Perspective
Flavor quality of fruits and vegetables

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Abstract: Fruits and vegetables are important sources of vitamins, minerals, dietary fiber, and antioxidants. The relative contribution of each commodity to human health and wellness depends upon its nutritive value and per capita consumption; the latter is greatly influenced by consumer preferences and degree of satisfaction from eating the fruit or vegetable. Flavor quality of fruits and vegetables is influenced by genetic, preharvest, harvesting, and postharvest factors. The longer the time between harvest and eating, the greater the losses of characteristic flavor (taste and aroma) and the development of off-flavors in most fruits and vegetables. Postharvest life based on flavor and nutritional quality is shorter than that based on appearance and textural quality. Thus, it is essential that good flavor quality be emphasized in the future by selecting the best-tasting genotypes to produce, by using an integrated crop management system and harvesting at the maturity or ripeness stage that will optimize eating quality at the time of consumption, and by using the postharvest handling procedures that will maintain optimal flavor and nutritional quality of fruits and vegetables between harvest and consumption.

Keywords: appearance life; aroma; consumer preferences; flavor life; odor; taste; texture

INTRODUCTION

Providing better-flavored fruits and vegetables at affordable prices is likely to increase their consumption, which would be good for producers and handlers (making more money or at least staying in business) as well as for consumers (increased consumption of healthy foods). Devoting more attention to flavor and nutritional quality of fruits and vegetables is strongly recommended. This should include identification of the reasons for postharvest life based on flavor being shorter than postharvest life based on appearance, selection of cultivars with flavor life that is close to appearance life, and modification of current postharvest handling recommendations on the basis of maximizing flavor life potential.[1]

New cultivars of fruits and vegetables with better flavor and nutritional quality are being and will likely continue to be developed using both biotechnology and plant breeding methods, especially for commodities for which easily monitored markers of good flavor and/or nutritional quality are identified. Developing innovative technologies for maintaining optimal temperature and relative humidity, for delaying losses of flavor and nutritional quality, and for assuring safety will require collaboration between public and private organizations.

Worldwide availability of both conventionally and organically grown fruits and vegetables and their value-added products continues to increase in terms of their number as well as their expanded season of availability with production in northern and southern hemisphere countries. Continued consolidation and vertical integration among producers and marketers will characterize the global marketing systems for fresh produce. This will facilitate collaboration among producers and marketers from various production areas to limit the marketing period on the basis of availability of superior flavor quality products from each production area.

COMPOSITION *VERSUS* FLAVOR

Fruit and vegetable flavor depends upon taste (balance between sweetness and sourness or acidity, and low or no astringency) and aroma (concentrations of odor-active volatile compounds). Although taste and aroma are well integrated in their contribution to the overall flavor, aroma is often considered to play a dominant role in flavor.[2–4] Thus, future research on flavor quality must include both non-volatile and volatile constituents that contribute to taste and aroma of fruits and vegetables.

Sweetness is determined by the concentrations of the predominant sugars, which are ranked relative to sucrose in the following order of sweetness: fructose (1.2) > sucrose (1.0) > glucose (0.64). Sourness or acidity is determined by the concentrations of the predominant organic acids, which are ranked relative to citric acid in the following order of sourness:

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citric (1.0) > malic (0.9) > tartaric (0.8); some amino acids, such as aspartic and glutamic, may also contribute to sourness. Minerals such as calcium, phosphorus, and potassium combine with the organic acids and influence the buffering capacity and the perception of acidity. Soluble sugars and organic acids contribute indirectly to phenolic metabolism by altering pH and through use as building blocks for phenolic compounds.[5] In fruits and beverages, tactile sensation of astringency is elicited primarily by flavanol polymers (proanthocyanidins or condensed tannins). Variations in proanthocyanidin composition, such as polymer size, extent of galloylation, and formation of derivatives, affect astringency;[6] individuals perceive astringency differently because of variations in salivary flow rates and in their preferences. Future research is needed to determine the extent of variation among individuals in perception of sweetness and sourness.

Soluble solids measured by a refractometer include sugars, organic acids, soluble pectins, anthocyanins and other phenolic compounds, and ascorbic acid. Thus the correlation between soluble solids and sweetness is low in some cases. Plant breeders can benefit from availability of quick methods for measuring total sugars and titratable acidity in fruits of their advanced breeding lines. Consumer acceptance of nectarine, peach, plum, and pluot cultivars is related to soluble solids concentration or the ratio of soluble solids to titratable acidity in ripe fruits.[7–9] Byrne[10] indicated that it is possible to combine high soluble solids with good fruit size in stone fruit cultivar development. Future research on correlating soluble solids to acidity ratio to sensory flavor should include alternatives, such as subtracting acidity from soluble solids.[11]

Volatile compounds are largely esters, alcohols, aldehydes, and ketones (low-molecular-weight compounds). Large numbers of volatile compounds have been identified in many fruits and vegetables, but more research is needed to identify which compounds contribute to the desirable aroma of each commodity, their threshold concentrations, potency, and interactions with other compounds. Metabolic pathways for volatiles biosynthesis, including those for amino acids, fatty acids, and carotenoids, are diverse and often highly integrated with other portions of both primary and secondary metabolism. More research is needed to identify the key substrates and enzymes involved to be able to target those that can increase desirable aroma compounds.

Voilley and Etievant[4] edited a book that provides an excellent overview of developments in flavor science and their implications for the food industry, including characterization of aroma compounds, flavor retention and release from the food matrix, and influences on flavor perception. Continued research is needed to match aroma sensory and instrumental data and to elucidate texture–aroma interactions and odor–taste interactions in flavor perception. Greger and Schieberle[12] concluded that odor-active components in a complex aroma profile can be elucidated using approaches of molecular sensory science, including aroma reconstitution experiments based on the results of quantitative data. They found that the responses of the human odorant receptors toward apricot aroma can be closely mimicked by a mixture of 18 volatiles of identical concentrations to those present in the apricot fruit. Similar studies should be conducted on other fruits and vegetables for which such information is not available. Odor threshold concentrations should be determined in the juice or purée of the commodity rather than in water.

Although work on non-destructive methods to measure quality using acoustical and near-infrared systems has led to commercial use (in a packing line situation) to select fruits with acceptable flavor quality, there is a need for continued development of non-destructive sensing of flavor quality. This should include sensing degree of freshness (time since harvest); use of near-infrared spectrophotometry to estimate concentrations of flavor-related, non-volatile constituents; use of aroma-sensing technology (electronic nose) to detect desirable and undesirable aroma volatiles;[13] and taste-sensing technology (electronic mouth or tongue).

GENETIC IMPROVEMENTS OF FLAVOR QUALITY

The relative importance of each of the flavor quality factors and their interactions depends upon the commodity. The greatest need is to produce new fruit genotypes with better flavor, which means high sugars and moderate to high acids (with balance between them), low phenolics, and enough of the desirable, odor-active volatiles for good aroma. Since flavor quality involves perception of the tastes and aromas of many compounds, it is much more challenging to manipulate than other quality factors. This has been true for plant breeders in the past and it will continue to be so with biotechnology approaches. This may be the reason that improvement of flavor quality has received much less attention from biotechnologists so far than textural quality of fruits.[14,15] Textural quality and related sensory attributes, such as juiciness, turgidity, and crispness, do influence human perception of flavor and future research should contribute to improved understanding of the physical and chemical changes that contribute to desirable texture and flavor of fruits and vegetables.

High priority should be given to replacing poor flavor cultivars with good flavor cultivars from among those that already exist and/or by selecting new cultivars with superior flavor and good textural quality. Flavor is a complex, multigenic trait providing unique challenges to breeders and has not been a high priority. Selection for yield, fruit size, and shelf-life characteristics in particular has had unintended negative consequences on fruit flavor.[3] Baldwin[2] concluded that the bottom line for flavor quality is still genetic. Breeders need more information and

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analytical tools in order to select for flavor quality. Use of wild material may be necessary in breeding programs to regain flavor characteristics that have been lost from some commodities. Use of molecular markers that relate to flavor may help identify important enzymes in flavor pathways.[2]

Bood and Zabetakis[16] concluded that techniques using radiolabeled compounds and precursor studies are important tools in providing information regarding potential biosynthetic pathways leading to flavor formation. In the next steps, biochemical techniques have provided information on the enzymes involved in these pathways. Once these enzymes were characterized, molecular biological techniques have been used to clone these enzymes. These studies have provided valuable information on how the genes involved in the biosynthesis of flavor are expressed during ripening, and whether it is feasible to overexpress these genes in order to maximize flavor production.[12,16] Future research should continue to identify the biochemical pathways responsible for production of the odor-active component for each commodity and the key enzymes involved and their controlling genes. Such information can be used by geneticists in their programs to select genotypes with superior flavor.

Pech *et al.*[17] listed the following pathways and targeted genes that are candidates for improving sensory quality: increasing the sucrose content of fruit through down-regulating genes encoding sucrose-hydrolyzing enzymes; lipoxygenase, which catalyzes the hydroperoxidation of lipid precursors of some aroma compounds; and phytoene synthase, which is involved in the carotenoid pathway, from which some volatiles are synthesized. Down-regulation of ethylene synthesis or perception aimed at extending shelf-life of climacteric fruits often results in lower production of aroma compounds.[17–22] Defilippi *et al.*[19] found that the alcohol acyltransferase (AAT) enzyme is under ethylene regulation and seems to play a role in determining ester formation. In addition, the availability of fatty acids and amino acids (especially isoleucine) showed important changes associated with ester production under ethylene regulation. Future research is needed to better understand how to reduce ethylene production and/or action without reducing ester biosynthesis.

PREHARVEST FACTORS

The influences of genome, growing conditions, harvest maturity, and storage regime on compounds that serve as precursors for ester formation are critical factors that determine the ultimate levels of volatile esters in fresh and stored apples.[18,23] Climatic conditions (temperature, light, rain, wind) and cultural practices (planting density, tree pruning, fruit thinning, nutrient and water quantities; control of weeds, diseases, and insects) that result in high yield often result in less than optimal flavor quality. Future research is needed to identify optimal cultural practices that maximize flavor quality, such as optimizing crop load and avoiding excess nitrogen and water, which along with low calcium shorten the postharvest life of fruits due to increased susceptibility to physical damage, physiological disorders, and decay.[24] Selection of optimal integrated crop management systems for each commodity should be based not only on yield but also on quality attributes including flavor. Adoption by producers of cultural practices that will improve flavor quality but slightly reduce yield will be encouraged by the willingness of buyers to pay a higher price for the products to compensate the producer for the loss in yield.

MATURITY AND RIPENESS STAGE AT HARVEST

I rate maturity stage at harvest as the second most important factor (after genotype) influencing flavor quality of fruits and vegetables. Non-fruit vegetables are best tasting when harvested immature, while fruit vegetables and fruits are best tasting when harvested fully ripe. Synthesis of non-volatile and volatile compounds influencing fruit flavor increases with maturation and ripening. However, harvesting fruits before they reach optimal maturity is a common commercial practice because of the higher prices when the supply is low at the beginning of the harvest season of each kind and cultivar of fruits. Minimum maturity indices are often not enforced by the regulatory authorities. Another reason for harvesting climacteric fruits before their optimal maturity stage based on flavor is to assure sufficient firmness to withstand handling procedures and to maximize their storage potential. However, Fellman *et al.*[23] showed that when apples are harvested at the early pre-climacteric stage and kept in either air or controlled atmospheres for various durations before marketing, they never reach good eating quality. Future research and development efforts should be directed to encourage producers to harvest fruits at partially ripe to fully ripe stages by developing handling methods that protect the fruits from physical damage.

POSTHARVEST FACTORS

Much of the published information about optimal harvesting and handling procedures has largely been based on reducing quantitative losses by maintenance of appearance and textural quality of fruits and vegetables.[25–29] Forney[30] concluded that controlling changes in volatiles and flavor that occur during marketing and storage presents an additional challenge: since the goal is to optimize fruit flavor upon delivery to the consumer, it is not enough to harvest fruit with good flavor; this flavor must be maintained or enhanced during storage and marketing. This produces many challenges to understanding the environmental and physiological factors affecting volatile composition during postharvest handling throughout the distribution chain. As technology develops to provide more precise control over the holding environment, including temperature, humidity, and atmosphere composition, these new capabilities can be used to optimize volatile composition and flavor.[30]

Kader *et al.*[31] reported that the longer the time between harvest and eating, the greater the losses of characteristic aroma and the development of off-flavors in tomatoes. My collaborators and I found similar trends in strawberries[32] and all the other fresh fruits that we have tested during the past 30 years. Thus, it is very important to identify optimal postharvest handling conditions (time, temperature, relative humidity, atmospheric composition) that maintain flavor quality of fruits and their value-added products. Postharvest life should be determined on the basis of flavor rather than appearance. The end of flavor life results from losses in sugars, acids, and aroma volatiles (especially esters) and/or development of off-flavors due to fermentative metabolism (accumulation of acetaldehyde, ethanol, and/or ethyl acetate to levels above their threshold concentrations that cause undesirable flavor) or transfer of undesirable odors, such as those caused by sulfurous compounds, from fungi or other sources. Off-flavors in foods can arise from environmental sources, such as air, water, and packaging materials, from chemical and biochemical reactions occurring within the food itself, and from flavor–matrix interactions, all of which can unbalance the intrinsic flavor profile.[33]

Baldwin *et al.*[34] concluded that the individual contributions of flavor compounds and their interactions in terms of the overall flavor quality of fresh produce need to be determined for many important horticultural crops. The effect of harvest maturity, handling, storage temperature and shelf-life duration needs to be evaluated for flavor quality shelf-life, which may be shorter than appearance shelf-life for many commodities.

More research is needed to determine both the positive and negative effects of using the ethylene action inhibitor, 1-methylcyclopropene, on flavor quality of fruits and vegetables that are currently treated or likely to be treated in the future to extend their postharvest life.[35–37]

VALUE-ADDED PRODUCTS

Research on how to maintain quality and safety of fresh-cut fruits and vegetables increased greatly during the past 15 years in response to commercial development of value-added, ready-to-eat products. Strategies for delaying browning and softening of wounded plant tissues and for maintaining their safety by minimizing microbial growth have been developed. However, more research is needed to enable extension of post-cutting life based on flavor and nutritional quality. Also, there is a need to develop new ready-to-eat, value-added products with good flavor and adequate shelf-life.

Beaulieu[38] hypothesized that recycling of esters during storage of certain fresh-cut fruits disturbs the delicate fine balance of characteristic volatiles. Consistently decreasing acetates along with increasing non-acetates could alter the overall perceived desirable flavor attributes during fresh-cut melon storage, even though volatile esters are still abundant. Fresh-cut 'Gala' apples displayed a slightly different trend whereby both acetates and non-acetate esters decreased appreciably during storage. Further research is needed to identify the underlying mechanism for loss of characteristic and desirable flavor in fresh-cut fruit and vegetable products and how to delay such losses.

PROCESSING FACTORS

In a recent review, Rickman *et al.*[39,40] concluded that the initial thermal treatment of processed products can cause loss of water-soluble and oxygen-labile nutrients such as vitamin C and the B vitamins. However, these nutrients are relatively stable during subsequent canned storage owing to the lack of oxygen. Frozen products lose fewer nutrients initially because of the short heating time in blanching, but they lose more nutrients during storage owing to oxidation. Phenolic compounds are also water-soluble and oxygen-labile, but changes during processing, storage, and cooking appear to be highly variable by commodity. These processed forms offer added convenience to the consumer and offer diversity to the diet, while generally sacrificing little in terms of nutrition.[39,40] It is very likely that changes in nutritional composition are accompanied by changes in flavor quality of fruits and vegetables.

Although processing methods, especially thermal processing, can alter textural and flavor quality, they are very useful in terms of year-round availability and convenience. Future research and development efforts should focus on selecting cultivars with better flavor and nutritional quality, optimizing maturity/ripeness stage in relation to flavor quality at the time of processing, and on identifying the processing methods that would retain good flavor and nutritional quality of the processed fruit and vegetable products.

CONCLUSIONS

Providing better-tasting fruits and vegetables to consumers, especially in convenient forms and at affordable cost, is likely to increase consumption of these healthy foods. To achieve this goal, future research and development efforts should address the following objectives:

1. Replacing poor-flavor cultivars with good-flavor cultivars from among those that already exist and/or selecting new cultivars with desirable flavor and textural quality.

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2. Identifying optimal cultural practices that maximize flavor quality, such as optimizing crop load and avoiding excess nitrogen and water.
3. Encouraging producers to harvest fruits at partially ripe to fully ripe stages by developing handling methods that protect the fruits from physical damage and methods for non-destructive determination of maturity and quality indices.
4. Identifying optimal postharvest handling conditions (time, temperature, relative humidity, atmospheric composition) that maintain flavor quality of fruits and vegetables and their value-added products. Postharvest life should be determined on the basis of flavor rather than appearance.
5. Developing ready-to-eat, value-added products with good flavor and adequate shelf-life.
6. Optimizing maturity/ripeness stage in relation to flavor quality at the time of processing and selecting processing methods to retain good flavor of the processed products.

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