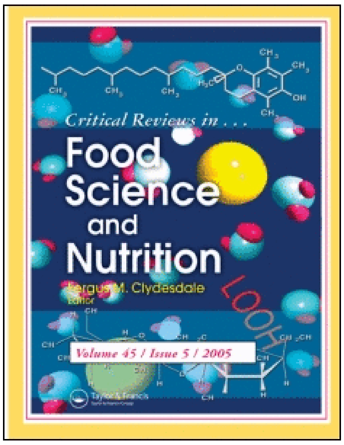

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Color, Flavor, Texture, and Nutritional Quality of Fresh-Cut Fruits and Vegetables: Desirable Levels, Instrumental and Sensory Measurement, and the Effects of Processing

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Color, Flavor, Texture, and Nutritional Quality of Fresh-Cut Fruits and Vegetables: Desirable Levels, Instrumental and Sensory Measurement, and the Effects of Processing

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The color, flavor, texture, and the nutritional value of fresh-cut fruit and vegetable products are factors critical to consumer acceptance and the success of these products. In this chapter, desirable and undesirable quality attributes of fresh-cut fruit and vegetable products are reviewed. Both instrumental and sensory measurements for determining these critical quality attributes are discussed. The advantages and disadvantages of sensory and instrumental quality measurements are described. A review of typical unit operations involved in the production of fresh-cut products is presented. The effects of fresh-cut processing techniques and treatments on sensory quality, including the appearance, texture, flavor (taste and aroma) of vegetables, and fruits are detailed.

Keywords fresh-cut, fruit, vegetable, quality, color, texture, flavor, nutrients

COMPONENTS OF FRUIT AND VEGETABLE QUALITY

Quality Defined

Quality is a term which denotes a degree of excellence, a high standard or value. Kramer (1965) stated that: *Quality of foods may be defined as the composite of those characteristics that differentiate individual units of a product, and have significance in determining the degree of acceptability of that unit to the user.*

Attributes of Fruit and Vegetable Quality

In reference to fruits and vegetables, the characteristics that impart distinctive quality may be described by four different attributes—1) color and appearance, 2) flavor (taste and aroma), 3) texture and 4) nutritional value. As consumers, these four attributes typically affect us in the order specified above, for example we evaluate the visual appearance and color first, followed by the taste, aroma, and texture. Kramer (1965) stated that the appearance of the product usually determines whether a product is accepted or rejected; therefore this is one of the most critical quality attributes. Nutritional value is a hidden characteristic that affects our bodies in ways that we cannot perceive, but this quality attribute is becoming increasingly valued by consumers, scientists, and the medical profession.

We eat with our eyes. The shape, size, gloss, and vibrant color of a fruit or vegetable attract us and entice us into picking it up by hand or fork. Once we are attracted by the appearance and color of a product, we put it into our mouths, where the aroma and taste take over. Freshness, spiciness, sweetness, and other flavor attributes are critical to our eating pleasure. Aroma refers to the smell of a fruit or vegetable product, whereas flavor includes both aroma and taste. Once the product is placed in the mouth, one can perceive the smoothness, thickness, firmness,

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hardness, or crispness of the fruit or vegetable material. As chewing proceeds, the perception of textural quality changes and products generally become softer. Nutritional value is an extremely important quality component that is impossible to see, taste, or feel. Nutrients are critical for the growth and long-term development of our bodies, and include both "micro" nutrients and "macro" nutrients. There are some associations between textural attributes, especially juiciness and flavor and between the color and nutritional composition of fruits and vegetables.

CHEMICAL AND PHYSICAL BASIS FOR FRUIT AND VEGETABLE QUALITY

Color

Color is derived from the natural pigments in fruits and vegetables, many of which change as the plant proceeds through maturation and ripening. The primary pigments imparting color quality are the fat soluble chlorophylls (green) and carotenoids (yellow, orange, and red) and the water soluble anthocyanins (red, blue), flavonoids (yellow), and betalains (red). In addition, enzymatic and non-enzymatic browning reactions may result in the formation of water soluble brown, gray, and black colored pigments. The enzymes involved in browning reactions include polyphenol oxidase, which catalyzes the oxidation of polyphenolic compounds, and phenylalanine ammonia lyase, which catalyzes the synthesis of precursors to phenolic substrates.

The chlorophylls are sensitive to heat and acid, but stable to alkali whereas their counterpart carotenoids are sensitive to light and oxidation but relatively stable to heat. Carotenoids may be bleached by an enzyme called lipoxygenase, which catalyzes the oxidation of lipid compounds. Anthocyanins are sensitive to both pH and heat, while the flavonoids are sensitive to oxidation but relatively stable to heat. Betalains are heat sensitive as well (Clydesdale and Francis, 1976).

Appearance is determined by physical factors including the size, the shape, the wholeness, the presence of defects (blemishes, bruises, spots, etc.), finish or gloss, and consistency. Size and shape may be influenced by cultivar, maturity, production inputs, and the growing environment. It is important for fruits and vegetables to be of uniform size and characteristic shape (Mitcham et al., 1996). Some consumers associate larger size with higher quality. The wholeness and absence of defects will be affected by exposure to disease and insects during the growing period and the harvest and postharvest handling operations. Mechanical harvesting, for example, may incur more bruises and cracks in fruits and vegetables than hand harvesting. Fruit and vegetable gloss are related to the ability of a surface to reflect light and freshly harvested products are often more glossy (Mitcham et al., 1996). Gloss is affected by moisture content, wax deposition on the surface, and handling practices postharvest. Consistency or smoothness may be used as an appearance term, but is typically applied to semi-solid products, where it indicates the product thickness.

Flavor—Aroma and Taste

Flavor has been defined (Anon, 1959) as: A mingled but unitary experience which includes sensations of taste, smell, and pressure, and often cutaneous sensations such as warmth, color, or mild pain. Flavor is typically described by aroma (odor) and taste. Aroma compounds are volatile—they are perceived primarily with the nose, while taste receptors exist in the mouth and are impacted when the food is chewed. While color and appearance may be the initial quality attributes that attract us to a fruit or vegetable product, the flavor may have the largest impact on acceptability and desire to consume it again. Taste has been divided into five primary tastes—sweet, sour, salty, bitter, and umami. Umami can be described as a taste associated with salts of amino acids and nucleotides (Yamaguchi and Ninomiya, 2000). Odors are much more diverse and difficult to classify, but an attempt by Henning (Gould, 1983) includes the following—spicy, flowery, fruity, resinous or balsamic, burnt, and foul.

Stevens (1985) stated that it is possible to classify vegetables into two major groups, depending on their flavor characteristics. The first group of fruits and vegetables has a strong flavor that can be attributed to a single compound or group of related compounds. Bananas with isoamylacetate, onions with characteristic sulfide compounds, and celery, with distinctive phthalides are examples of this group. The second group of fruits and vegetables includes those whose flavor is determined by a number of volatiles, none of which conveys the specific characteristic aroma. Examples in this group include snap beans, muskmelons, and tomatoes.

In the evaluation of fruit and vegetable flavor, it is important to consider "off-flavors" as well as desirable ones. These off-flavors may be produced through the action of enzymes such as lipoxygenase or peroxidase, which form reactive free radicals and hydroperoxides that may catalyze the oxidation of lipid compounds. When these reactions occur, the result may be the development of undesirable flavors described as rancid, cardboard, oxidized, or wet dog. However, there are instances of enzyme-catalyzed reactions that result in desirable flavors. For example, hydroperoxide lyase catalyzes the production of typical tomato flavors (Anthon and Barrett, 2003).

Texture

Textural parameters of fruits and vegetables are perceived with the sense of touch, either when the product is picked up by hand or placed in the mouth and chewed. In contrast to flavor attributes, these characteristics are fairly easily measured using instrumental methods. Most plant materials contain a significant amount of water and other liquid-soluble materials surrounded by a semi-permeable membrane and cell wall. The texture of fruits and vegetables is derived from their turgor pressure, and the composition of individual plant cell walls and the middle lamella "glue" that holds individual cells together. Cell walls are composed of cellulose, hemicellulose, pectic substances, proteins, and in the case of vegetables, lignin. Tomatoes are an example of a fruit vegetable that is approximately 93–95% water and 5–7% total solids, the latter comprised of roughly 80–90% soluble and 10–20% insoluble solids. The greatest contributor to the texture of tomato products are the insoluble solids, which are derived from cell walls. The three-dimensional network of plant cell walls is still unresolved, but is a topic of great interest to scientists in that to a large degree it dictates the perception of consistency, smoothness, juiciness etc. in fruit and vegetable tissues (Waldron et al., 2003).

According to Bourne (1982) the textural properties of a food are the "group of physical characteristics that arise from the structural elements of the food, are sensed by the feeling of touch, are related to the deformation, disintegration and flow of the food under a force, and are measured objectively by functions of mass, time, and distance." The terms texture, rheology, consistency, and viscosity are often used interchangeably, despite the fact that they describe properties that are somewhat different. In practice the term texture is used primarily with reference to solid or semi-solid foods; however, most fruits and vegetables are viscoelastic, implying that they exhibit combined properties of ideal liquids, which demonstrate only viscosity (flow), and ideal solids, which exhibit only elasticity (deformation).

Nutritional Value

Fruits and vegetables are a major source of both "macro" nutrients such as fiber and carbohydrates, and "micro" nutrients such as Vitamin C, B complex (thiamin, riboflavin, B_6, niacin, folate), A, E, minerals, and the lesser-studied polyphenolics, carotenoids, and glucosinolates. Nutrients may be classified as either water or lipid soluble—meaning they dissolve in water or a lipid medium. Water soluble nutrients include Vitamin C, B complex, polyphenolics, and glucosinolates. Fat soluble nutrients include Vitamin A, E, and other carotenoids such as lycopene and β-carotene. Vitamin C is one of the most sensitive vitamins, being degraded relatively quickly by exposure to heat, light, and oxygen. For this reason it is often used as an index of nutrient Department of Health and Human Services and the degradation.

The 2005 Dietary Guidelines for Americans, published jointly by the U.S.Department of Agriculture (http://www.health.gov/DietaryGuidelines/), suggest that both males and females increase their overall fruit and vegetable consumption to 9 servings (about 4.5 cups) a day for a 2000 calorie diet. This is an increase of 50 to over 100 percent from current average consumption by U.S. consumers.

USDA AND CALIFORNIA GRADE STANDARDS

U.S. and California grade standards for fresh and processed fruits and vegetables have been summarized by Kader (2002). U.S. standards (USDA, 1998) are voluntary, except when they are required by state and local regulations, industry marketing orders, or for export marketing. In addition to these federal grade standards, the California Agricultural Code specifies mandatory minimum standards for the quality of many fruits and vegetables (CDFA, 1983). Quality factors for fruits include the following—maturity, firmness, the uniformity of size and shape, the absence of defects, skin and flesh color. Many of the same quality factors are described for vegetables, with the addition of texture-related attributes such as turgidity, toughness, and tenderness.

DESIRABLE AND UNDESIRABLE QUALITY ATTRIBUTES IN FRESH-CUT FRUITS AND VEGETABLES

Fresh-cut fruits and vegetables must have an attractive appearance, acceptable flavor, appropriate texture, and a positive nutritional image to attract initial and continued purchases by consumers. Consumers may try a new product if attracted by its appearance, but they are unlikely to repurchase an item if it fails to deliver on the promise of that appearance. Quality can be viewed from either a product or a consumer orientation (Shewfelt, 1999). A consumer orientation views the product through the sensory perspective of the consumer at the points of purchase and consumption (Shewfelt and Prussia, 1993). Consumers often buy the first time based on appearance, but repeat purchases are driven by expected quality factors determined by flavor compounds and texture (Beaulieu, 2006a; Waldron et al., 2003).

Color and Appearance

Color and appearance attract the consumer to a product and can help in impulse purchases. At the point of purchase the consumer uses appearance factors to provide an indication of freshness and flavor quality. External appearance of a whole fruit is used as an indicator of ripeness, although it can be a misleading one (Shewfelt, 2000a). Consumers have a preferred color for a specific item (Crisosto et al., 2003). Bananas are supposed to be yellow with no brown spots, tomatoes red not orange, cherries red not yellow, and kiwifruit green-fleshed not yellow. With the exception of the outside of a few fruits like Bosc pears and kiwifruit, fresh fruits and vegetables should not be brown. Gloss on the outside of whole fruits tends to be a desirable attribute for whole fruits. Fresh-cut fruits and vegetables must appear to be fresh, generally indicated by the brightness of color and the absence of visual defects or drip. Sheen on the outside of most cut fruits is preferred to a dried appearance. Color and appearance of the package can also influence the purchase decision.

Just as an attractive product can stimulate impulse purchases, an unattractive appearance can repel a consumer away from an intended purchase. Colors that are not appropriate for the item, indicative of loss of freshness or suggestive of a lack of ripeness, can turn away willing consumers. Some consumers tend to reject sweet (yellow with brown spots) bananas, nutritious, high β-carotene (yellow and orange) tomatoes, and flavorful Ranier (yellow with red blush) cherries due to unexpected coloration. Wilting, browning, dull colors, and drip are all indicators of loss of freshness in fresh-cut vegetables (Shewfelt, 1993).

White blush in cut carrots is a quality defect (Emmambux and Minnaar, 2003). Russet (brown) spotting and brown stain (Kader and Saltveit, 2003) (two separate disorders) are undesirable visual defects in lettuce. Visible wilting in lettuce and celery and shriveling in fruits reduce consumer acceptability. Yellowing in green vegetables due to loss of chlorophyll is unacceptable (Shewfelt, 2003). Less intensity of color indicates lack of ripeness in fresh-cut fruits. Browning is a serious quality defect in fresh-cut fruits. Many purchasers of organic fruits and vegetables may actually favor items with visual defects as evidence of authenticity.

Flavor

Flavor of fresh-cut fruits is more important than for fresh-cut vegetables due to the way the products are consumed. Fresh-cut vegetables tend to be consumed as components of salads or sandwiches. Since fresh-cut fruits are more likely to be consumed without other ingredients, they must be sweet without the presence of off-flavors. Since sweetness increases with ripening and ripe fruits deteriorate more rapidly, most fruits are harvested before full sweetness has been achieved. Sweetness does not increase in coated, cut cantaloupe during storage (Eswaranandam et al., 2007), and it is unlikely that significant increases in sweetness will occur in other fresh-cut fruits after packaging. Development of more intense aroma has been achieved by feeding precursors into the atmosphere of strawberry tissue cultures and fruit (Zabetakis and Holden, 1997), but this technique is not being used commercially.

Bitterness is an undesirable taste found in some fresh-cut vegetables such as salad greens (Dinehart et al., 2006). When Cruciferae cells are ruptured, glucosinolates undergo enzymatic hydrolysis with the endogenous myrosinase enzymes, releasing thiocyanates, isothiocyanates (Wattenberg, 1978), sulphate, and glucose (Ju et al., 1982). Processing and packaging precautions must be taken to ensure that off-odors and off-flavors do not jeopardize the marketability of shredded Crucifer products. Sourness is an indication of the use of immature fresh-cut fruits such as may occur in the case of apples (Harker et al., 2003).

Texture

Consumers have clear expectations for the texture of fresh-cut vegetables and fruits. Salad vegetables like lettuce, carrot, celery, and radish should be crisp. Soft fruits such as cantaloupe and peach should yield to chewing without being mushy. Other fruits like apples should be crisp and crunchy. While consumers generally cite flavor as the most important quality attribute for fruits and vegetables, textural defects and the interaction of flavor and texture are more likely to cause rejection of a fresh product (Harker et al., 2003). Consumer and panel testing indicates that they are actually more sensitive to small differences in texture than flavor (Beaulieu et al., 2004; Shewfelt, 1999). Undesirable textural attributes are the opposite of the desirable ones. Wilted lettuce, limp carrots or celery, and flaccid radish are unacceptable as are crunchy or mushy cantaloupes and peaches. Soggy or mealy apples are also likely to be rejected.

Nutritional Value

Consumers expect fresh fruits and vegetables to be good sources of dietary fiber and many vitamins and minerals. Unfortunately they have no way of distinguishing between individual products that have high versus low concentrations of phytonutrients. Many factors contribute to the nutrient content of a fruit or vegetable available for sale including genetics, growing conditions (light, temperature, etc.) and production practices (fertilization, irrigation, etc.), maturity at harvest, and postharvest handling conditions. During storage little change occurs in dietary fiber and mineral content, but the vitamins are lost. Cutting stimulates ethylene production which in turn increases respiration and senescence leading to even more rapid loss of certain vitamins. Vitamin C is the vitamin that usually degrades most rapidly and can be used as an index of freshness. Vitamin C is unstable in many vegetables such as asparagus (Saito et al., 2000) and jalapeno pepper (Howard and Hernandez-Brenes, 1997). Slight vitamin C losses in stored fresh-cut cantaloupe were also reported recently (Beaulieu and Lea, 2007; Gil et al., 2006).

Convenience

The attribute that drives fresh-cut products is convenience (Raegert et al., 2004). Consumers purchase cut fruits and vegetables for consumption right out of the package. The former International Fresh-Cut Produce Association defined fresh-cut produce as trimmed, peeled, washed, and cut into 100% usable product that is subsequently bagged or prepackaged to offer consumers high nutrition, convenience, and value while still maintaining freshness (Beaulieu and Gorny, 2004). These products should be clean with no evidence of soil or odor of chlorine or other sanitizers. All pieces in the package should be edible and require no further preparation steps other than transfer from package to plate.

ADVANTAGES AND DISADVANTAGES OF SENSORY AND INSTRUMENTAL QUALITY MEASUREMENTS

The quality of fresh-cut fruits and vegetables can be measured by sensory and instrumental methods. In general, sensory methods are more useful in developing new products and determining product standards while instrumental methods are superior in measuring quality on a routine basis (Shewfelt, 1993).

Sensory evaluation of food products is divided into two components—analytical and affective measurements. Analytical measurements can be used to detect differences (difference tests) or to describe the product (descriptive analysis). Analytical sensory tests are usually conducted by small panels with some training of the panelists. Affective measurements determine preference (which samples are preferred over others) and usually require large numbers of naïve panelists (Institute of Food Technologists, 1981).

There are many advantages to sensory methods of quality measurement. Since human perception is involved in sensory testing, quality attributes are clearly defined in terms that are relevant to consumer acceptability. Affective consumer tests are the only way to determine what consumers like and what they do not like. Sensory descriptive panels can be used to identify small differences in quality between similar samples. Well-trained descriptive panels are able to screen out competing attributes to focus on an attribute of specific interest. Among the disadvantages of sensory methods, analytical and affective (consumer) sensory panels are the complex logistics. Descriptive panels require extensive training and can produce highly variable results if training is inadequate. The results from consumer panels tend to be highly variable. In addition, it is difficult to relate sensory data to chemical composition in an effort to determine mechanistic reasons for differences in samples.

Instrumental measurements encompass a wide range of techniques used to determine color, appearance, flavor, texture, and nutritional quality. Instrumental techniques are advantageous in that they tend to provide accurate and precise results. The results of instrumental tests can generally be related directly to chemical and physical properties allowing the investigator to gain a mechanistic understanding of observed differences. Instruments tend to be more sensitive to small differences between samples and may be able to detect trends in quality loss before they can be detected by humans (Thai et al., 1990; Brosnan and Sun, 2004). Instruments do not object to working at nights and weekends and can produce large amounts of data without complaint, making them excellent monitors in Quality Control operations. A primary disadvantage of instrumental testing is that many instrumental measurements have little relevance to consumer acceptability and thus should never be used to define quality attributes for a specific product. In other words "it is better to measure what is really important than to believe something is important because you measure it really well." (Shewfelt and Phillips, 1996).

Sensory and instrumental tests are best used in conjunction with each other using the most appropriate test to meet the desired objective. Affective testing helps determine which attributes are important to the consumer. Difference tests can determine if individual units are noticeably different, and sensory descriptive analysis can identify the attributes that cause the differences. When carefully coordinated, the sensory tests can be very effective in developing new products and establishing quality standards. Instrumental tests are more useful in measuring standards in a quality control setting and in determining the mechanistic reason for differences.

SENSORY METHODS OF QUALITY MEASUREMENT

In-depth descriptions of sensory techniques are available for measuring food quality in general (Institute of Food Technologists, 1981; Meilgaard et al., 1999; Lawless and Heymann, 1998) and fruit and vegetable quality specifically (Shewfelt, 1993). As described above, sensory evaluation is divided into two components—analytical and affective measurements. Two types of analytical tests are difference tests and descriptive analysis.

Analytical Measurements

Difference tests are conducted to determine if there is a detectable difference between two samples, for example two different varieties of cut cantaloupe. The most common difference test is the triangle test. Each panelist is given three samples, two are similar and one is different. The panelist is asked to identify the different sample. Panelists in this type of test are not trained. At least 30 panelists are required for difference tests, and 50 or more panelists are preferred. Samples should be presented as the item is normally consumed and presented in a controlled environment. The order of sample presentation must be randomized. Precautions in running a difference test include making sure that there are no unintentional clues to signal the difference. For example, if the test is to determine possible differences in flavor, steps must be taken to make sure that differences in color, size, shape, and texture are not providing clues to the panelists. Also, investigators must ensure that all samples are at a similar stage of ripeness.

Descriptive analysis involves the development of a lexicon and panel training (Meilgaard et al., 1999). A lexicon is the list of terms used as descriptors and a precise definition of these terms. If the testing material is an item like tomatoes that has been well characterized (Krumbein et al., 2004), terms and definitions are selected from previous studies. For other items such as eggplant (Sesena et al., 2002) the descriptive panel evaluates an extensive range of varieties for that item to develop terms that describe the range of products to be tested. Lexicons can be extensive with up to 50 descriptors of minimalist with as few as 5 descriptors. Upon selection or determination of a lexicon, the panel must go through training and calibration to ensure that the panel results are accurate and precise. Training can be as extensive as two hours a week for six months to less intensive sessions over a one-to-two week period. Panelists who are outliers undergo additional training or are dismissed. Upon the completion of training, the evaluation of the samples is conducted in partitioned booths using one of several evaluation methods including Spectrum (Meilgaard et al., 1999) and Quantitative Descriptive Analysis (QDA; Stone and Sidel, 2004). The primary differences between the two techniques are that Spectrum uses standards for the descriptors and involves more extensive training than QDA. For a discussion of the differences in analysis and data interpretation, see Harker, et al. (2003).

A more limited approach to descriptive analysis is the use of an experienced panel. Experienced panelists have had some training on similar items in the past, but the panel director usually selects a limited number of descriptors for evaluation. The panel is convened with a few training sessions primarily to ensure that the panelists are familiar with the terminology. Expert evaluations may be most appropriate when visual evaluation of a large number of samples is needed over the life of the product (Shewfelt, 1993). Usually two to five judges evaluate the samples independently of each other to prevent bias.

Affective Measurements

Affective testing can take many forms, but the most widely used techniques are the focus group, surveys, and the consumer preference test. Focus groups involve group interviews of 8–12 participants of current and potential consumers of the item(s) being evaluated (Krueger and Casey, 2000). A focus group is an excellent way to determine the range of opinions about a fruit or a vegetable, but the panel size is too small to obtain quantitative relationships. Focus groups are usually repeated for a given topic until little or no additional qualitative information is collected. Focus groups are also very effective in selecting questions for a survey. At least 50, and preferably over 200, participants are needed for a survey to be useful. It is important to collect basic demographic information in a survey and frequency of purchase or consumption of the item(s) being studied. The results should be partitioned by categories of interest.

Consumer preference tests (Table 1) provide ground truth to any study as what consumers indicate in a focus group or survey questionnaire may not be verified when presented with actual samples. For example, many consumers indicate that items can be too sweet, but the sweetest sample is consistently rated as the most preferred (Civille, 1991). Once again, a minimum of 50 participants is required with over 200 preferred. When a small number of treatments (<5) are being tested, every participant should taste a sample from every treatment. With large numbers of treatments, careful randomization of sampling is needed with at least 50 participants evaluating every treatment. The most frequently used evaluation scale is the 9-point hedonic scale (Meilgaard et al., 1999; Lawless and Heymann, 1998), but this scale suffers from many problems including the lack of unequal intervals making analysis of variance invalid. More useful scales are the 5-point willingness to purchase (Moskowitz et al., 2006) and the 3-point acceptability scale (Dubost et al., 2003, Table 1), although the latter scale is not balanced. When all participants are tasting samples from all of the treatments, an alternative is the ranking of the samples.

Table 1 Scales used in the evaluation of food quality

Hedonic	Purchase	Acceptability
9 – Like extremely	5 – Definitely would	3 – Tastes great
8 – Like very much	4 – Probably would	2 – Acceptable
7 – Like moderately	3 – Might or might not	1 – Unacceptable
6 – Like slightly	2 – Probably would not	
5 – Neither like or dislike	1 – Definitely would not	
4 – Dislike slightly		
3 – Dislike moderately		
2 – Dislike very much		
1 – Dislike extremely		

The use of a single sensory technique provides limited information. Integration of two or more techniques can be a powerful tool in the quality evaluation of fresh-cut produce (Shewfelt, 2000a). For example, a focus group can be used to determine the potential market segments for an item with a follow-up survey quantifying the extent of each market segment. Sensory descriptive analysis coupled with a consumer preference test can establish the relative importance of the characteristics that drive acceptability. Difference tests can be used to select the best treatments for use in a consumer preference test.

INSTRUMENTAL METHODS OF QUALITY MEASUREMENT

Instrumental methods of measuring appearance, color, texture, aroma, and flavor in fruits and vegetables were first described by Kramer (1965), and later amended by Kader (2002). A modified list of methods of quality measurement appears in Table 2.

Color

Color may be determined using nondestructive methods founded on visual or physical measurements. These methods are based on evaluation of either the light reflected from the surface of a product or transmitted through it. There are three components necessary to the perception of color— 1) a source of light, 2) an object that modifies light by reflection or transmission and 3) the eye/brain combination of an observer (Leggett, 2004). Simple color charts and dictionaries are routinely used in the field, packing house, fresh-cut processor facility or retail store. An example of a color disc used for canning peaches is shown in Fig.1.

Analytical sensory methods of evaluating color, as described above, are faster and easier in many ways than instrumental methods. They have the advantage of requiring no specialized equipment, but may be standardized through the use of color charts or discs such as those in Fig. 1. The disadvantages are that these methods may vary considerably due to human differences in perception and human error. Inadequate or poor quality available light may also affect accuracy (Mitcham et al., 1996).

Table 2 Instrumental methods for determination of fruit and vegetable quality

Quality Attribute	Fruits	Vegetables	Objective method of measurement
Appearance			
Size	Diameter, drained weight	Sieve size, drained weight	Dimensions (scales, screens, sizing rings, micrometers, etc.), weight and volume
Shape	Height/weight ratio	Straightness	Dimension ratios, displacement, angles, diagrams and models
Wholeness	Cracked pieces	Cracked pieces	Counts, percent whole, photographs, models
Gloss	Gloss, finish		Gloss meters, goniophotometers, wax platelets
Consistency	Consistency	Consistency	Consistometers, viscometers, flow meters, spread meters
Defects	Blemishes, bruises, spots, extraneous matter	Blemishes, bruises, spots, extraneous matter	Photographs, drawings, models, scoring systems, computer-aided visual techniques
Color	Color	Color	Color charts, dictionaries, reflectance and transmittance colorimeters, pigment extraction and spectrophotometers
Texture	Texture, firmness, grit, character, mealiness	Texture, mealiness, succulence, fiber, maturity	Tenderometers, texture analyzers – compression, shearing, extrusion meters, analysis of solids, moisture, grit, fiber
Aroma	Aroma, ripeness, sweetness, fruitiness	Aroma	Gas chromatograph, enzymes
Flavor	Flavor, sweet, sour, bitter	Flavor, sweet, sour, salty, bitter	Hydrometer, refractometer, pH meter, determination of acidity and sugars, sodium chloride, enzymes, amines, bitter alkaloids or glucosides
Nutritional value	Vitamin A, B, C, E, polyphenolics, carotenoids	Vitamin A, B, C, E, polyphenolics, carotenoids, glucosinolates	HPLC and spectrophotometric methods

Instrumental methods are less variable and can be used to measure small differences. Some instruments are portable (Fig. 2) and others may be adapted for packing lines (Mitcham et al., 1996). Disadvantages to instrumental methods are that many instruments used to measure color may be expensive and may be slower than sensory measurements.

At the back of the retina of the human eye, there are two kinds of receptors—rods, which are light sensitive at low light levels, and cones, which function at higher light levels (Leggett, 2004). Cones may be further divided into receptors sensitive to red (long wavelength), green (medium wavelength), and blue (short wavelength) light. The integrated, trichromatic response of the red, green, and blue-sensitive cones stimulates how we perceive color. Each pigment in fruits and vegetables corresponds to a primary hue—red, blue, and green (Gross, 1987). Tristimulus colorimeters simulate the human eye by replacing the receptors with filters—one for each primary hue. Color may be further characterized by determining lightness or degree to which an object reflects light, and chroma or saturation, which is the intensity of color or difference from gray of the same lightness.

The Commission Internationale de l'Eclairage (CIE) or International Commission on Illumination is the international body that governs the measurement of color. Publications from this body may be found on-line at www.cie.co.at. Color space may be divided into a three-dimensional (L, a and b) rectangular area (Fig. 3) such that L (lightness) axis goes vertically from 0 (perfect black) to 100 (perfect white) in reflectance or perfect clear in transmission (HunterLab, 1996; Leggett, 2004). The a axis

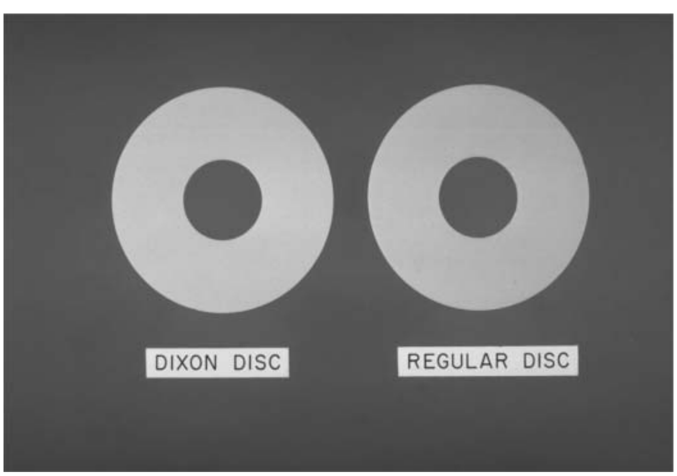

Figure 1 Canning peach color discs for Dixon cultivar (left) and other cultivars (right)

Figure 2 Measuring external color of apples using a Minolta colorimeter.

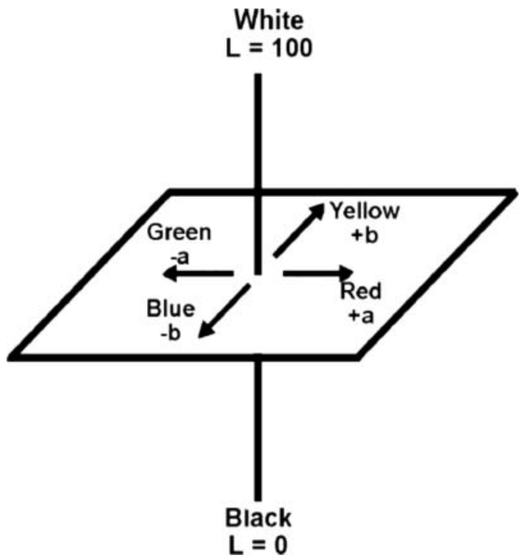

Figure 3 Diagram depicting three dimensional L, a and b color space.

(red to green) considers the positive values as red and negative values as green; 0 is neutral. The b axis (blue to yellow) expresses positive values as yellow and negative values as blue; 0 is neutral. Fruits and vegetables are often described in terms of their L, a, and b values. For fruits, the a/b ratio is quite useful, as the ratio is negative for green fruits, approximately 0 for yellow fruits, and positive for orange to red fruits (Gross, 1987).

Color may be determined instrumentally using either colorimeters or spectrophotometers. Colorimeters give measurements that can be correlated with human eye-brain perception, and give tristimulus (L, a and b) values directly (HunterLab, 1995). Colorimeters are typically quite rugged and desirable for routine quality control measurements. Spectrophotometers provide wavelength-by-wavelength spectral analysis of the reflecting and/or transmitting properties of objects, and are more commonly used in research and development laboratories (HunterLab, 1995).

Fruit and vegetable pigments may also be analyzed quantitatively by extraction with specific solvents, filtration, and the use of various methods based on spectrophotometry. Prior to extraction it is necessary to homogenize, grind, or cut up the fruit and vegetable material in order to improve the degree of extraction. Separation using reversed phase high performance liquid chromatography (HPLC) may be useful prior to measurement of absorption of light in the uv/visible wavelength spectrum. Colorimetric methods are based on the Lambert-Beer law, which describes the relationship between the concentration of a substance and its color intensity:

$$E = \varepsilon' l c$$

The extinction coefficient E is proportional to $\acute{\varepsilon}$, the molar extinction coefficient of the substance, l, the length of the light path in centimeters, and c, the concentration in g l^{-1}.

Water-miscible solvents such as acetone, methanol, or ethanol are used to extract chlorophyll and other carotenoids from the cellular matrix. Anthocyanins are sensitive to light and heat, therefore the extraction of the pigments is done with methanol acidified with 1% HCL (Gross, 1987). Chlorophyll absorption is typically measured in the region between 600 and 700 nm, and it is possible to mathematically separate the contribution of chlorophyll $a(E = 663$ nm) and chlorophyll $b(E = 645$ nm) (Gross, 1987). Quantitative determination of carotenoids and anthocyanins is spectrophotometric and extinction coefficients for most major pigments have been tabulated. Measurement of lycopene in a hexane medium following extraction using hexane:ethanol:acetone solvents has recently been optimized for routine analysis (Anthon and Barrett, 2005). In red tomatoes, trans-lycopene absorbs at 503 nm and there is little interference (less than 5% error determined by excluding) from cis-lycopene or other carotenoids such as ß-carotene (Fig. 4).

Appearance

Appearance factors other than color include the size, the shape, the wholeness, the pattern, the presence of defects, gloss, and consistency. Most appearance factors may be measured fairly easily using simple devices such as the ones listed in Table 1. Size may be determined either by dimensions, weight, or volume, and there is usually a good correlation between size and weight (Kader, 2002). Shape is actually a ratio of different dimensions to each other, for example the length/width dimensions may describe carrot shape. Gloss may be easily determined either with an instrumental (Table 1) or visual evaluation of wax platelets on the surface of a fruit or vegetable.

In many cases, such as in the determination of defects, it is difficult to quantify the degree or severity of a defect. In

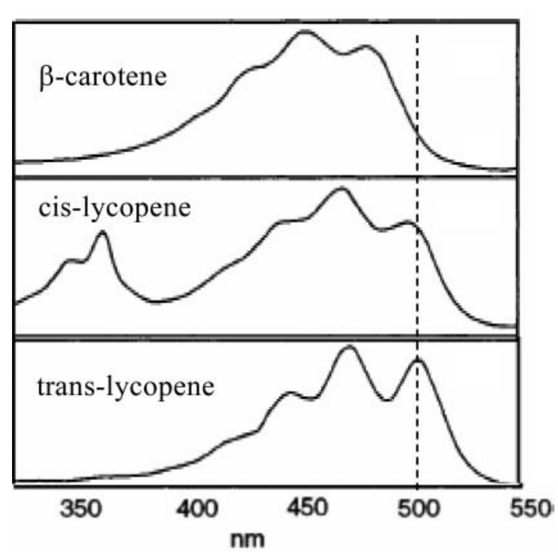

Figure 4 The absorbance spectra of β-carotene and cis- and trans- lycopene (adapted from Ishida et al., 2001). The dashed line indicates 503 nm.

this instance it is useful to take photographs, or use models or drawings to develop a somewhat quantitative scoring system. Kader (2002) has developed a five-grade scoring system (1 = no symptoms, 2 = slight, 3 = moderate, 4 = severe, 5 = extreme) for many fruit and vegetable defects, which may be accompanied by detailed descriptions and photographs. The recently published Produce Quality Rating Scales and Color Charts (Kader and Cantwell, 2006) includes color photos and descriptions for numerous commonly consumed fruits and vegetables.

Flavor—Aroma and Taste

Flavor may be evaluated with either instrumental or sensory methods, but most scientists would agree that sensory methods are the most critical to this particular quality attribute. Instrumental techniques may determine that tens or hundreds of compounds are present in a particular fruit or vegetable product, but such methods do not give a measure of the contribution of that specific compound unless they are accompanied by a sensory measurement of odor or flavor activity. For this reason, flavor may be the most challenging quality attribute to both measure and correlate to consumer acceptability. That said, there are some characteristics of flavor that may be determined instrumentally, and these will be described in the following section.

Taste has been described as being comprised of five primary components—sweet, salty, sour, bitter, and umami. It is possible to measure these basic taste components instrumentally. Sweetness can be approximated by HPLC determination of individual sugars, or more rapidly but less accurately by a refractometer or hydrometer that measures total soluble solids (Kramer, 1965). Indicator papers exist for rapid determination of glucose in some commodities, such as potatoes (Kader, 2002). It is possible to measure chloride and/or sodium content as an approximation of saltiness. Sourness may be determined by either pH or more accurately by measurement of total acidity. Both indicator papers and pH meters are available for the determination of pH. The total acidity methods involve adding 0.1 N NaOH to titrate the acid in a fruit or vegetable, and measuring how much of the base is required to reach a pH of 8.1. Finally, astringency may be indicated by measuring total phenolics and bitterness by analysis of compounds such as alkaloids or glucosides.

A relatively simple estimation of flavor may be obtained by a comparison, or ratio, of the sugar and acid content of a specific fruit. This is referred to as the "sugar/acid" ratio and specific target values have been established by some companies. Kader (2002) proposed minimum soluble solids content (SSC) and maximum titratable acidity (TA) for acceptable flavor quality of some fruits. For example, it was proposed that apricots, cherries, and persimmons be harvested at minimum SSC values of 10, 14–16, and 18%, respectively. Likewise, the maximum TA values of 0.6, 1.0, and 1.4 were proposed for nectarine, pineapple, and pomegranate, respectively. Unless more sophisticated instrumentation is available, a rapid and inexpensive measure of general flavor may be obtained using sugar/acid ratios along with a minimum sugar and/or a maximum acid content.

Aroma volatiles may be very accurately measured using gas chromatography, but this method is time-consuming and the equipment is relatively expensive. Estimation of volatile acids or amines has been suggested to be indicative of off-flavor in stored fruit and vegetables (Kramer, 1965). Hexanal is a compound typically produced as a result of the activity of lipoxygenase, and quantitative determination may correlate well to the sensory perception of off-flavor (Theerakulkait and Barrett, 1995). The determination of hexanal is also carried out using a gas chromatograph. Nonetheless, aldehyde generation in fresh-cut and damaged tissue is considered normal, and actually often contributes to important characteristic flavor/aroma profile in several commodities. Masticating food products in the mouth generates secondary products in situ, and numerous character impact aroma compounds in foods are known to be secondary compounds (Buttery and Ling, 1993; Carson, 1987; Crouzet et al., 1990; Maarse, 1990). Some of the consequences are considered desirable such as allium flavor release (Carson, 1987), C_6 and/or C_9 aldehyde/alcohol generation in tomato (Riley and Thompson, 1998), cucumber (Fleming et al., 1968), and bell peppers (Wu and Liou, 1986), and the likely release of certain melon (Schieberle et al., 1990) and seedless watermelon volatiles (Beaulieu and Lea, 2006). Some off-flavors result from the accumulation of acetaldehyde, ethanol, and/or ethyl acetate due to fermentative metabolism when the product is exposed to very low oxygen and/or very high carbon dioxide concentrations. The presence of fungi or bacteria can result in musty or foul odors in the host fruit or vegetable product.

Texture

Instrumental or objective methods of texture evaluation can be grouped into three classes (Szczesniak et al., 1963)—fundamental, empirical, and imitative tests. Fundamental tests measure properties that are familiar to engineers, e.g. strength, Poisson's ratio, and various moduli such as Young's modulus, Shear modulus, and Bulk modulus (Bourne, 1982). Empirical tests cover a wide range of simple and rapid tests, including puncture, compression, extrusion, shear, and others, which measure one or more textural properties and are commonly used in quality control applications. Most methods used for the evaluation of the textural properties of fruits and vegetables are empirical or semi-empirical. Finally, imitative tests are those which utilize instruments in an attempt to mimic what occurs in the mouth as the food is masticated. Experience teaches us that these empirical and imitative tests correlate well with sensory judgments, but we usually have little or no fundamental understanding of the test.

In choosing an objective test for measuring textural properties, one must first determine which specific textural properties are of interest, then evaluate which objective test(s) will best measure those properties, and finally correlate the results to sensory analysis prior to predicting consumer response (Barrett et al., 1998). The most commonly used methods for the evaluation of textural properties are those which apply large deforming forces (e.g. via puncture or compression) and are therefore destructive. The use of a texture analyzer has illustrated consistent firmness loss in stored fresh-cut cantaloupe with both a puncture test (Gil et al., 2006; Luna-Guzmán and Barrett, 2000) and a compression test (Beaulieu et al., 2004). Because of the empirical nature of these tests, however, they do not provide us with an understanding of food microstructure or force-deformation and failure mechanisms at the cellular level. Recently, there has been a resurgence of interest in nondestructive tests which rely on well-defined fundamental principles and thereby may provide a better understanding of tomato tissue microstructure and the forces which lead to tissue failure. Destructive (puncture, compression, and extrusion) and nondestructive tests will be briefly described below.

Destructive Texture Tests

The puncture test, which is a force measuring method that has the dimensions mass, length, and time, is probably the most frequently used method for textural evaluation. It consists of measuring the force and/or deformation required to push a probe or punch into a food to a depth that causes irreversible damage or failure. Hand-held puncture testers or penetrometers have been conveniently used by horticulturists in the field and laboratory for many years. Puncture probes of a specific diameter may also be easily fitted to laboratory-scale instruments such as the Maturometer, the Instron, and the Texture Technologies TA-XT2 machine for more controlled measurements (Barrett et al., 1998).

Flat plate compression is a technique very similar to that of puncture, except that the perimeter effect is eliminated through the use of flat plates of an area exceeding that of the sample. This test may be used in either a destructive or nondestructive manner. Flat plate compression is assumed to be nondestructive when restricted to less than the elastic limit of 3% strain; however, in some cases permanent damage may occur. Similar to the puncture test, this is a force measuring method with the dimensions mass, length, and time. Extrusion tests are another example of a force-measuring test in which units are expressed as mass, length, and time. A number of different test cells, including the standard shear-compression cell (or Shear Press) and the back extrusion cell have been designed for the measurement of extrusion behavior. Although use of shear-compression cells primarily involves extrusion, some compression and shear also take place (Barrett et al., 1998).

Nondestructive Texture Tests

Pioneering efforts in the development of vibration techniques for the evaluation of fruit and vegetable texture were made by Abbott et al. (1968) and Finney and Norris (1968; 1972). Using vibrational responses in the frequency range from 20–10,000 Hz it was deemed possible to separate fruit by maturity and textural properties. In studies carried out primarily on apples, numerous investigators have since found good correlation between resonance (also termed dynamic oscillation, acoustic, or sonic) methods and both sensory and destructive compression and puncture tests (Abbott, 1992; 1995).

The resonance theory has its basis in dynamics and is founded on the fact that any body that possesses both mass and elasticity is capable of vibrating. Free vibration may be exhibited at one or more frequencies, and is dependent on the specific physico-mechanical properties of the food itself. On the other hand, forced vibration over a range of frequencies results when an external force is applied periodically and a series of resonance peaks may be observed. The two lowest frequencies correlate with fruit firmness and overall elastic behavior, and stiffness factors are commonly used as indices of textural quality (Jackman and Stanley, 1995; Peleg et al., 1990). Resonance tests may be used to measure solid samples of known dimensions or liquid samples placed in a container with standard dimensions. The sample is subjected to repeated small sinusoidal deformations that are nondestructive and do not impart fracture (Bourne, 1993).

Nutritional Value

Fruits and vegetables are good sources of fiber, minerals, vitamins, and some beneficial phytochemicals such as carotenoids, phenolics, and glucosinolates. The determination of the nutrients in fruits and vegetables is carried out using chemical methods following their extraction in either water or lipid mediums.

Soluble dietary fiber in plant tissues may be analyzed in a phosphate buffer extract using an enzymatic-gravimetric method (AOAC method 993.19; AOAC, 2006). Fiber may also be determined by the loss on incineration of dried residue remaining after digestion of a sample with dilute $H_2SO_4$and NaOH (Meloan and Pomeranz, 1980). Mineral analysis is typically carried out using atomic absorption spectroscopy (AOAC method 968.08). Vitamins may be determined following extraction using high performance liquid chromatography (HPLC) or using older methods that employ microbiological, turbidimetric, or titrimetric methods (AOAC method 960.46).

There is increasing interest in the phytochemical content of fruits and vegetables, and these may be extracted according to their water or lipid solubility and are typically analyzed using HPLC. In the case of lycopene, it is possible to approximate its content by measuring the intensity of red color (Anthon and Barrett, 2005) or a/b value with a colorimeter, but such a physical method is not available for most nutrients. There is a wealth of papers available on appropriate methods for the analysis of specific nutrients.

EFFECTS OF FRESH-CUT PROCESSING ON QUALITY

Overview of Fresh-Cut Processing Operations

Unit operations typically involved in the production of fresh-cut fruits and vegetables include the following:

1. Receiving and storage
2. Preliminary washing and sorting
3. Maturity and ripeness stage at cutting
4. Pre-cutting and processing treatments
5. Peeling (if necessary)
6. Size reduction and cutting
7. Washing and cooling
8. Dewatering
9. Packaging

Objectives of the processing of fresh-cut products include the reduction of the microbial load on incoming raw materials and efficient preparation of fresh-cut products in an environment that is not only clean but temperature and humidity controlled. In the following section we will review literature published over the past ten years on the effects of various unit operations on the final quality of fresh-cut fruit and vegetable products. There were no publications found specific to the effects of dewatering on quality, therefore this unit operation will not be included in the following discussion. However, it is well known that the presence of free water on the surface of plant tissues may provide a desired environment for microbial growth.

Effects of Fresh-Cut Processing on Quality Using Instrumental and Sensory Methods

The quality of fresh-cut products is affected by temperature, atmosphere, relative humidity, and sanitation during processing operations (Watada et al., 1996). The physical action of cutting and processing plant tissues imparts stress, and depending on the control of the factors mentioned previously, this may lead to faster deterioration. For this reason, there has been more attention paid to the unit operation of cutting than any other step in the fresh-cut process.

Receiving and Storage

In an excellent review on preharvest and postharvest factors influencing vitamin C content, Lee and Kader (2000) found that postharvest temperature management was the most important tool for the extension of shelf-life and maintenance of fresh fruit and vegetable quality. They state that delays between harvesting and cooling may result in direct losses due to water loss and decay and indirect losses in flavor and nutritional quality. Vitamin C is generally more stable in acidic mediums, such as those that exist in fruits, than in vegetables which are more basic (Lee and Kader, 2000).

Preliminary Washing and Sorting

In a unique study, the "processability" of baby salad leaves, as affected by their ability to tolerate postharvest washing and packing processes, was evaluated by the measurement of biophysical properties of the cell wall (% plasticity) and epidermal cell size (Clarkson et al., 2003). It was determined that stress treatments (either salt or mechanical) resulted in a reduction of epidermal cell area and modifications to cell wall plasticity and elasticity (Figs. 5a and 5b), and ultimately resulted in longer shelf lives for the salad leaves. Organoleptic measurements over storage time (wetness, breakdown and bruising, discoloration, and texture) correlated well with the degree of stress imparted (Fig. 5c).

Maturity and Ripeness Stage at Cutting

Oftentimes, a firm product is desired for improved shipping, handling, and storability in fresh-cut fruits and vegetables. Firm fruit that is harvested immature or mature-green to withstand mechanical damage during postharvest handling may have excellent visual quality and acceptance by retailers and consumers. However, there appears to be a detrimental trade-off between firmness and acceptable volatiles and flavor/aroma attributes in fresh-cut fruits prepared with less ripe fruit (Bai et al., 2004; Beaulieu et al., 2004; Beaulieu and Lea, 2003; Gorny et al., 1998; Gorny et al., 2000; Soliva-Fortuny et al., 2004). Harvest maturity significantly affects the level of flavor volatiles recovered in fresh-cuts from soft-ripe versus firm-ripe mangos (Beaulieu and Lea, 2003), and 1/4-, 1/2-, 3/4-, and full-slip "Sol Real" cantaloupe (Beaulieu, 2006b). Cantaloupe fruit harvested at different maturity stages deliver stored cubes differing significantly in quality (Beaulieu and Lea, 2007), flavor, textural attributes, and volatiles (Beaulieu et al., 2004; Beaulieu, 2006b). In general, cubes prepared with less mature fruit, that are excessively firm, lack flavor volatiles (Beaulieu, 2006b) and have inferior, less acceptable sensory attributes (Beaulieu et al., 2004).

Although maturity-related changes in flavor volatile profiles in fresh-cut cantaloupe have been demonstrated, the balance of the non-acetate to acetate esters changed uniformly during storage, and independently of initial processing maturity in fresh-cut cantaloupe (Fig. 6), apple, and honeydew (Beaulieu, 2006a; Beaulieu, 2006b). Further analysis led to the finding that several correlations with flavor compounds and classes of compounds were made between several quality and sensory attributes in fresh-cut cantaloupe (Beaulieu and Lancaster, 2007). Also, whole cantaloupe fruit and cube firmness was positively correlated with increasing acetate ester levels (Beaulieu, 2005), and acetate loss was correlated with firmness loss in stored fresh-cuts (Beaulieu, 2006b). However, these descriptive sensory appraisals were not correlated with consumer acceptability. Likewise, no instrumental measurement was a satisfactory predictor of sensory acceptability scores in fresh-cut "GoldRush" apples (Abbott et al., 2004).

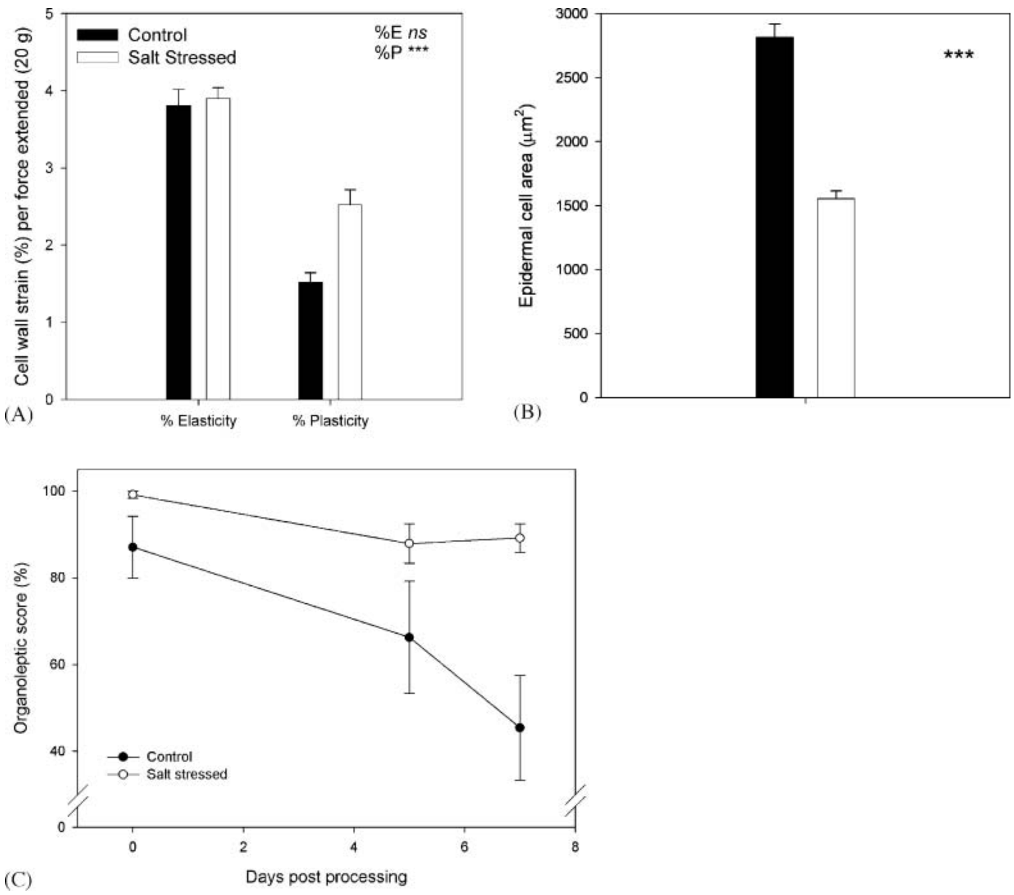

Figure 5 Percent elasticity and plasticity (a) and epidermal cell area (b) in baby salad leaves following growth in 0 (closed bars) or 50 mM sodium chloride (open bars) solutions. Organoleptic scores in control and salt stressed baby salad leaves is presented (c) following processing. Reprinted with permission from Elsevier.

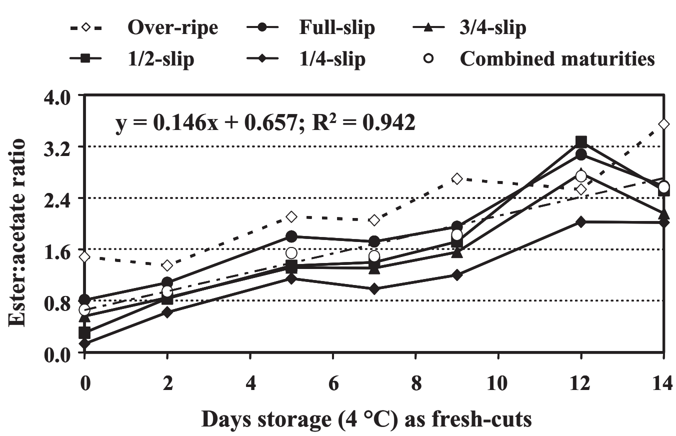

Figure 6 Solid phase microextraction GC-MS non-acetate ester to acetate ratios in fresh-cut "Sol Real" cantaloupe prepared from 5 maturities (1/4-, 1/2-, 3/4-, FS, and OR). Linear equation represents five combined maturities. Calculations based on the composite averages of n = 6 runs repeated over two years for each maturity, except OR and day 12 and 14 (n = 3), where 11 of the 58 integrated compounds were acetates, and 17 were non-acetate esters. Adapted from (Beaulieu, 2006a).

Pre-Cutting and Processing Treatments

A vast amount of work has been accomplished in the fresh-cut arena revolving around maintaining or improving storability (postcutting life) via technologies and chemical applications (mainly anti-browning, anti-microbial, and firmness agents). In order to avoid a comprehensive review, as already published (Beaulieu and Gorny, 2004; Brecht et al., 2004), we will only present a few salient, recent examples. Several investigators have focused on 1-MCP (an inhibitor of ethylene action) treatments, alone or in concert with combined treatments.

Application of 1-MCP to partially ripe fruit before and post-cutting generally suppressed firmness and color loss in fresh-cut kiwifruit, mango, and persimmon (Vilas-Boas and Kader, 2007). Use of ethanol vapor treatment on intact apple (Bai et al., 2004) or mango (Plotto et al., 2006) to inhibit ethylene production and reduce decay in fresh-cut slices extended the appearance shelf-life, yet resulted in altered or off-flavor. Fresh-cut apples exposed to 1-MCP have decreased ethylene production, respiration, softening, color change, and synthesis of aroma/volatile compounds (Bai et al., 2004; Calderon-Lopez et al., 2005; Jiang and Joyce, 2002; Perera et al., 2003). Detailed volatile and genetic analysis indicates that marketing of 1-MCP-treated fruit shortly after treatment might result in the delivery of fruit to the consumer with poor likelihood of ester volatile recovery (Ferenczi et al., 2006; Kondo et al., 2005), even when browning is inhibited with NatureSeal (Rupasinghe et al., 2005). Volatile genesis via alcohol acetyl transferase (ATT) is thought to act independently of ethylene. This is apparently why there is occasional maturity- and application-dependent recovery of volatiles in 1-MCP treated climacteric fruit, and an apparent recycling of ester volatiles resulting from in vivo catabolism during senescence (fresh-cut storage) (Beaulieu, 2006a; Beaulieu, 2006b) or resulting from exogenous application of substrates (Ferenczi et al., 2006).

Peeling, Size Reduction, and Cutting

Saltveit (1996) states that the immediate physical effects of wounding tissue, such as what occurs during peeling or size reduction operations, are to cause mechanical stress to the tissue, to remove the protective epidermal layer, to accumulate surface moisture, and to expose tissue to contaminants. Dramatic changes in gas diffusion occur with tissue wounding, and as moisture at the cut surface evaporates, additional changes in diffusion occur.

Bolin and Huxsoll (1991), Babic et al. (1993) and Avena-Bustillos et al. (1994) were some of the first groups to investigate the phenomenon of white blush development on the surface of fresh-cut carrots. Early studies suggested that the whitish appearance was due to lignin formation, and it has been reported that wounding is accompanied by both metabolism of phenolics and increased activity of phenylalanine ammonia lyase (PAL), the enzyme catalyzing phenolic metabolism (Babic et al., 1993; Howard et al., 1994). Lignin formation on the surface of fresh-cut carrots has been measured by the "whiteness index" (WI) established by Bolin and Huxsoll (1991):

$$WI = 100 - [(100 - L^*)^2 + a^{*2} + b^{*2}]^{1/2}$$

In a recent study (Lavelli, et al., 2006) evaluating various physicochemical, microbial, and sensory indices for the determination of quality of fresh-cut carrots, investigators measured a multitude of parameters during storage at 4 and 10°C and determined that WI was the most sensitive, easily measured indicator of sensory quality of fresh-cut carrot sticks. Other parameters measured included chlorogenic acid, carotenoids, and sugars as physicochemical indices; the total acterial count, coliforms, lactic acid bacteria, and yeasts as microbial indices; and fruity aroma, color and off-odor as sensory indices. Figure 7 illustrates that both chlorogenic acid and WI increased in fresh-cut carrot sticks during storage following pseudo-first order kinetics (Table 3), while the sugar content decreased at a slower rate.

A consequence of slicing carrots with dull apparatus is white blush formation resulting in desiccation and cell sloughing (physical process) (Tatsumi et al., 1991), and/or lignin formation (Barry-Ryan and O'Beirne, 1998). Avena-Bustillos et al. (1994) showed that the application of hydroscopic sodium caseinate-stearic acid coatings helped retain water at the surface and reduced the appearance of white tissue. Saltveit (1996) states that white blush can be further reduced by cutting with sharp knives or by removing the dead cell layer at the surface using mechanical or enzymatic means. More recently, peeled baby carrots dipped in a xanthan gum coating solution containing 5% calcium lactate plus gluconate and 0.2% α-tocopheral acetate (vitamin E) had improved the surface color, and no deleterious effects on taste, texture, fresh aroma, and flavor (aside from a slightly slippery surface) after storage at 2°C (85% RH) for up to 3 weeks (Mei et al., 2002).

Table 3 Kinetics parameters for variation in chlorogenic acid, sugars and whiteness index during storage of fresh-cut carrot sticks at 4 and 10°C. Adapted from Lavelli et al. (2006)

	Kinetic equation	T (°C)	k, k_1, k_2 (day^{-1}, day^{-2}, (day^{-1})	r[3]
Chlorogenic acid	$\ln(C/C_0) = kt$	4	$k = 0.309$	0.99
		10	$k = 1.93$	0.96
Sugars	$C/C_0 = -k_1t^2 - k_2t + 1$	4	$k_1 = 0.0036, k_2 = 0.0353$	0.99
		10	$k_1 = 0.0072, k_2 = 0.0409$	0.99
Whiteness index	$WI/WI_0 = 1 + kt$	4	$k = 0.0045$	0.95
		10	$k = 0.021$	0.93

[a] $P < 0.001$
[b] Quality indices are expressed as the ratio between the value at a given storage time and the initial value.

Although the effects of cutting on carrots have been studied more than other fruits and vegetables, there are also indications from other commodities of the effects of this unit operation on quality. Wright and Kader (1997) studied the effects of slicing and various controlled atmosphere storage conditions on ascorbate content and quality of strawberries and persimmons. Quality evaluation in this study included visual ratings on a 9 point hedonic scale, L*a*b* color measurements of the cut surface, firmness as measured by puncture testing, soluble solids, and titratable acidity measurements. These authors found that controlled atmospheres of 2% 0_2, air + 12% $C0_2$, or 2% 0_2+ 12% $C0_2$ had no significant effect on total ascorbate for either fruit, but did affect the color, the pH, and the titratable acidity. Both fruits lost the total ascorbate during storage, depending on the storage atmosphere, but in some cases there was a recovery of reduced ascorbate content. The aformentioned hedonic scale, as published for fresh-cut mango (Beaulieu and Lea, 2003) and cantaloupe (Beaulieu, 2005), provides a comprehensive manner by which researchers can uniformly perform subjective appraisals.

The ascorbate content in lettuce has been found to be significantly affected by the method of slicing. In a study comparing manually tearing of lettuce into strips to shredding with a sharp knife, it was found that the retention of ascorbate in lettuce sliced by a machine was 25–63% lower than lettuce shredded by manual tearing (Barry-Ryan and O'Beirne, 1999). It is assumed that slicing with a sharp knife resulted in the rupture of more cells and exposure of ascorbate to oxygen, as compared to manual

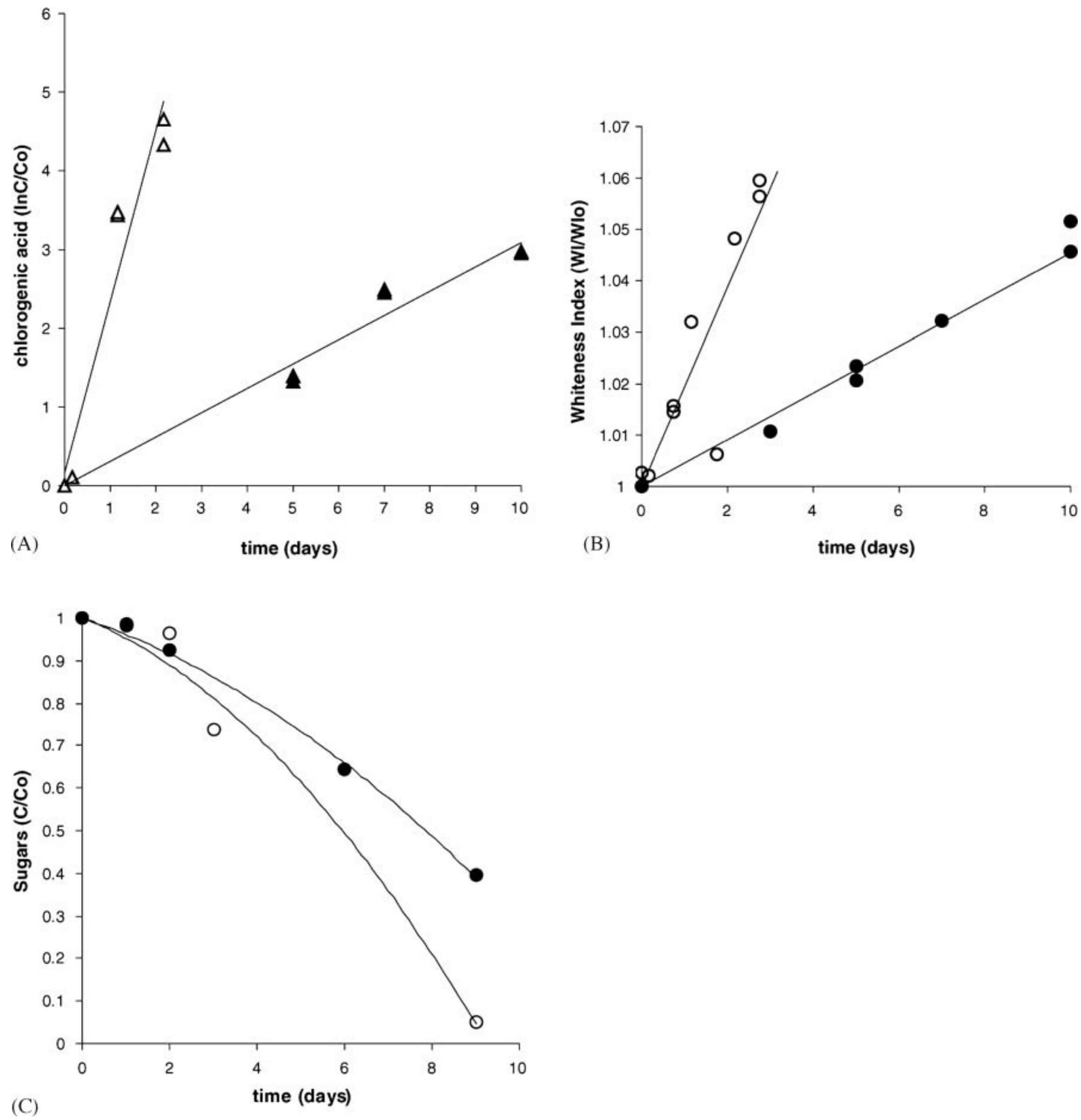

Figure 7 Changes in chlorogenic acid (a), whiteness index (b) and sugars (c) during storage of fresh-cut carrot sticks at 4 (closed symbols, ▲, ●) and 10°C (open symbols, Δ, ◯).

tearing. The use of blunt knives resulted in bruising of cells adjacent to the cut surface and a further degradation in the ascorbate levels. Likewise, the blunt-cut cantaloupe pieces had increased off-odor scores, ethanol concentrations, and electrolyte leakage compared to the sharp-cut pieces (Portela and Cantwell, 2001).

The effects of slicing and shredding radishes on quality during storage at 1, 5, and 10°C was determined by Aguila et al. (2006). On the 10th day, intact radishes stored at 1°C had the lowest respiration rate, while sliced radishes stored at 10°C had the highest. Quality attributes measured included soluble solids, weight loss, titratable acidity, ascorbic acid content, and color. In general, shredded radishes showed the most undesirably low levels of soluble solids, weight, ascorbic acid, and lightness (L*) as compared to intact or sliced radishes, particularly when stored at 10°C. There were only limited changes in quality when either shredded or sliced radishes were stored at either 1 or 5°C, therefore the authors suggested that these temperatures be utilized.

Washing and Cooling

The study by Wright and Kader (1997) described above also included an evaluation of washing treatments applied to intact and cut strawberries and persimmons. It was determined that washing sliced strawberries in distilled water caused an increased proportion of total ascorbate to be in the oxidized

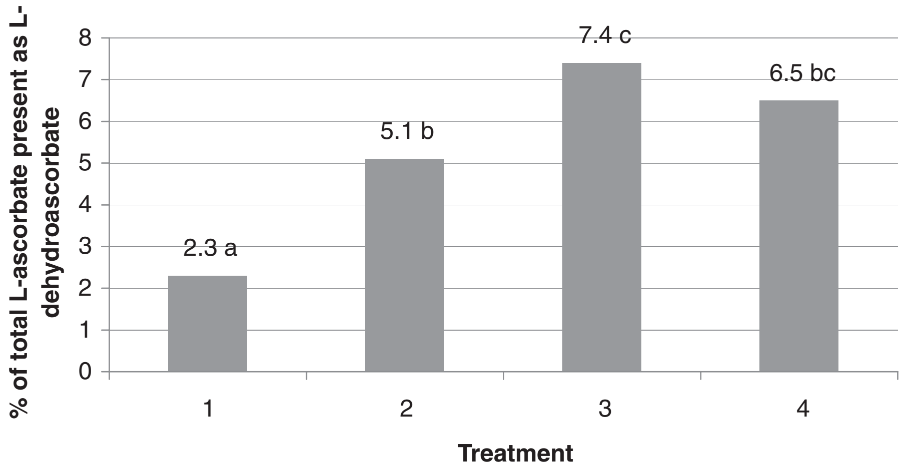

Figure 8 Percentage of total ascorbate in oxidized dehydroascorbate form as influenced by washing procedures. The treatments are— (1) control, sliced without washing, (2) sliced, washed in water, (3) sliced, washed in water with 100 ppm chlorine and (4) washed in water with 100 ppm chlorine, then sliced. Adapted from Wright and Kader (1997).

dehydroascorbate form (Fig. 8). Washing with 100 ppm sodium hypochlorite for 1 min resulted in an even further degree of oxidation, while dehydroascorbate levels in strawberries washed prior to slicing were intermediate between the water and chlorine treatments. It is obvious that oxidation of beneficial nutrients, such as ascorbic acid, may occur during simple washing procedures.

Packaging

Several fresh-cut studies have illustrated that a products sensorial attributes often decline prior to the physiological appearance. For example, an informal taste panel determined that fresh-cut honeydew melon stored in air at 5°C for 6 days lacked acceptable textural characteristics and had flat flavor (Qi et al., 1998). Fresh-cut pineapple stored at 4°C had excellent visual appearance after 7 to 10 days storage; however, fruit in the bottom of the container developed off flavors associated with microbial fermentation (Spanier et al., 1998). Fresh-cut orange segments having acceptable appearance after 14 days storage were found to have unacceptable flavor quality after 5 days at 4°C (Rocha et al., 1995). Likewise, undesirable flavor was the limiting factor in sliced wrapped watermelon stored 7 days at 5°C, even though aroma was still acceptable and microbial populations were not problematic until after day 8 (Abbey et al., 1988). Subsequently, modified atmosphere packaging (MAP) has been sought as an alternative, with partial success.

MAP prolongs the shelf-life of fresh-cut products by decreasing O_2 and increasing CO_2 concentrations in the package atmosphere, which is accomplished by the interaction between respiratory O_2 uptake and CO_2 evolution of the produce, and gas transfer through the package films (Beaudry, 2007). The effects of MAP on the quality of fresh-cut fruits and vegetables have been studied by numerous authors, and subsequently only some examples will be cited here.

The selection of packaging films with suitable oxygen transmission rates (OTRs) is critical to the development of a MAP environment. Kim et al. (2004) studied the quality of fresh-cut salad savoy stored in polyethylene bags prepared with films of OTRs at 8.0, 16.6, 21.4, and 29.5 pmol s^{-1} m^{-2} Pa^{-1}. These authors found that there were no significant differences between films of different OTRs in instrumental measurements of either the chroma or the hue angle. However, there was minor browning observed on the cut surfaces of white salad savoy, and visual scoring by a trained panel indicated more intense browning on samples packaged in 29.5 OTR films, while no browning was detected in samples stored in 8.0 OTR films. In this instance, the analytical sensory measurement of cut surface browning was more sensitive at detecting differences than the instrumental measurement of chroma and hue.

The quality of fresh-cut tomato slices stored for 7 and 10 days at 0 and 5°C under active (12–14 kPa O_2+ 0 kPa CO_2) was evaluated by Gil et al. (2002). These authors monitored changes in the soluble solids, the pH, the titratable acidity, the firmness and color, the maturity index, and the microbiological and sensory attributes. Fresh-cut sliced tomatoes were stored in polypropylene trays that were packed into heat-sealed bags made of 3 different polymeric films—1) control–perforated polypropylene film (33 holes of 2 mm dm^{-2}) and 35 μm thickness provided an air atmosphere, 2) a composite file of 80 μm thickness and 3) a bioriented polypropylene film (Gil et al., 2002). The results indicated that the best quality was obtained when slices were stored at 0°C, regardless of the packaging film used. In this case, the temperature was the overriding factor affecting safety and quality rather than the packaging film.

In a comparison of passive versus active flushed MAP against perforated film packages, the actively flushed MAP (4 kPa O_2 plus 10 kPa CO_2) at 5°C held fresh-cut cantaloupe cubes best for 9 days (Bai et al., 2001). Cubes in active MAP had superior color

Table 4 Visual quality and aroma of fresh-cut honeydew cubes harvested in the winter and spring and stored in 3 atmospheres at 3 temperatures

Season	Storage Temp (°C)	Visual Perforate	Quality Passive MAP	Active MAP	Aroma Perforate	Passive MAP	Active MAP
Winter	5°C	9.7 bcd	11.0 a	11.0 a	11.0 a	11.0 a	11.0 a
	5–10°C	4.0 h	7.7 defg	9.0 c	7.0 d	7.7 cd	8.3 bc
	10 °C	2.0 i	4.0 h	8.3 bcde	4.0 e	4.0 e	6.0 bcd
Spring	5°C	8.3 bcde	10.3 ab	11.0 a	11.0 a	11.0 a	11.0 a
	5–10°C	4.0 h	6.0 defg	7.0 f	7.0 d	7.0 d	7.0 d
	10°C	2.0 i	4.0 h	5.0 gh	4.0 e	4.0 e	6.0 bcd

retention, reduced translucency, respiration rate, and microbial populations. Bai et al. (2003) determined the quality factors in fresh-cut honeydew cubes harvested in both the winter and summer and stored in three different atmospheres (passive MAP, active MAP and perforated film packages), held at three different temperatures for a total of 11 days. Cubes held in active MAP (5 kPa O_2+ 5 kPa CO_2) had the best quality followed by the passive MAP packaging and finally the perforated film packages. Table 4 shows the effects of the various storage and packaging conditions on visual quality and aroma, as measured using hedonic scales by a five member trained panel. The analytical sensory measurements correlated well with the instrumental measurements of pH, soluble solids, color, translucency, and headspace volatiles. Fresh-cut Amarillo melon was stored under passive modified atmosphere packaging (MAP) for 14 days at 5°C, using 3 commercial films resulting in a final atmosphere of 4 kPa O_2 plus 12–13 kPa CO_2. These MAPs were also effective in avoiding weight loss and translucency, and maintaining sensorial quality and microbial safety (Aguayo et al., 2003). The sweetness of fresh-cut cantaloupe cubes coated with soy protein (SP) + glycerol and lactic acid (LSP) was higher than the non-coated and the SP + malic acid (MSP)-coated samples at 7 days at 5°C. However, other sensory attributes of taste and appearance in the MSP and LSP coatings on cubes showed no significant difference on days 7 and 14 (Eswaranandam et al., 2007).

Microbial and sensorial shelf-life of fresh-cut mixed lettuce, bell peppers, and cucumber slices was only 4 to 5 days in "worst-case" scenario cold chain storage (up to 10°C for 24 hour distribution) in equilibrium modified atmosphere (EMA)-packaged (3–5% O_2+ 3–4% CO_2) products (Jacxsens et al., 2002). These findings were predominately based on undesirable color modifications, juice loss, and excessive microbial loads. Fruity aroma, as determined by a trained sensory panel, in "Julienne" style fresh-cut carrot sticks packed in heat sealed polypropylene trays overwrapped with polyvinyl chloride film decreased after 5 days of storage at 4°C, prior to unacceptable microbial contamination (Lavelli et al., 2006).

Incorporation of vitamin E (0.4% to 0.8% α-tocopherol) into honey-based vacuum impregnation (VI) solutions was recently used to maintain fresh-cut pear quality. Instrumental color analysis and sensory evaluation indicated that VE fortified pear slices had significantly higher lightness, lower browning index, and a higher consumer acceptance rating than unfortified control after 7 days in hinged clamshell containers at 2°C (88% RH) (Lin et al., 2006). Similar results were also attained for VI-treated fresh-cut apples stored at 3°C for up to 14 days (Jeon and Zhao, 2005).

Storage

Quality changes and nutrient retention during storage of whole and fresh-cut fruits was examined in a very comprehensive recent publication (Gil et al., 2006). These authors measured changes in visual quality, color, the pH, the titratable acidity, the soluble solids, phenolics, carotenoids, and vitamin C in pineapple, mango, cantaloupe, watermelon, strawberry, and kiwifruit stored for up to 9 days in air at 5°C. In general, they determined that fresh-cut fruits visually spoil before any significant nutrient loss occurs. Based on visual appearance, the postcutting life was less than 6 days for fresh-cut kiwifruit and less than 9 days for fresh-cut pineapple, cantaloupe, and strawberry. Fresh-cut watermelon and mango were still marketable after 9 days at 5°C. The results for quality indices in kiwifruit, which had the shortest post-cutting life, are illustrated in Table 5. In fresh-cut cantaloupe cubes prepared from four harvest maturities, significant decreases in vitamin C content occurred at or just after 7 d in 4°C storage, and this was also the first report of maturity-dependent vitamin C loss in fresh-cut fruits (Beaulieu and Lea, 2007). Similar to the aforementioned study, marked declines in various physiological parameters (subjective scores, pH, °Brix) did not occur until 12 to 14 days into storage. However, instrumental texture and hand-held firmness measures decreased significantly during storage in all maturities (Beaulieu and Lea, 2007).

In another recent publication (Marrero and Kader, 2006), the effects of storage temperature and modified O_2 and CO_2 concentrations in the atmosphere were examined for their influence on quality and post-cutting life of pineapples. Fresh-cut pineapple was stored for up to 15 days at 0, 2.2, 5, 7.5, and 10°C, and under continuous flow of humidified air or 2, 5, and 8 kPa atmospheres. These authors measured the soluble solids, the pH, the titratable acidity, the color, the texture, the juice leakage, and the off-odors and off-flavors. The temperature was determined to be the main factor affecting post-cutting life, and use of both MAP and storage temperatures of 5°C or lower allowed for a two week shelf life. Some of the best instrumental quality indicators were chroma (Fig. 9a), which was representative of translucency development, lightness (L value, Fig. 9b) and juice leakage (Fig. 9c).

Table 5 Whole and fresh-cut "Hayward" kiwifruit quality indices after stored at 5°C for up to 9 days. (Adapted from Gil et al., 2006)

Days	Kiwifruit	Visual quality (1–9)	Firmness (N)	Color (L*)	Soluble solids (%)	Titratable Acidity (%)	pH
Initial		9.0	0.95	39.97	11.1	0.92	3.50
3	Whole	8.3 a	0.90 a	47.17 a	11.6 a	0.98 a	3.49 a
	Fresh-cut	5.0 b	0.52 b	34.88 b	11.2 a	0.96 a	3.52 a
6	Whole	6.8 a	0.76 a	47.37 a	10.9 a	0.97 a	3.48 a
	Fresh-cut	4.0 b	0.41 b	35.06 b	11.1 a	0.91 a	3.56 a
9	Whole	6.5 a	0.61 a	46.88 a	11.9 a	1.02 a	3.50 a
	Fresh-cut	2.5 b	0.42 b	34.57 b	11.5 b	0.92 b	3.51 a
	Fresh-cut (light)	2.5 b	0.44 b	33.87 b	11.1 c	0.94 b	3.52 a

CONCLUSIONS

Fruit and vegetable quality is comprised of four primary attributes, 1) color and appearance, 2) flavor (taste and aroma), 3) texture and 4) nutritional value. These attributes have been defined, and may be evaluated as either sensory or instrumental measurements, or preferably a combination of the two. Sensory measurement are generally more useful in the development of new products and determining product standards while instrumental methods are superior in measuring quality on a routine basis (Shewfelt, 1993). There are advantages and disadvantages to both types of measurements, and one should use appropriate methods with potential limitations in mind.

The effects of various unit operations on the quality of fresh-cut products was reviewed, and it was noted that there has been more attention paid in the literature to the effects of cutting operations, packaging, and modified atmosphere storage than other operations. Since these operations are most likely to adversely affect quality, this focus and prioritization seemed appropriate. Investigators have determined that some simple instrumental measurements of color (hue, chroma, the L value, and the whiteness index), soluble solids, changes in weight or juice leakage, and the ascorbate content (as an indicator of nutritional value) may be used as indices of quality changes in fresh-cut fruits and vegetables.

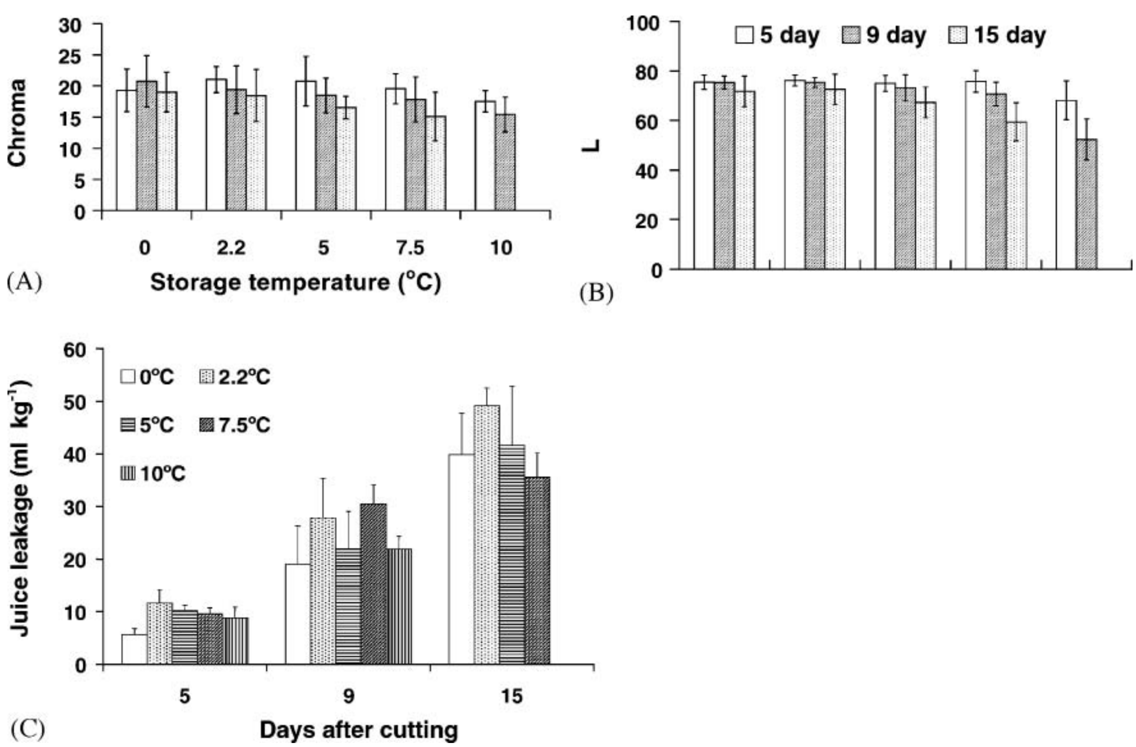

Figure 9 Changes in fresh-cut pineapple during storage under continuous flow of humidified air at 0, 2.2, 5, 7.5, or 10°C. (a) chroma, (b) L value and (c) juice leakage.

Although a fair amount of work has been performed on volatile analysis, ascribing specific importance or assigning volatile markers with quality attributes is extremely dubious due to—1) the aforementioned dilemma concerning lack of data illustrating correlation between specific volatiles and consumer satisfaction, 2) the fact that ethylene-dependent and independent ripening-related events have been demonstrated in climacteric fruits (e.g. Bauchot et al., 1998; Defilippi et al., 2005; El-Sharkawy et al., 2005; Flores et al., 2001; Flores et al., 2002; Guis et al., 1997; Hadfield et al., 2000; Manriquez et al., 2006), and 3) the important ATT system can generate volatile esters independent of ethylene inhibition/action (Fan and Mattheis, 1999; Ferenczi et al., 2006) and receptor turn-over (Dal Cin et al., 2006). Subsequently, more complex measures involving descriptive sensory analysis and volatile profiles will have more meaningful impact only when correlated with consumer acceptance and desirability. Unfortunately, few studies as such exist in the fresh-cut literature, and this remains a challenging area for the entire fresh produce arena.

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