Fresh-Cut Fruits

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Introduction and Overview

Fresh-cut fruit products for both retail and food service applications have enjoyed an increasing presence in the marketplace due to demand by the consumer. In the coming years, it is commonly perceived that the fresh-cut fruit industry will have unprecedented growth. For this reason, many leading fresh-cut salad manufacturers have targeted development of fresh-cut fruit products as part of their long-term business plans. However, processors of fresh-cut fruit products face numerous challenges not commonly encountered during fresh-cut vegetable processing. The difficulties encountered with fresh-cut fruit, while not insurmountable, require a new and higher level of technical and operational sophistication.

Fresh-Cut Defined for Fruits

The USDA and FDA definitions for "fresh" and "minimally processed" fruits and vegetables imply that fresh-cut (precut) products have been freshly cut, washed, packaged, and maintained with refrigeration. Fresh-cut products are raw, and even though processed (physically altered from the original form), they remain in a fresh state, ready to eat or cook, without freezing, thermal processing, or treatments with additives or preservatives (AMS 1998, Anonymous 1998). The United Fresh Produce Association defines a fresh-cut product as fruits or vegetables that have been trimmed and/or peeled and/or cut into 100% usable product that is bagged or prepackaged to offer consumers high nutrition, convenience, and flavor while still maintaining freshness. Several commodities, although botanically fruits (for example*,* cucumber, pepper, and tomato), will not be covered in this section since they are commonly classified as vegetables.

Fresh-Cut Physiology and Physiological Concerns

Once harvested, fruits are removed from their source of water, minerals, and sustenance. Fruit tissues continue to respire, using available and stored sugars and organic acids, and they begin to senesce rapidly. Postharvest quality loss is primarily a function of respiration, onset or progression of ripening (climacteric fruit), water loss (transpiration), enzymatic discoloration of cut surfaces, decay (microbial), senescence, and mechanical damage suffered during preparation, shipping, handling, and processing (Schlimme and Rooney 1994, Watada et al. 1996). Fruits destined for fresh-cut processors should be harvested as ripe as possible. This makes it critical that temperature-dependent events related to respiration, water loss, pathological decay, and ethylene production be strictly regulated during shipment (or storage) of the fruit.

During the climacteric ripening stage of many fruits, there is a dramatic increase in respiratory production of CO_2 and ethylene. Non-climacteric fruit, leafy vegetables, non-fruit vegetables, and roots and tubers do not have a surge in ethylene production and generally have only slightly increased respiration as senescence approaches. However, if severely wounded (for example, by fresh-cut processing), significant stress-induced production of CO_2, and often ethylene, occurs (Abeles et al. 1992, Brecht 1995). Fresh-cut processing increases respiration rates and causes major tissue disruption as enzymes and substrates, normally sequestered within the vacuole, become mixed with other cytoplasmic and nucleic substrates and enzymes. Processing also increases wound-induced ethylene, water activity, and surface area per unit volume, which may accelerate water loss and enhance microbial growth since sugars also become readily available (King and Bolin 1989, Watada et al. 1990, Wiley 1994, Watada and Qi 1999).

These physiological changes may be accompanied by flavor loss, cut surface discoloration, color loss, decay, increased rate of vitamin loss, rapid softening, shrinkage, and a shorter storage life. Increased water activity and mixing of intracellular and intercellular enzymes and substrates may also contribute to flavor and texture loss during and after processing. Therefore, proper temperature management during product preparation and refrigeration throughout distribution and marketing are essential for maintenance of quality.

Physical alterations and potential low-O_2 atmospheres in packages may create significant negative changes in flavor, aroma, and "mouth-feel." There are also synergistic interactions between numerous factors such as variety, source, season, initial maturity, optimum processing maturity, slicing and cutting equipment, sanitation and GRAS chemical treatments, packaging (including MAP), temperature management, shipping, handling, and length of shelf-life. The combined effect of these factors may have negative consequences on postharvest shelf-life and sensory quality. Therefore, improperly preparing, packaging, and handling fresh-cut fruit may compromise overall quality and decrease consumer acceptability.

Defining Fresh-Cut Fruit Quality

Postharvest quality and post-cutting quality are unfortunately ambiguous or confused terms. Harvest indices used to deliver optimum quality whole fruits to storage facilities, terminal markets, and the fresh markets oftentimes may not be appropriate for fruits destined to be processed (see also *Factors Affecting Fresh-Cut Fruit Quality*). Growers often destructively sample fruit before making a decision to harvest. Processor assessment of fruit maturity before cutting either upon receipt or after in-house storage is also advisable. For example, a lot of peaches that are optimally mature for fresh market may be shipped to a processor and rejected because the fruit are too soft or ripe for cutting. Determination of optimum maturity depends on the commodity and the use. The processor must understand the physiology of the fruit and the finished product (and packaging) to accurately determine when fruit is at the appropriate maturity stage to process. Choice of variety, harvest condition, maturity, storage, and shelf-life for various fresh-cut fruits are active areas of research.

Proper initial maturity of fruit is essential. However, once processed, quality is most commonly, and sometimes only, assessed visually. Visual appearance is generally the determinant for commercial shelf-life. Although some studies have found that vitamin C and carotene degrade very little during short-term (about 1 week) refrigerated storage in some fresh-cut fruits (Wright and Kader 1997a,b), other researchers are attempting to retain fresh-cut quality for 3 to 4 weeks.

Although some quality attributes may still be acceptable, overall quality in terms of aroma, taste, and texture may be jeopardized (Anonymous 2000a).

Firmness and Texture

Tissue softening is a very serious problem with fresh-cut fruit products and can limit shelf-life. Fresh-cut fruit firmness is an important quality attribute that can be affected by cell softening enzymes present in the fruit tissue (Varoquaux et al. 1990) and by decreased turgor due to water loss. For example, there was 26 to 49% firmness loss in four varieties of fresh-cut cantaloupe processed from three-quarters to full-slip maturity fruit when stored in air at 4 °C (39 °F) (Beaulieu 2002, unpublished data). Unwrapped watermelon slices lost 47% of their firmness after 4 days at 5 °C (41 °F) (Abbey et al. 1988), and firmness decreased in stored cantaloupe cubes (12 days in air at 5 °C) by more than 25% (Cantwell and Portela 1997).

Flesh firmness of fresh-cut fruit products can be maintained by application or treatment with calcium compounds. Dipping fresh-cut products in solutions of 0.5 to 1.0% calcium chloride is very effective in maintaining product firmness (Ponting et al. 1971, 1972). However, calcium chloride may leave bitter off flavors on some products. Firmness of slices from 12 untreated apple cultivars stored at 2 °C (36 °F) decreased steadily for 7 days and more rapidly thereafter (Kim et al. 1993). However, mild heat treatment of whole apples before processing maintained firmness during storage in some fresh-cut apple cultivars (Kim et al. 1994).

Firmness can sometimes be maintained by CA storage. Firmness loss averaged 2.2 lb (10 N) in honeydew cylinders after 12 days of storage in air at 5 °C (41 °F), while CA storage (air + 15% CO_2) reduced the loss significantly in one of four cultivars tested (Portela and Cantwell 1998). CA treatments (2% O_2 + 10% CO_2 at 5 °C [41 °F] and 4 % O_2 + 10% CO_2 at 10 °C [50 °F]) were more beneficial than air storage in maintaining honeydew cube quality for up to 6 days at 5 °C (41 °F) (Qi et al. 1999).

Color at the Cut Surface

An important issue in fresh-cut fruit processing is the control of discoloration (pinking, reddening, or blackening) or browning on cut surfaces. Oxidative browning is usually caused by the enzyme polyphenol oxidase (PPO), which in the presence of O_2 converts phenolic compounds in fruits and vegetables into dark-colored pigments. Outlined below are a number of strategies that may be used to reduce PPO-mediated cut-surface discoloration.

Reduced O_2. Because PPO requires O_2 to induce cut surface discoloration, reducing the amount of O_2 in a package of fresh-cut product by vacuum MAP or gas flushing may reduce cut surface discoloration, but not completely stop it. Careful design of a fresh-cut package is essential to assure that the proper amount of O_2 is present. Excessive levels of O_2 in a package may allow for cut surface discoloration to occur, while too little O_2 may cause anaerobic metabolism and production of off flavors and odors.

Acidification. PPO most effectively catalyzes cut surface discoloration at a neutral pH of approximately 7. Therefore, browning can be slowed by dipping products in mildly acidic food grade solutions of acetic, ascorbic, citric, tartaric, fumaric, or phosphoric acid. However, these acids may leave off flavors and promote tissue softening and therefore must be used with care.

Reducing Agents. Ascorbic acid or erythorbate (an isomer of ascorbic acid) are two common compounds used in the food industry to prevent PPO-mediated cut-surface discoloration. Ascorbic acid and erythorbate reduce PPO-induced discoloration at the cut surface by converting quinones (formed by PPO from phenolics) back to phenolic compounds. Unfortunately, once all the ascorbic acid or erythorbate is exhausted, PPO browning will proceed uninhibited. Ascorbic acid or erythorbate are commonly used as 1% solutions to prevent browning and discoloration of cut surfaces. These compounds are organic acids, so they may also reduce surface pH of commodities, further slowing browning.

Sensory Aspects

Fresh-cut vegetable salads have great consumer appeal because of their convenience, flexibility of use, and probably the fact that their desirable flavor often comes about via condiments (croutons, spices, or dressing) or because numerous products make up a medley mixture. However, consumer acceptance of fresh-cut fruits most often relies on the inherent flavor and texture quality of the product, seldom with accompaniments. It is generally and unfortunately assumed that "if it looks good, it tastes good." Improving consistency in fresh-cut fruit product flavor and texture may enhance consumers desire to repeatedly purchase such products.

Soluble Solids Content (SSC) and Titratable Acidity (TA). Sweetness, flesh firmness, and taste are very important characteristics for fresh-cut melon quality. In a midseason trial of 17 western cantaloupe varieties, there was an average 5% decrease in SSC (range 0 to 11%) and an average 8% decrease in sugar (range 0 to 21%) when cubes were stored 12 days (in air) at 5 °C (41 °F) (Cantwell and Portela 1997). After 9 days at 10 °C (50 °F) or 15 days at 5 °C (41 °F), SSC in CA-stored melon pieces were higher than in air: 10.3 vs. 9.5% and 10.2 vs. 9.1% at 10 and 5 °C (50 and 41 °F), respectively (Cantwell and Portela 1997). Cantaloupe balls prepared from four eastern varieties stored 8 days at 0 °C (32 °F) had an average SSC decrease of 9.7% with a range of 2.3 to 13% (Lange 1998). SSC remained somewhat constant for 7 days storage at 4 °C (39 °F) in fresh-cut cantaloupe when harvest maturity was at least half-slip, and cubes prepared from fruit harvested at quarter-slip had significantly lower initial SSC, which rapidly declined after only 5 days storage (Beaulieu and Baldwin 2002). It is well established in the food industry that sugar content (SSC) is generally positively correlated with desirable flavor quality. However, occasionally too much sugar is perceived negatively. The best sugar range for storage of fresh-cut cantaloupe was 10 to 13 °Brix. However, some judged the 13 °Brix fruit as too sweet (Anonymous 2000b).

TA and SSC have also been used to assess quality via the SSC:TA ratio in some fresh-cut fruits. Changes in TA, pH, and SSC in apple slices from 12 cultivars that were stored at 2 °C (36 °F) for 12 days were small and varied by cultivar (Kim et al. 1993). Likewise, there were changes in SSC in fresh-cut strawberries stored under various CA for 7 days at 5 °C (41 °F). However, pH increased over time (Wright and Kader 1997b). Fresh-cut persimmons stored under various CA had increased SSC for 3 days, then decreased SSC by day 8; pH tended to increase through storage (except when stored under 2% O_2) (Wright and Kader 1997b). In cantaloupe slices, a

17% loss in SSC and a 2-fold increase in TA occurred after only 2 days storage at 20 °C (68 °F), but the acidity change was attributed to lactic acid bacteria (Lamikanra et al. 2000). TA in fresh-cut oranges stored 8 days at 4 °C (39 °F) decreased 36% (Rocha et al. 1995).

Aroma and Flavor. An acceptable post-cutting visual appraisal does not necessarily imply that a product has satisfactory flavor quality. Excellent visual quality and acceptance by retailers and consumers often occur with fruits processed when immature. For example, immature peaches and nectarines will process and hold visual quality for extended periods, but rehardening and poor eating-quality limit their use (Gorny et al. 1998b, Beaulieu et al. 1999). A mature green cantaloupe at less than half-slip delivers a fresh-cut product with optimum visual shelf-life but insufficient sugar or volatile composition compared to a desirable ripe whole melon (Pratt 1971, Beaulieu and Grimm 2001, Beaulieu and Baldwin 2002). 'Makdimon' melons harvested 2 days before fully-ripe (full-slip) developed only about 25% the total volatiles as 3 day-old, fully-ripe fruit (Wyllie et al. 1996). Volatiles increased with harvest maturity, and cubes prepared from quarter-slip fruit contained only 25 to 33% of the total volatiles of full-slip fruit (Beaulieu and Baldwin 2002). Furthermore, these trends were conserved during 10 days at 4°C (39 °F) in fresh-cut products.

Flavor and aroma quality are important attributes for consumers, and these attributes should be seriously examined when determining the shelf-life of fresh-cut fruit products. Nevertheless, the quality of intact vegetables and fruits is often determined almost exclusively based on appearance, sometimes to the exclusion of flavor and texture (Sapers et al. 1997). Much variability exists in the literature regarding acceptability based on sensory evaluations, and this variability oftentimes can be attributed to different experimental designs or sensorial analyses and cultural bias. For example, sensory evaluation determined that fresh-cut honeydew, kiwi fruit, papaya, pineapple, and cantaloupe stored at 4 °C (39 °F) were unacceptable after 7, 4, 2, about 7, and 4 days, respectively (O'Connor-Shaw et al. 1994). However, fruit were not sanitized, nor were gloves worn during preparation and subsequent microbial decay and associated texture loss most likely limited post-cutting life. Sterilized, diced cantaloupe stored at 4 °C (39 °F) in various controlled atmospheres were acceptable from a sensory quality standpoint after 28 days (O'Connor-Shaw et al. 1996). Cantaloupe pieces stored at 2 °C (36°F) in ready-to-serve tray-packs were visually acceptable after 19 days, but flavor scores fell after 13 days storage (Silva et al. 1987). An informal taste panel determined that fresh-cut honeydew melon stored in air at 5 °C (41 °F) for 6 days lacked acceptable textural characteristics and were flat in flavor (Qi et al. 1998).

Fresh-cut pineapple stored at 4 °C (39 °F) had excellent visual appearance after 7 to 10 days storage; however, fruit in the lower portion of containers developed off flavors associated with microbial fermentation (Spanier et al. 1998). Fresh-cut orange segments that had acceptable appearance after 14 days storage were found to have unacceptable flavor quality after only 5 days at 4 °C (39 °F) (Rocha et al. 1995). Likewise, undesirable flavor was the limiting factor in sliced wrapped watermelon stored 7 days at 5 °C (41 °F), even though aroma was still acceptable and microbial populations were not problematic until after 8 days (Abbey et al. 1988).

Establishing overall shelf-life limits for fresh-cut fruit, taking flavor quality into consideration, is difficult since initial product variability, potential post-cutting treatments, and packaging affect flavor attributes differently. Washing whole products prior to processing and other proper sanitation practices, in combination with optimum storage temperature, are critical to maintaining quality and prolonging product life. Little is known concerning what effect storage temperature has on volatile production and little flavor and sensory work has been performed on fresh-cut fruits.

Microbiology

Microbial decay can be a major source of spoilage of fresh-cut produce (Brackett 1994). Microbial decay of fresh-cut fruit may occur much more rapidly than in vegetable products because of the high levels of sugars found in most fruit. The acidity of fruit tissue usually helps suppress bacterial growth but not growth of yeast and molds. There is no evidence to suggest that lower aerobic plate counts (APC) or total plate counts (TPC) immediately after processing correlate with increased shelf-life in fresh-cut vegetables. However, for fresh-cut fruit, very low APC, TPC, and especially yeast and mold counts correlate with increased shelf-life.

The dominant microorganisms associated with spoilage of fresh-cut vegetables are bacteria (for example, *Pseudomonas* spp.), whereas the dominant microorganisms associated with the spoilage of fresh-cut fruit products are yeasts and molds. In fresh-cut vegetables the proliferation of bacteria may be a symptom associated with tissue senescence and may not be a true cause of spoilage except in a few rare exceptions when pectinolytic *Pseudomonas* are present. However, in acidic fresh-cut fruit products, yeasts and molds are typically associated with product spoilage. Reducing initial yeast and mold counts, as well as slowing growth by low temperature storage at <5 °C (41 °F), affects product shelf-life (O'Connor-Shaw et al. 1994, Qi et al. 1999). In fresh-cut fruit with a neutral pH, such as cantaloupe, bacteria were the main source of spoilage (Lamikanra et al. 2000), and bacterial development was inhibited in fresh-cut watermelon by CA (3% O_2 and 15 or 20% CO_2). However, visual quality was compromised (Cartaxo et al. 1997).

Little research has been performed on food-borne human pathogens on fresh-cut fruits. Recently, Conway et al. (2000) determined that *Listeria monocytogenes* survived and proliferated on 'Delicious' apple slices stored at 10 or 20 °C (50 or 68 °F) in air or CA (0.5% O_2 + 15% CO_2), but did not grow at 5 °C (41 °F). CA had no significant effect on the survival or growth of *L. monocytogenes* at elevated temperatures. Botulinal toxin was not recovered in fresh-cut cantaloupe or honeydew inoculated with a 10-strain mixture of proteolytic and nonproteolytic *Clostridium botulinum* after 21 days at 7 °C (45 °F). However, toxin was recovered in some inoculated honeydew samples stored 9 days at 15 °C (59 °F) in hermetically sealed packages (Larson and Johnson 1999).

Factors Affecting Fresh-Cut Fruit Quality

Major factors affecting fresh-cut fruit quality are cultivar (Kim et al. 1993, Romig 1995), preharvest cultural practices (Romig 1995), harvest maturity (Gorny et al. 1998b), physiological status of the raw product (Brecht 1995), postharvest handling and cold storage (Watada et al. 1996), processing technique (Bolin et al. 1977, Saltveit 1997, Wright and Kader 1997b), sanitation (Hurst 1995), and packaging (Solomos 1994, Cameron et al. 1995).

General Fresh-Cut Physiology and Physiological Concerns. Most fruit are very susceptible to bruising and mechanical injury. This is very different from most fresh-cut vegetables, which may be derived from very durable root tissues (carrots, radishes) or pliable leaf tissue (iceberg lettuce, cabbage). Fresh-cut processing removes the fruit's natural cuticle, or skin barrier, to gas diffusion and microbial invasion, and severe disruption of the tissue often provokes increased respiration, ethylene production, and enhanced susceptibility to water loss and microbial decay. All of these factors may contribute to decreased shelf-life via browning, off color, softening, or decay.

Subsequently, methods for cutting and peeling fruit differ from those for vegetables. Therefore, mechanical size reduction (trimming, peeling, deseeding, etc.) by high-speed cutting equipment may not be appropriate for some fresh-cut fruit products. Knife sharpness has a significant effect on shelf-life of fresh-cut lettuce products (Bolin et al. 1977, Bolin and Huxsoll 1991), and this also applies to fresh-cut fruits. Pear slices cut with a freshly sharpened knife retained visual quality longer than fruit cut with a dull hand-slicer (Gorny and Kader 1996). Sharpening of machine and hand knives as often as possible prolongs shelf-life of fresh-cut fruit because there is less tissue injury.

Chilling Injury and Holding Temperatures. A significant number of fresh-cut fruits are not as chilling injury (CI) sensitive as the corresponding intact fruit before processing. Examples include pineapple, cantaloupe, honeydew, watermelon, peach, nectarine, and mango. If these intact fruits are stored at chilling temperatures, typically <12 °C (54 °F), accelerated physiological breakdown and increased incidence of pathological decay occurs. CI symptoms are often manifested when fruit are subsequently placed at non-chilling temperatures and may not be visible if maintained at chilling temperatures (Saltveit and Morris 1990). Nonetheless, precooling whole cantaloupe to below their optimal long-term storage temperature shortly before cutting is effective at increasing product shelf-life (Cantwell and Portela 1997, Lange 1998).

Fruit tissues normally damaged by storage at chilling temperatures are the inedible outer rind or skin portions. During fresh-cut processing, these tissues are normally removed and discarded. Although the optimal storage temperature for many whole CI-sensitive fruit is above 10 °C (50 °F), after processing storage at 0 °C (32°F) is almost always the temperature that provides optimal shelf-life by reducing growth of spoilage microorganisms. However, the edible flesh of CI-sensitive fruits may still be susceptible to chilling injury, and no studies have indicated if flavor biosynthesis is inhibited or negatively affected by chilling.

Variety, Growing Region, and Season. Seed companies and numerous fresh-cut processors are already aware that a given variety performs optimally in certain growing regions and oftentimes has variable postharvest quality attributes depending on cultural practices, climate, season, and harvest maturity. For example, the desirable volatile oil content of pineapple flesh is higher in summer fruit (Haagen-Smit et al. 1945), and the proportions of dominant apple volatiles vary by season (López et al. 1998). The aforementioned interactions, in concert with breeding against or for specific traits to optimize shelf-life, must be considered when developing cultivars tailored for the fresh-cut industry (Romig 1995). Several reports have documented that certain cultivars out-perform others with regard to fresh-cut shelf-life and quality (Kim et al. 1993, Cantwell and Portela 1997, Lange 1998, Gorny et al. 1999, Anonymous 2000b). However, no single study can encompass all desirable varieties, and singling out a "winner" can be compromised by seed source and seasonal/climactic variations. Furthermore, the industry may also be historically driven toward specific varieties (such as western cantaloupes) when indeed optimum alternatives exist for local seasonal production (such as eastern cantaloupes) (Lange 1998).

Gorny et al. (1999) determined the shelf-life of peach and nectarine slices made from 13 cultivars of peaches and eight cultivars of nectarines that had been ripened to between 4 to 7 lb (18 to 31 N) firmness, cut, and then held at 0 °C (32 °F) with 90 to 95% RH. Shelf-life was 2 to 12 days among the cultivars tested. Of the peach cultivars tested, 'Cal Red,' 'Red Cal,' and 'Elegant Lady' had the longest marketable shelf-life of 7.4, 7.2, and 6.7 days, respectively; while 'Summer Lady' and 'Ryan Sun' had the shortest (<2 days). Among nectarines, 'Sparkling Red,' 'Arctic Queen,' and 'Zee Grand' had the longest shelf-life of 12, 8, and 8 days, respectively, while the other cultivars had a shelf-life of 4 to 6 days. White-flesh peaches and nectarines had a comparable shelf-life to yellow-fleshed cultivars, with similar browning characteristics.

Based on visual quality, fresh-cut pear slices prepared from partially ripened 'Bosc' and 'Bartlett' fruit had the longest shelf-life in air at 10 °C (50 °F), being 3 and 4 days, respectively (Gorny et al. 1998a). d'Anjou' and 'Red Anjou' pear slices had a very short shelf-life of <2 days each, due to severe enzymatic browning on cut surfaces (Gorny et al. 1998a). However, 'Bartlett' and 'Bosc' pear slices experienced a much greater loss in firmness after slicing and storage in air at 10 °C (50 °F) than d'Anjou' and Red d'Anjou' slices.

Fruit Size and Yield. Typically, fresh-cut fruit processors will use either very large or very small fruit to maximize yields or to reduce the cost of raw ingredients. For example, fresh-cut melon processors will typically use very large 9-count-per-box fruit. This is because large melons are often available at lower prices in the marketplace, the yield from larger melon fruits is almost always higher, and the labor to process one large fruit is often less than processing many smaller fruit. Very little research has been done to document the effects of fruit size on post-cutting shelf-life and quality. One study by Gorny et al. (2000) found that 'Bartlett' pear fruit size did not have a significant effect on fresh-cut slice shelf-life, based on flesh color and firmness, if slices were treated after cutting with 2% ascorbate + 1% calcium lactate + 0.5% (w/v) cysteine, pH 7. However, if slices were not treated, smaller fruit discolored at their cut surface more rapidly than slices from large fruit). Small fruit also had lower SSC than large fruit, which may affect eating quality. These findings demonstrate that, in some cases, smaller whole fruit, which often receive lower prices in the marketplace, should be avoided for value-added fresh-cut products.

Physical Treatments

Many physical and chemical techniques have been studied as alternatives or adjuncts to MAP, especially for fresh-cut fruit: edible coatings (Baldwin et al. 1995a,b, 1996, Howard and Dewi 1996, Li and Barth 1998), disinfection (Hong and Gross 1998, Sapers and Simmons 1998), natural plant products (Kato-Noguchi and Watada 1997, Leepipattanawit et al. 1997, Buta et al. 1999, Moline et al. 1999), ethylene absorbents (Abe and Watada 1991), gamma irradiation (Chervin and Boisseau 1994, Hagenmaier and Baker 1997), heat treatments or heat shock (Loaiza-Velarde et al. 1997), microbial competition (Liao 1989, Breidt and Fleming 1997), non-thermal physical treatments (Hoover 1997), and pulsed-microwave irradiation (Shin and Pyun 1997)

Storage Time, Temperature, and Atmosphere. The beneficial effects of CA storage for whole fruit have been well documented, and CA is widely employed throughout the industry. However, CA storage markedly inhibits apple volatile production (Yahia 1991, 1994, Mattheis et al. 1995). Furthermore, fruit maturity at harvest has been shown to be important in terms of volatile production in melons (Pratt 1971, Wyllie et al. 1996, Beaulieu and Grimm 2001, Beaulieu and Baldwin 2002) and in apples (Hansen et al. 1992, Brackmann et al. 1993, Yahia et al. 1990), especially once apple fruit were removed from CA and ripened 10 days at 20 °C (68 °F) (Mattheis et al. 1995). In fresh-cut 'Gala' apples stored for 14 days at 1 °C (34 °F) in sealed pouches, sugars remained constant during storage, pH decreased, and TA, sweetness, and sweet aromatic flavor all increased and then decreased (Bett et al. 2001). Therefore, certain packaged fresh-cut products may require active modification of the atmosphere to ensure desirable flavor during consumption.

Gorny et al. (2002) determined that, compared to air storage, CA (2% O_2 + 98% N_2) storage at -1 °C (30 °F) of whole mature-green pears extended shelf-life of slices 1 to 2 days. There was a significant reduction in shelf-life of pear slices stored at -1 °C (30 °F) in air or CA compared to slices from freshly harvested pears. Therefore, it seems beneficial to use CA for off-season pears (as opposed to air-stored) to maximize post-cutting life of slices. However, research is needed to determine if volatile synthesis is impaired, as in CA-stored apples.

Modified Atmosphere Packaging (MAP). MAP is widely used for fresh-cut vegetables, but with fruits occasionally undesirable atmospheres can reduce quality due to off flavor and discoloration (Gil et al. 1998).

Heat Treatment. Slices prepared from heat-treated apples at 45 °C (113 °F) for 105 min, that did not display browning after treatment ('Delicious,' 'Empire,' 'Golden Delicious,' 'McIntosh' and 'New York 674'), were firmer (differences ranging from 12% for 'McIntosh' to 48% for 'Delicious') after 8 days storage at 2 °C (36 °F) than those prepared from untreated apples (Kim et al. 1994). However, heat treatments often led to undesirable flesh browning in many other cultivars tested (Kim et al. 1994).

Irradiation. Irradiation of fresh-cut fruit products may be beneficial in reducing the number of bacteria present on the product. The current FDA limit for irradiation on fresh produce is 1.0 kGy, but to destroy yeasts and molds that may exist as spores, irradiation levels of 1.5 to 20 kGy are necessary (Brackett 1987); and these levels are damaging to fruit tissues. Irradiation reduced ethylene production of all pre- versus post-climacteric apple slices and irradiation doses of up to 2.4 kGy had minimal effect on the respiratory physiology of tissues (Gunes et al. 2000). However, tissue softening occurred at doses above 0.4 kGy. Therefore, the use of irradiation to extend the shelf-life of fresh-cut fruit products has only limited benefits since the main spoilage microorganisms on fresh-cut fruit products are yeasts and molds.

Chemical Treatments

Retention of fresh-cut product firmness and inhibition of browning are common measures used to determine efficacy of chemical treatments. Calcium has been used as an agent for maintaining firmness on whole produce (Poovaiah 1986), and its use in fresh-cut was inevitable. Other chemical treatments have also been explored, and most GRAS applications used today involve chlorine, ascorbic acid, or calcium salts for preservation.

Chlorination and Washes. In general, fresh-cut fruit should be rinsed just after cutting with cold (0 to 1°C, 32 to 34 °F) chlorinated water at pH 7.0. This may help extend product shelf-life by reducing microbial load, removing cellular juices at cut surfaces that may promote cut surface discoloration, and actually inhibiting the enzymatic reactions involved in fruit browning (Brecht et al. 1993, Hurst 1995).

Chlorination, as commonly used for fresh-cut salad sanitation (not exceeding 200 $\mu L\ L^{-1}$ total chlorine), may not be desirable for all fresh-cut fruits. Post-cutting washing or dipping may have negative consequences regarding increased water activity and "washing away" of desirable flavor attributes. Processors may or may not wash freshly cut commodities that develop little or no browning (cantaloupe and honeydew, for example), since chemical treatments are seldom applied and because removal of free surface water (centrifugation or spinning) from the cut fruit can be damaging. On the other hand, honeydew and cantaloupe pieces dipped in hypochlorite (pH 6, 50 $\mu L\ L^{-1}$) prior to packaging in 95% N_2 + 5% O_2 at 2 °C (36 °F) had no deleterious effect and microbial counts were lowered throughout storage (Ayhan et al. 1998).

Hydrogen peroxide (H_2O_2) is a strong oxidizing agent and a powerful surface-contact sterilizer. It has been shown experimentally to reduce microbe populations on the surface of many produce items with minimal to no residue (Bolin and Huxsoll 1989, Sapers and Simmons 1998). However, the GRAS status regarding use on fresh-cut products is currently unclear.

Calcium Compounds and Firmness Retention. Application of aqueous calcium compounds (generally 1% $CaCl_2$ dips) helps maintain firmness of fresh-cut apples, pears, and strawberries (Ponting et al. 1971, 1972, Morris et al. 1985, Rosen and Kader 1989, Gorny et al. 1998a). Softening of muskmelon sections was affected differently depending on calcium concentration (Lester 1996). Softening was the major factor in quality loss in kiwifruit slices. However, these slices had a shelf-life of 9 to 12 days if treated with 1% $CaCl_2$ or 2% calcium lactate and stored at 0 to 2 °C with >90% RH in 2 to 4% O_2 and/or 5 to 10% CO_2 (Massantini and Kader 1995, Agar et al. 1999). Cantaloupe cylinders treated with 1, 2.5, and 5% $CaCl_2$ for 1 to 5 min and stored 10 days at 5 °C (41 °F) generally increased in firmness (Luna-Guzmán et al. 1999).

Calcium lactate has recently been shown to be as effective as the chloride form without imparting a bitter flavor at higher concentrations (Luna-Guzmán and Barrett 2000). A 1% calcium lactate dip was an effective alternative to ascorbate in fresh-cut 'Bartlett' pears stored 1 to 2 days at 20 °C (68 °F), and 1% calcium lactate with 2% ascorbate was most effective (Gorny et al. 1998a).

Antibrowning Compounds. Many fruits brown rapidly after cutting, and extensive work has been performed to address this quality loss. Cut surface discoloration or enzymatic browning, caused by formation of quinones in the presence of O_2 and PPO, has been the subject of much research (Vámos-Vigyázó 1981, Sapers 1993). Since sulfite use as an anti-browning agent in the United States requires labeling for fresh produce, alternative GRAS and experimental compounds have been investigated. Nevertheless, enzymatic browning still represents a major challenge with fresh-cut fruit (Weller et al. 1997, Sapers and Miller 1998).

Ascorbate, citrate, isoascorbate, and sodium erythorbate are some of the most commonly used agents to reduce or eliminate cut-surface discoloration. Ascorbate was more effective than erythorbate in preventing surface browning in 'Winesap' and 'Red Delicious' apple plugs stored 24 h, and 1% citric acid enhanced their effectiveness (Sapers and Zoilkowski 1987). Cut surface discoloration was restricted in vacuum-packed carambola slices stored at 4 °C (39 °F) that were treated with 1 or 2.5% citrate plus 0.25% ascorbate (Weller et al. 1997). Ascorbate-2-phosphate and ascorbate-2-triphosphate also decreased cut surface discoloration in 'Red Delicious' apple plugs for 24 h (Sapers et al. 1989). 'Fuji' apple slices treated with 2% ascorbate had no browning or loss of visual quality for up to 15 days when stored at 10 °C (50 °F) in 0.25% O_2 (Gil et al. 1998). Calcium, in combination with ascorbate, was effective in preventing discoloration of fresh-cut apples (Ponting et al. 1972) and pears (Rosen and Kader 1989, Gorny et al. 1998a). Browning was also reduced in fresh-cut 'Carnival' peaches treated with 1% calcium lactate plus 2% ascorbate (Gorny et al. 1999).

Browning was retarded in slightly under-ripe 'Bartlett' and 'd'Anjou' pears treated with a combination of sodium erythorbate, $CaCl_2$, and 4-hexylresorcinol after 14 days storage at 4 °C (39 °F). However, fresh-cut 'Bosc' pears browned severely irrespective of inhibitor treatment (Sapers and Miller 1998). On the other hand, a combination dip with 0.01% 4-hexylresorcinol, 0.5% ascorbate, and 1% calcium lactate extended shelf-life of 'Anjou,' 'Bartlett,' and 'Bosc' pear slices for 15 to 30 days (Dong et al. 2000). Furthermore, combined treatments with 1 mM 4-hexylresorcinol, 0.5 M isoascorbate, 50 mM potassium sorbate, and 25 mM *N*-acetylcysteine decreased browning in fresh-cut 'Anjou,' 'Bartlett,' and 'Bosc' pears for 14 days. The preservative effect was unaffected by initial firmness (4.7 to 11.7 lb, 21 to 52 N) for 'Anjou' slices (Buta and Abbott 2000).

'Red Delicious' apple slices treated with a combined antibrowning dip (4-hexylresorcinol, isoascorbic acid, *N*-acetylcysteine, and calcium propionate) and held at 5 °C (41 °F) maintained visual quality for 5 weeks, yet microbial decay was evident after 4 weeks (Buta et al. 1999). Analyses of organic acids and sugars revealed that slices treated with combinations of antibrowning compounds retained higher levels of malate and had no decrease in sugar levels at 5 and 10 °C (41 and 50 °F), indicating that higher quality was maintained during storage. Fresh-cut mangoes treated with 1 mM 4-hexylresorcinol, 50 mM potassium sorbate, and 500 mM ascorbic acid in MAP at 10 °C (50 °F) maintained color and sensory characteristics, with low microbial growth, for 14 days (Gonzalez-Aguilar et al. 2000). Cut-surface discoloration was significantly reduced in fresh-cut banana slices treated with 500 mM citrate and 50 mM *N*-acetylcysteine and stored at 5 °C (41 °F) or 15 °C (59 °F) for 7 days, and no microbial decay was observed (Moline et al. 1999). A combination of 0.5% carrageenan and 0.5% citrate also inhibited browning in diced 'Granny Smith' and 'Red Delicious' apples for 7 to 9 days at 3 °C (37 °F) (Tong and Hicks 1991).

Cysteine inhibits PPO-mediated enzymatic browning (Joslyn and Ponting 1951, Molnar-Perl and Friedman 1990, Gunes and Lee 1997). Three mechanisms have been proposed to explain how thiol compounds inhibit enzymatic browning: reduction of *o*-quinone back to *o*-dihydroxyphenol (Kahn 1985); direct inhibition of PPO (Dudley and Hotchkiss 1989, Robert et al. 1996); and formation of a colorless cys-quinone adduct (Richard et al. 1991).

When cysteine is used as an inhibitor of enzymatic browning on sliced apples (Walker and Reddish 1964) or pears (Sapers and Miller 1998), pinkish-red off-colored compounds are formed due to phenol regeneration with deep color formation (Richard-Forget et al. 1992). If off-color formation can be prevented, cysteine may prove to be an effective replacement to bisulfites. Cysteine is a naturally occurring amino acid that has GRAS status for use as a dough conditioner (Code of Federal Regulations 21:184.1271 and 21:184.1272). Development of cut surface discoloration was reduced for only 1 day at 0 °C (32 °F) in 'Golden Delicious' fresh-cut apples treated with 0.1% cysteine (Nicoli et al. 1994). Ineffectiveness of the cysteine treatment was attributed to oxidation in the package and likely was due to the low concentration applied. Recently, Gorny et al. (2002) reported that a post-cutting dip (pH 7.0) of 2% ascorbate, 1% calcium lactate, plus 0.5% (weight by volume) cysteine significantly extended shelf-life of 'Bartlett' pear slices by inhibiting loss of firmness and preventing browning. Consumer panelists could not distinguish between pear slices treated with the preservative and controls. After 10 days in air at 0 °C (32 °F), 82 and 70% of consumers judged treated pear slices to be acceptable in appearance and flavor, respectively.

When used in combination with ascorbic acid, 4-hexylresorcinol is an effective inhibitor of cut discoloration on many fresh-cut fruit, including apples and pears especially (Monslave-Gonzalez et al. 1993, Luo and Barbosa-Cánovas 1996, 1997, Sapers and Miller 1998, Moline et al. 1999, Buta and Abbott 2000, Dong et al. 2000). Between 1 and 7 $\mu L\ L^{-1}$ of residual 4-hexylresorcinol was necessary to prevent browning on fresh-cut pear slices stored up to 14 days at 2 to 5 °C (36 to 41 °F) (Dong et al. 2000). Although it is effective in preventing cut surface browning, it is not currently considered GRAS by the FDA and may not be used on fresh-cut fruit. It may also impart an unacceptable off flavor on fruit products.

Antimicrobials, Edible Coatings, and Other Treatment Compounds. Hexanal is a natural aroma precursor in apples that is readily converted to aroma volatiles in vivo by fresh-cut apple slices (Song et al. 1996). Hexanal can not only enhance aroma, but it also reduced enzymatic browning at cut surfaces, as well as inhibiting molds, yeasts, and mesophilic and psychrotrophic bacteria in 'Granny Smith' slices stored at 15 °C (59 °F) (Lanciotti et al. 1999). The inclusion of hexanal and *(E)*-hexenal in the MAP (70% N_2 + 30% CO_2) of sliced 'Granny Smith' apples reduced spoilage microbe populations and increased color stability for up to 16 days at abusive storage temperatures (Corbo et al. 2000). Research is currently in the initial stages for the use of volatile compounds on fresh-cut products; hexanal is not currently approved for use.

Methyl jasmonate is a naturally occurring volatile compound, found in many plants, that has hormonelike activity at low concentrations. Exogenously applied methyl jasmonate is effective in reducing mold growth on fresh-cut celery and peppers and may have applications as a naturally derived fungicide (Buta and Moline 1998).

Edible coatings have been used in an attempt to preserve fresh-cut products because the coatings act as barriers to water loss and gas exchange, creating a micromodified atmosphere around products, and can serve as carriers for other GRAS compounds (Baldwin et al. 1995a). Ethylene production and CO_2 evolution were reduced in apple slices coated with double layers of buffered polysaccharide/lipid, stored at 23 °C (73 °F) (Wong et al. 1994). Use of a cellulose-based edible coating on fresh-cut apple cylinders stored in overwrapped trays at 4 °C (39 °F) increased shelf-life by about 1 week (Baldwin et al. 1996). The effectiveness of ascorbate to reduce browning and potassium sorbate to decrease microbial growth was superior when incorporated into this edible coating. A commercially available sucrose ester edible coating also inhibits browning of fresh-cut fruit by acting as an O_2 barrier.

Peeled, packaged citrus products have a shelf-life of approximately 17 to 21 days, but fluid leakage can be problematic. Edible wax microemulsion coatings (up to 12% SSC) reduced leakage of dry-packed grapefruit segments by 80% after 2 weeks and by 64% after 4 weeks (Baker and Hagenmaier 1997). Coatings could be made with polyethylene, candelilla, or carnauba wax with lauric, stearic, palmitic, oleic, or myristic acids. Carnauba wax was most effective, and coatings were not detected by informal taste panels (Baker and Hagenmaier 1997).

Compendium of Recommendations and Data Related to Fresh-cut Fruit Products

Proper storage temperature and atmosphere are the two most important factors that influence post-cutting shelf-life of fresh-cut fruit. Tables 1 and 2 identify optimum storage atmospheres, temperatures, and respiration rates for a range of fresh-cut fruits. This information may be used as a starting point for design and testing of MAP for fresh-cut fruit products. Fresh-cut fruit respiration rates, as well as responding to atmospheric modification, will vary depending on many factors, including variety and maturity of fruit at cutting.

Table 1. Respiration rates for fresh-cut fruits in air at various storage temperatures.

Fresh-cut product	Temperature (ºC)				
	0 to 2.5	4 to 5	10	15	20 to 23
	mg CO_2 kg^{-1} h^{-1}				
Apple, sliced					
'Fuji'	—	—	6.7-19.0	—	—
Cantaloupe, cubed	4.0-16.0	5.9-31.2	11.4	—	54.0
Honeydew, cubed	3.6-10.2	—	—	18.9-85.1	—
Kiwifruit, sliced	2.0-6.0	—	—	—	32.4-46.8
Orange, sliced	—	5.3-5.7	—	—	30.8-32.9
Peach, sliced	6.0-12.0	11.7-44.9	32.3-100.7	—	—
Pear, sliced					
'Bartlett'	0.0-10.0	—	22.8-30.4	—	90.0
'Bosc'	—	—	15.2-26.6	—	—
'd'Anjou'	—	—	13.3-26.6	—	—
'Red d'Anjou'	—	—	11.4-26.6	—	—
Pineapple, cubed					
mature green	4.0-5.0	—	6.7-15.2	—	—
Golden	11.0-14.0	—	24.7-30.4	—	—
Pomegranate, arils	1.0-4.0	2.9-5.9	5.7-11.4	—	—
Strawberry, sliced	—	11.1	—	—	315.0

From Gorny (1998), updated based on references cited in this chapter.

To get mL CO_2 kg^{-1} h^{-1}, divide the mg kg^{-1} h^{-1} rate by 2.0 at 0 °C (32 °F), 1.9 at 10 °C (50 °F), and 1.8 at 20 °C (68 °F). To calculate heat production, multiply mg kg^{-1} h^{-1} by 220 to get BTU ton^{-1} day^{-1} or by 61 to get kcal $tonne^{-1}$ day^{-1}.

Table 2. Storage atmosphere recommendations for selected fresh-cut fruits.

Fresh-Cut Product	Temperature	Atmosphere O_2	CO_2	Efficacy
	ºC	-------------%	------------	
Apple, sliced	0-5	<1	—	moderate
Cantaloupe, cubed	0-5	3-5	6-15	good
Honeydew, cubed	0-5	2	10	good
Kiwifruit, sliced	0-5	2-4	5-10	good
Mango, cubed	5	2-4	10	moderate
Orange, sliced	0-5	14-21	7-10	moderate
Peach, sliced	0	1-2	5-12	poor
Pear, sliced	0-5	0.5	<10	poor
Persimmon, sliced	0-5	2	12	poor
Pomegranate, arils	0-5	-	15-20	good
Strawberry, sliced	0-5	1-2	5-10	good
Watermelon, sliced	3	3	10-20	poor

From Gorny 1998, updated based on references cited in this chapter such as Rattanapanone and Watada 2000.

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