of any water used for washing should be 5°C above the temperature of the flesh of the commodity and cooling should be accomplished using forced air.

Cleaning produce

During postharvest handling, one major objective, besides removal of field heat, is to clean produce for packaging and sale while avoiding bruising and contamination. Most produce should be cleaned of major debris during harvest. Additionally, most produce is relatively free of harmful microorganisms at harvest and only becomes contaminated with harmful pathogens during harvest and post-harvest processing. To minimize contamination, produce that can tolerate water after harvest is often sanitized during the packaging process. Some produce such as raspberries (*Rubus* spp.), strawberries (*Fragaria* × *ananassa*) and grapes (*Vitis* spp.) cannot tolerate water after harvest and thus cannot be sanitized.

After harvest any remaining surface soil or debris is removed with brushes or forced air, depending on the product's ability to tolerate each. In products that can tolerate water after harvest, a thorough spray wash with chlorinated water is utilized. Food-grade detergents might be used if produce is extremely dirty. A second spray wash may be needed and several spray washes are usually more effective than one long-soaking wash. Again the main concern is to use chlorinated, potable water for the washes. Soft produce is normally washed using only water sprays, while other products may be washed in flumes or with brushes. If brushes are used, they must be routinely cleaned and sanitized.

After cleaning, a sanitizing step is often used, followed by a final wash. It is important to remember that sanitizing reduces the level of pathogens on produce and does not completely eliminate them. Only sterilization, a much more rigorous process, can completely eliminate pathogens. Sterilization is usually accomplished by heat. A chlorine solution is usually used for sanitizing. Immersing produce in a chlorine solution with 50–200 ppm free chlorine for 1 to 2 min is usually sufficient for sanitizing. Chlorine solutions contain molecules of hypochlorous acid (HOCl) and its ions H^+ and OCl^-. The HOCl is the toxic component that kills microorganisms and the equilibrium between HOCl and H^+/OCl^- is determined by the pH of the solution. A lower pH favors the lethal HOCl, but can quickly corrode metal sanitizing equipment. Generally, a pH of 6.0–7.5 at 20°C is a good compromise as it allows enough of the HOCl to exist to sanitize the produce yet at the same time minimize the corrosion of equipment. Other sanitizing agents occasionally used include chlorine dioxide, bromide, iodine, trisodium phosphate, quaternary ammonium compounds, organic acids, hydrogen peroxide, peracetic acid, and ozone.

Irradiation is often cited as a controversial method of produce sanitation. To kill most pathogens, most produce would require irradiation doses that are too high and lead to softening and off-flavor development (Farkas *et al*., 1997).

Sanitation during packing, storage, and transportation

The major concern during packing, storage, and transportation of produce should once again be sanitation and prevention of contamination by harmful microorganisms while maintaining product quality. Worker hygiene and sanitation must be maintained during these stages in the handling chain and all facilities utilized during these stages, including vehicles used for transportation, must be kept clean, safe, and sanitary.

Packaging

How commodities are packaged for storage, transportation, and sale has a marked effect on how well their quality holds up during the process. Some commodities such as strawberries (*Fragaria* × *ananassa*) and raspberries (*Rubus* spp.) are harvested into the containers in which they will be stored, transported, and marketed. Other commodities such as broccoli and kale (*Brassica oleracea*) are harvested into the containers that they will be stored and shipped in, then repackaged for marketing. No matter which types of packaging are used, they all seek to maximize product longevity while maintaining quality.

The major factors that govern product stability during the marketing chain are: (i) water loss; (ii) respiration (loss of sugars); and (iii) senescence accelerated by ethylene. These factors will be investigated more thoroughly in Chapter 16, this volume. However, it makes sense to briefly consider them here.

Water loss

Water loss is important during storage, transport, and marketing from two perspectives. First, since many commodities are sold by weight, water loss is weight loss which translates into a loss in value of the product. Secondly, water loss is usually associated with a loss of textural quality of the product. Consider wilted lettuce or a head of broccoli that has dehydrated somewhat.

Most products are stored in some sort of water-retaining package after harvest. This may be a waxed box, a plastic-lined cardboard box, plastic bags, or clamshell containers. Containers are often vented to prevent the build up of excessive moisture on the produce and to allow CO_2 and ethylene to escape while maintaining the minimum O_2 requirements for maintenance respiration.

Modified atmosphere packaging (MAP)

Quality of many commodities is often maintained from harvest to market using MAP (Mir and Beaudry, 2004). MAP was originally developed in the 1940s for apple marketing. The packaging maintains an internal predetermined, commodity-specific atmosphere which is generated by the product itself. In general a high CO_2 level coupled with a low O_2 level is desired to reduce the metabolism of the produce and any potentially harmful decay organisms that may be present. MAP films are often impermeable to water, thus they retain moisture so important in product quality. The films also isolate the product from external pathogens and contaminants. A major drawback to MAP is the potential development of fermentation products and off-flavors due to excessively low O_2 levels or excessively high CO_2 levels. Commodities vary significantly in the optimum concentrations of O_2 and CO_2 and ranges for successful storage are available in Mir and Beaudry (2004).

Containers used for MAP achieve the desired gas concentrations through selective permeability, perforations in the film, or a combination of the two. Different films are available to achieve desired atmospheres. The permeability of most films changes over time and responds to changes in humidity and temperature following physical chemistry laws. The gas composition inside the container can be controlled by altering the external environment. The response of the commodity to the container's internal atmosphere can vary with species, cultivar, cultural practices, harvest method, and postharvest handling. Flushing the container with a specific gas mixture is often incorporated into the postharvest plan to achieve optimum initial internal conditions for the commodity.

In continuous films where gases must diffuse through the film, a steady state of O_2 and CO_2 is achieved only if the respiration rate is constant. The rates of O_2 uptake and CO_2 production must also be equal to their rate of diffusion through the film, which is driven by the gradients of the two gases across the film. In perforated films, gas movement is a combination of movement through the perforations and diffusion through the film. Gas movement through the perforations is usually much greater than diffusion through the film and this type of film is usually used for products having a high demand for O_2. The permeability of continuous film packaging increases with temperature while permeability of perforated packaging is not sensitive to changes in temperature.

The internal atmosphere of MAP containers is mainly a function of commodity, film characteristics, and temperature. In order to account for changes in temperature a commodity is likely to experience along the marketing chain, companies must select a strategy to maximize storage life and maintain quality. Most companies select packages based on the highest temperatures normally encountered along the marketing chain and as much as possible maintain the product at the lowest acceptable temperature. This approach accounts for the fact that temperature has more of an effect on maintaining product quality than internal-package gas concentrations (Kays, 1997). Most packages are designed to maintain internal O_2 concentrations well above the lower limit set for a specific commodity to essentially guarantee aerobic conditions at all times. Anaerobic conditions at any time would lead to rapid quality deterioration.

Condensation inside the packaging can be a problem if the commodity experiences moderate to rapid temperature changes. Condensation is often unsightly and may contribute to product decay. Films are often treated with different chemicals during manufacturing that help reduce condensation or that result in ultra-fine droplets that are nearly invisible when condensation does occur.

Ethylene is the potent, autocatalytic hormone that can accelerate or induce ripening and senescence in many commodities. Once ethylene initiates its effects, the senescing process cannot be stopped. Small sachets filled with potassium-permanganate-impregnated zeolite are often placed in the package as an ethylene scrubber. Zeolite is a mineral that is known for its odor-absorbing properties, thus these sachets also help reduce any off-odors as well. The potassium permanganate reacts with ethylene to form CO_2 and water.

Transportation

Adequate transportation from harvest to market is an integral component of successful horticultural production. An excellent reference for transportation of horticultural commodities is Ashby (2006). If the farm is a pick-your-own facility, no transportation at all is required. If products are sold on farm only transport from the field to an on-farm grading, packing, storage, and sales facility is required. In many cases, longer distance transport begins on the farm via truck, followed by transport to a main distribution center via truck, rail, ship, or air, then finally from the distribution center via truck to the marketplace. In all cases the two main concerns for any horticultural product during short- and long-distance transport are sanitation and temperature.

Temperature

Sanitation was reviewed earlier in this chapter. All vehicles and facilities involved in transport must be maintained in a clean, sanitary condition. Product temperature must be maintained as close to that recommended for any particular commodity to ensure longevity and quality. Field heat must be removed and the product transported, stored, and marketed at the appropriate temperature.

While some commodities can be shipped at ambient temperatures, most products must be maintained at an acceptable temperature by refrigeration during transport. Any deviation, either high or low, from the desired temperature can lead to a decrease in storage life and product quality. These deviations are additive in that while any individual deviation may seem inconsequential, the net effect on the product is one that is the sum of each individual infraction (Ashby, 2006). An important consideration regarding the response of commodities to temperature infractions is that injury they cause may not show up until the consumer has already purchased them and is preparing them for consumption. For example, sugar depletion in sweet corn (*Z. mays*) due to handling at warmer than required temperatures is not visible and is normally not detected until consumption. Other commodities may fail to ripen properly, have internal browning, or external pitting due to temperature extremes.

Temperature control during transport is often difficult for a number of reasons. The external environment is usually in constant flux as the transportation vehicle moves along. Heat from the vehicle and any heat entering the transport vehicle from the outside via conduction through the transport vessel or via infiltration through small cracks and holes in the vessel must be removed. Any excess heat in the commodity that was not previously removed and heat generated by product respiration must also be removed during transit. Finally, several different commodities each with separate temperature optima are often transported together.

Most transport vehicles utilize mechanical refrigeration for cooling. Mechanical cooling systems move heat from inside the transport vessel and release it outside the vessel via a circulating refrigerant. The refrigerant absorbs heat in an evaporator coil located inside the cargo container, is circulated to the condenser coil on the outside of the container to release the heat, then re-circulated via a gasoline, diesel or electric compressor back to the evaporator to absorb more heat. Most refrigeration units are controlled by a microprocessor which constantly monitors temperature and performance. Container and commodity temperature as well as transport location are often monitored via satellite uplink. Some commodities are topped with crushed ice before transport to: (i) reduce their temperature; (ii) decrease the refrigeration requirement; and (iii) reduce water loss during transit. Depending on the length of the trip and container temperature, ice may need to be replenished during transport.

When commodities are shipped during winter months in cold climates, the transport container may require heating rather than cooling to maintain an appropriate temperature. The potential for both freezing and chilling injury must be considered during transit and appropriate measures taken to ensure that neither occurs.

Humidity

Most horticultural commodities should be maintained at 85–95% RH. One of the detrimental aspects of using mechanical refrigeration systems is that they inherently remove water from the air around them, causing water to be removed from the commodity via evaporation. Water loss can be minimized by: (i) transporting only pre-cooled product which minimizes the temperature differential between the product and the air in the transport vehicle, which minimizes the water lost during cooling; (ii) maintaining a coil temperature of just a few degrees below the desired air temperature; (iii) waxing the product; (iv) utilizing semi-permeable containers or wraps; and (v) installing a humidity controller in the cargo vessel.

Controlled or modified atmospheres

Many commodities that are shipped long distances are shipped under controlled or modified atmospheres. The atmosphere inside the shipping vessel is modified with one or more gases (usually O_2, CO_2, N_2) to reduce product metabolism and retard growth of organisms that may cause spoilage. Controlled atmospheres are constantly monitored to maintain a specific gas composition while modified atmospheres are initially established at a specific composition but not monitored during transit. Modified atmospheres may also be established within containers used for retail marketing, such as bags or clamshells, rather than within the entire transit vessel. Nearly every commodity has a specific ideal atmospheric composition for storage and transit. The ideal composition of one commodity may adversely affect another, thus caution must be taken when transporting mixed loads under controlled or modified atmospheres. Additionally, temperature and humidity may modify the commodity response to the controlled or modified atmosphere.

Ethylene

Consideration should also be given to ethylene generation or sensitivity during storage. Some commodities produce large quantities of ethylene during storage and transit while others produce little or none and may be harmed by exposure to the ethylene produced by other commodities in a mixed load. Ethylene scrubbers can help reduce this problem.

Odors

In addition, some commodities have a tendency to absorb odors and should not be shipped with those producing a strong odor. For example, apples (*M. domestica*), citrus (*Citrus* spp.), onions (*Allium cepa*), and pineapples (*Ananas comosus*) often give off considerable odors. Some commodities such as apples can both give off and absorb odors (Ashby, 2006). Some transport combinations to avoid include apples or pears (*Pyrus* spp.) with potatoes (*S. tuberosum*), as the apples or pears will often acquire an 'earthy' taste if shipped with potatoes. Also apples and pears should never be shipped with celery (*A. graveolens*), cabbage (*B. oleracea* Capitata Group), onions (*A. cepa*), or carrots (*D. carota*). Citrus (*Citrus* spp.) should never be transported with onions, cabbage, cauliflower (*B. oleracea* Botrytis Group), broccoli (*B. oleracea* Italica Group), or any other strongly scented commodity.

Marketing

Once a commodity reaches its destination market, its quality and safety must be maintained via good attention to sanitation and storage conditions, most notably temperature, humidity, and ethylene levels. Some products may need to be repacked or packaged from bulk shipping containers before sale. Products should not be excessively handled during repackaging or sale, as significant bruising and quality deterioration may result. Certain commodities such as avocados, bananas, and tomatoes may require pre-sale ripening.

Food Laws and International Regulations

Food safety and security is an important global issue. Various laws and regulations within countries attempt to ensure that all food offered for sale is safe and fit for human consumption and produced, packaged, stored, and transported under sanitary conditions. Many countries also require adequate labeling of food products to provide information regarding content, country of origin, and nutritional content. Since it is far beyond the scope of this text to review the food regulations of nations individually, it is appropriate to review the international codes for food safety adopted by most countries.

Human, animal and plant health standards are necessary to ensure a safe and secure food supply and to help prevent the spread of diseases and pests from one region of the world to another. In 1994 the World Trade Organization (WTO) was formed and established two binding agreements focused on agriculture: (i) the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS); and (ii) the Agreement on Technical Barriers to Trade (TBT) (JIFSAN *et al.*, 2002). The SPS agreement seeks to ensure that measures established by governments to protect human, animal and plant health in the agricultural sector are consistent with attempts to prevent trade discrimination among adhering countries. The agreement also requires that participating countries adhere to guidelines adopted by the Food and Agriculture Organization (FAO)/World Health Organization (WHO) Codex Alimentarius Commission (CAC). Countries may, however, employ stricter guidelines when justified. Thus it provides a minimum stand by which countries must abide regarding human, animal and plant health in an agricultural context. The SPS agreement encompasses all food hygiene and safety measures including pesticides and other agricultural chemicals, as well as plant quarantine measures as established by the International Plant Protection Convention (IPPC). Animal health standards are set by the International Office of Epizootics.

The TBT agreement prevents localized technical requirements from becoming barriers to international trade and includes many measures to protect consumers from deception and fraud. For example, the TBT agreement covers standardization of quality and labeling considerations as related to international agricultural products and trade.

Codex Alimentarius literally means 'food code' and it is a set of food standards set up by the CAC that countries can adapt to their local food regulations to keep them in line with international trade. The main benefit of the code is that it provides reasonable assurances that food products are produced in a safe and hygienic manner and that they are nutritious and provide acceptable health protection. The specific codes that have been adopted by he CAC can be found online at: http://www.codexalimentarius.org/standards/en/.