Recent Developments in Noninvasive Techniques for Fresh Fruit and Vegetable Internal Quality Analysis

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ABSTRACT: This review covers developments in the field of noninvasive techniques for quality analysis of fresh fruit and vegetables over the past decade up to the year 2005. A chapter on the concept of quality is followed by a discussion of various methods and applications including optical, spectroscopic, and mechanical techniques but also the application of X-rays and some noninvasive methods of minor dispersal. An extra section on research needs reflects on possible future developments. It is concluded that during the last year, much progress has been made in developing nondestructive techniques for the assessment or inspection of quality parameters of fruits including internal disorders but also taste, sugar content, and so forth. As sensors often measure only a single constituent or quality property, combined techniques have to be optimized to measure overall quality. Commercial application of these techniques will be beneficial for the consumer as well as the producer and for trades in which merchants will be able to comply with consumer demands for uniform high-quality products.

Keywords: noninvasive, internal quality, fresh fruit, vegetables, spectroscopy, near infrared, magnetic resonance, ultrasonic, imaging

Introduction

Increasing consciousness of quality, particularly in the food and health sector, strongly demands research activities regarding the production of defined quality, the preservation of quality during marketing, and thus also the possibilities of evaluating quality parameters and of integrating this into production processes. Due to the rapid development of technology and mathematical methods, as well as the multiplicity of investigations all over the world, up-to-date reviews are needed to offer an orientation over technological applications at the interface of horticulture and food science.

Scientific literature dealing with nondestructive or noninvasive analytical methods in food science and technology has been increasing exponentially during the last half century as shown in Figure 1, demonstrating also the great interest in that topic today. The question of the speed with which a procedure can be executed, is to be seen differentiated: Does a new procedure need less time for an assessment than the reference method? Is a faster but less sensitive method sufficient? Can operational sequences be better organized with other analysis systems, for example, by automation? Some procedures have the potential to deliver online results of measurements of different quality parameters in so short a time that their use in assorting or packaging facilities appears possible. In Japan, devices are already in operation that assess apples with a speed of 4 to 6 pieces/s for sugar content, glassiness, and internal damage. European and U.S. manufacturers offer similar equipment (for example, www.greefa.nl, www.aweta.nl, accessed Sept. 2005).

Quality

Quality of fresh fruit and vegetables is evaluated by trade, consumers, processors, and producers on the basis of certain but not seldom different characteristics. The term "quality" is a frequently used and multilayered expression that is usually neutral or positively occupied. Products offered to consumers in the market should fulfill certain external requirements that are perceived by the senses of sight and touch because they are important for the purchase decision. Internal characteristics, perceivable by the senses of taste, smell, and touch (mouthfeel), will determine the decision to repurchase that product (Shewfelt 1990). Characteristics like nutritional value, wholesomeness, and safety can not readily be determined by consumers because they require measurement, but if this information is given to the consumer, it will influence acceptability of the product (Shewfelt 1987). As an example it could be shown that for certain cherries on the U.S. market, consumer acceptance was mainly dependent on fruit soluble solids content and visual skin color (Carlos and others 2003). Tijskens (2003) pointed out that we have to understand the different meaning the word quality can have in various circumstances. Usually when talking about quality at the consumer's side of the chain, acceptability is really what is meant. We have to realize that quality exists only in the mind of an observer. It is the result of all interactions of a consumer (or observer) with a product and its circumstances, the market and its circumstances, and the social situation the consumer is in. All these effects and influences will be different for each individual, for each situation. And it will result in a different acceptability for each individual. What, however, remains the same in all circumstances is the way quality attributes are generated from product properties, the way economic stimuli are interpreted, and the way the psycho-social indicators are read and evaluated. That is really the central and invariable kernel to view and interpret the manifold appearances of quality.

For producers of agricultural products, quality also involves the cultivation of specific factors, for example, resistances and potential of yield, as well as uniformity of the harvest products, for example, in size, shape, and color, for efficient treatment and straightforward marketing. Merchants are also interested in freshness and durability, whereas the processing industry has to contemplate the suitability for process-

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ing and preservation. Finally, the consumer should buy the produce in the consciousness to receive tasty commodities with nutritionally valuable and health-promoting contents. Also aspects such as origin, ecological production, or convenience are considered by consumers. Quality of fresh fruit of apple 'Gala' clones, for example, can be defined on the basis of internal and external characteristics, the parameters of external fruit quality like the fruit surface coloring, firmness, weight, diameter, and height of fruits, length and thickness of fruit stalk and internal fruit quality attributes like content of total soluble solids, of individual sugars like fructose and sorbitol and organic acids like malic and citric shikimic and fumaric acids, which mostly are to be measured instrumentally (Sturm and others 2003). On the other hand, it may well be that based on consumer acceptability, a mathematical relationship exists between the sensory descriptor aroma and consumer acceptability, and between superior quality (tastes great) and aroma and mouthcoating, but no significant relationships are observed between instrumental analysis and consumer acceptability testing as shown for different peanut soy spreads (Dubost and others 2003). Frequently, however, designations are used such as freshness, ripeness, or grade of relish, which as generic terms for quality consist of diverse factors. Apart from some other characteristics, the freshness of vegetables is determined considerably by the water content and the concentration of valuable constituents whereby these items often change rapidly during postharvest decay. The product may already be withered; however, the decay of constituents must not necessarily have progressed far yet. If a product is judged as fresh by optical impression, special expectations about its internal components are created in the consumer (Geyer and others 1999). The stage of ripeness and thus the "correct" harvesting date to be set when all expected characteristics show their optimal development. As indications are generally rated morphologic conditions, such as size, color, softness, or firmness (depending upon the kind of the plant organ that can be harvested) considering also the weather of course during the development phase. After harvest degradations of the quality are to be expected, which can be partly retarded by suitable site conditions (for example, cooling). Due to the temporal change of the constituents such as total soluble solids (TSS or Brix degree), starch, and firmness, all these items are taken as measure for maturity: the fruit grower uses, for example, the Streif-Index, a mathematical relation including firmness, TSS, and starch content, or other indices for the determination of the optimal harvesting date. Due to fructification physiology, the quality criterion shelf life inherits an area of conflict between the development stage with optimal durability and the development stage with optimal relish value (Friedrich and Fischer 2000). External characteristics and also combined terms and individual internal components have found entrance, for example, into marketing standards. Minimum characteristics are demanded and, depending upon the kind and assortment, additional quality characteristics are also required (color, shape, firmness, and so forth).

The pallet of possible damage to fruit and vegetables is extremely extensive and is often a criterion of quality determination methods, for example, malformations, rust fungi, formation of cork, splits, bitter pit, insect damage, rots, scalds, temperature damage, and glassiness or other physiological diseases of the storage phase. In addition, there are various risks for injuries during harvest and transport.

To characterize the internal quality apart from the texture (essentially including consistency or firmness, and the turgescence (water saturation) components may be consulted that are responsible for taste value (for example, content of sugar, acids, and the relationship among themselves, flavor (flavor materials such as acids, esters, and alcohol), the physiological value (vitamin and mineral content and the content of carbohydrates, fats, and proteins). Quality-reducing components are subject to legal regulations (for example, Pesticides Regulation Standards by the U.S. Environmental Protection Agency, EPA (http://www.epa.gov/customerservice/standards/pesticides.htm; accessed Feb. 2005) or are the subject of breeding research with the aim of their removal or reduction (for example, oxalic acid or allergens).

Methods and Applications

Methods for the assessment of quality parameters were developed over centuries and instrumental analysis could develop fast due to the technical progress in the 20th century. Today, emphasis is put on the development of sensors for nondestructive assortment in real-time mode. The continuous examination of connections or relations between measured variables and quality criteria are of fundamental importance for the application of these new methods (Akimoto 1996). By increasing physiological knowledge, chances increase for both the influencing and also the indirect measurement of such relationships. It was shown that the processes of maturing could be used as forecast pattern. However, disturbances can occur by influences of

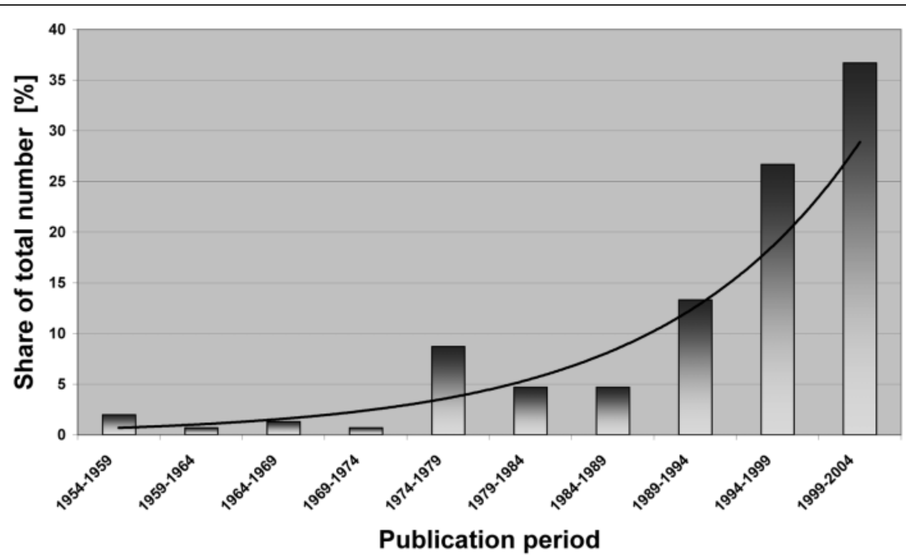

Figure 1—Course of share of total number of scientific publications listed in ISI web of science in the field of Food Science and Technology containing "noninvasive" or "nondestructive" in the title during the y 1953 to 2004.

cultivation procedures and postharvest treatments. Humans use all their senses for the evaluation of horticultural products. A strategy when using other measuring devices for different quality parameters should therefore be an integrated approach. Today an Internet search engine will find about 66000 items for the key words "nondestructive" or "noninvasive" in the context of "food." Figure 2 shows the distribution of these entries on the different techniques of nondestructive analysis of food. Vision-based methods with about 50% of all seem to be the by far most frequent. They include many different applications, from traditional manual evaluation by trained inspectors to computer vision using modern image acquisition apparatus like multispectral cameras, and so forth, and highly sophisticated image-processing software for object measurement and classification utilizing for example, fuzzy logic and neural network methods. The other 50% are shared proportionately by acoustic and spectroscopic techniques, most of which are not less sophisticated as the vision based. This article discusses these methods in varying detail and gives information to readers with deeper interest about which books and articles to refer to for further details. Although not covered by this review on the quality of fresh fruits and vegetables, there has also been a considerable body of work that has been completed using noninvasive sensors on other materials, for example, in online food-processing applications. A good source of information on those topics are the biannual reviews in Analytical Chemistry entitled "process analytical chemistry" (the most recent article: Workman and others 2005).

Spectroscopy Analysis

Spectroscopic methods of analysis use interactions between atoms or molecules and electromagnetic radiation to supply qualitative and quantitative chemical and physical information. Spectroscopy here is to be understood as optical spectroscopy. Photons from certain wavelength or frequency ranges of the spectrum are absorbed or emitted according to their energy content. The usual spectrophotometers mainly supply absorption spectra. Contrary to the classical chemical methods of analysis, spectroscopic methods are nondestructive with a broad range of applications. In the past decade, technological progress and also the availability of useful statistical procedures increased rapidly (Scotter 1997). Dardenne and others (2000) evaluated the 4 most important regression methods on very large data sets: Multiple Linear Regression (MLR), Partial Least Squares (PLS), Artificial Neural Network (ANN), and a new concept called "LOCAL" (PLS with selection of a calibration sample subset of the closest neighbors for each sample to predict). The Standard Errors of Prediction (SEPs) were statistically tested, and the results showed that the regression methods were almost equal and that the data matrices were more important than the fitting methods themselves.

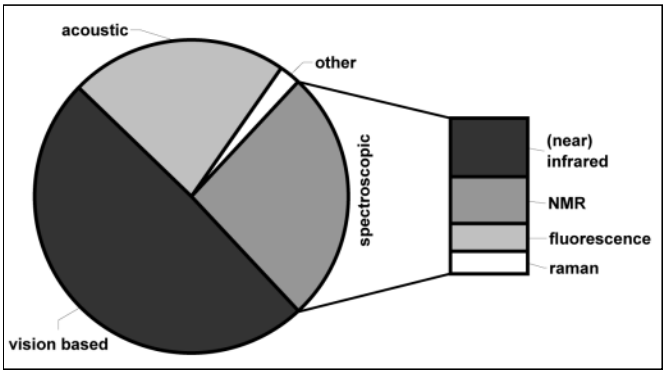

Figure 2—Distribution of results of an internet search on the keywords "nondestructive" or "noninvasive" in the context of "food" on the different sensor techniques of nondestructive food analysis (Jan. 2005).

Electromagnetic radiation are free electromagnetic waves, which are caused by oscillations of electrical charges. The whole electromagnetic spectrum ranges from ultra-short gamma-rays to the very long radio waves. Ranges of different spectroscopic techniques, the radiation effects being probed, and the information obtained by these methods are specified. If subjects are illuminated with a suitable range of the electromagnetic spectrum, certain wavelengths are absorbed and an absorption spectrum can be recorded. These spectra are characteristic of atoms, functional groups, and also large molecules and permit statements about the chemical composition of the sample by comparison with spectra from data bases. The online NIST Chemistry WebBook, for example, contains IR spectra for more than 16000 compounds, mass spectra for over 15000 compounds, and UV/VIS spectra for more than 16000 compounds (http://www.nist.gov/srd/analy.htm accessed Sept. 2005).

Visible Spectral Range (VIS) and Image Analysis

The visible light (VIS) covers the wavelengths of approx. 380 to 770 nm. Many products are assigned to commercial grades according to their color. The main absorbing molecules in the visible range are pigments such as chlorophyll, carotenoids, and anthocyanins. They contain functional groups in which electrons can be excited by absorption of light energy. For color description, there are different color coordinate systems. In the well-known 3-dimensional RBG system, the 3 basic colors, red, blue, and green, are represented as the 3 axles of a cube. But also other geometries are used, for example, the spherical L*C*h * system, different CIE systems (Commission Intl. de l'Eclairage), or the Hunter *L*, *a*, *b* system, which additionally describe brightness and saturation and are frequently used. They are aligned to adapt color distinctions to human seeing. Because color is a sensory perception, it was reasonable to adapt also the functionality of instrumental measurement to the physiology of the human eye. Sensors in colorimeters are provided with filters to simulate the 3 color receptors of the eye. The spectral data are mathematically corrected using standard spectra that reflect the average responses of the 3 different color receptor cell types of human eyes. This color evaluation principle is commercially used to sort apples and peaches and other products at packaging lines (Abbott 1999). Color determination of strawberries and carrots was accomplished by Quilitzsch (1999) who used solely the characteristics color and saturation. Scheer and others (1999) could determine high correlation between peel color and taste-giving contents of cape gooseberries, *Physalis peruviana* L. Ripeness of bananas is usually judged by comparison with color templates. Li and others (1997) searched for a nondestructive and fast method being more economical than, for example, a colorimeter for measuring an appropriate correlation between the optical "chlorophyll perception" and the chemically measured chlorophyll content of the banana peel. The measuring instrument was developed based on results of a preceding study that selected wavelengths for inexpensive light emitting diodes (LED), which delivered the best prediction of the chlorophyll content. The wavelengths were 610 and 660 nm, as transducers phototransistors were used. The results showed that with such an equipment, a reliable determination of the chlorophyll content could be accomplished. In practical application, however, differences between different banana sorts would require individual calibration. In addition, fruit damage such as bruises or some surface defects cause changes of diffuse reflectance. According to Aneshansley and others (1997) and Throop and Aneshansley (1997), 4 wavelengths (540, 750, 970, and 1030 nm) are useful to distinguish between sound and damaged tissues in several apple cultivars. The reduction to only a few wavelengths shortens measuring and analysis time but may also mean information loss. Chlorophylls and carotenoids are very common pigments, which give color to vegetables and several fruits. Because of their color and their physicochemical properties, they are also used as additives to food products. Both pigment types are fragile and can be easily altered or destroyed, modifying the perception and the quality of the products. Schoefs (2002) reviewed analytical processes, including nondestructive methods, to control the pigment content of food products. The Dutch company Aweta offers an apple-sorting equipment (Falcon™) that is able to recognize and classify defects (www.aweta.nl, accessed Jan. 2005). Data received by special cameras (for example, multispectral or hyperspectral cameras) can be converted into images, which represent for example, the spatial distribution of contents below the fruit surface. A fast and very simple method was applied by Haffner and others (2000) for the assessment of raspberries: they used a normal scanner and common software to receive color information as well as data about the size and shape of the fruits. Often color CCD cameras are used together with computers and appropriate software (Edan and others 1997). In recent years, computer vision has been attracting much R&D attention from the agri-food industry, and rapid development has been taking place increasingly on quality inspection, classification, and evaluation of a wide range of agri-food products. A special journal issue on "Applications of Computer Vision in the Food Industry" focuses on these advances [J Food Eng 61 (2004) 1–2]. There are 14 articles written by international experts covering, for example, segmentation in image analysis/processing, high spatial resolution hyperspectral imaging systems as a tool for selecting better multispectral methods to detect defective and contaminated surfaces of apples (Mehl and others 2004), NMR-imaging on 5 raw potato varieties in combination with different image analysis methods to predict the sensory texture quality attributes of cooked potatoes (Thybo and others 2004), the applications of imaging technologies for quality control of agricultural materials in a visible and nonvisible spectrum, and, using computer vision technology, an automated inspection system for color grading of oil palms and also the application of computerized radar tomography to map moisture content of grain (Abdullah and others 2004). Microwave imaging is applied in biomedical, subsurface detection and nondestructive evaluation applications (Pastorino 2004). There is a recent review by Du and Sun (2004) on recent developments in the applications of image processing techniques for food quality evaluation, which include CCD cameras, ultrasound imaging, magnetic resonance imaging (MRI), computed tomography (CT), and electrical tomography (based on computerized analysis of electrical resistivity, capacitances, and inductance changes).

Fluorescence and Delayed Light Emission (DLE)

The term "photoluminescence" summarizes the 2 effects of fluorescence and phosphorescence of materials. They are based on the radiation of electromagnetic energy within the visible range after excitation by short wavelength light, usually UV light. The 2 similar processes differ in the initial state from which molecules are excited. Many biological materials fluoresce; however, the main application of fluorescence is that of chlorophyll fluorescence. Fluorescence measurements of chlorophyll-containing biological materials give information on photosynthesis activity (for example, Georgieva and Lichtenthaler 1999). The relaxation of excited electrons to their original energy levels under emission of fluorescence light is very fast (in less than 10 to 8 s). A dark period of at least 10 min must precede DLE or fluorescence measurements to avoid disturbing influences of the photosynthesis apparatus. Delayed light emission, DLE, is fluorescence, which develops after chlorophyll is excited by backward reactions of intermediate products of photosynthesis. Chlorophyll loss and decreasing photosynthesis rates are usually coupled to progressive ripening of vegetable organs. In addition, the tissue chlorophyll content is impaired by injuries and stress. In an early study Abbott and Massie (1985) reported about DLE for the detection of chilling injuries of cucumbers and red peppers. Toivonen (1992) published fluorescence measurements of the freshness of broccoli, and Dell and others (1995) reported on the detection of postharvest defects of apples. An application, which did not involve chlorophyll, was reported by Uozumi and others (1987): oil from injured oil cells of mandarin peels could be discovered by means of fluorescence. The desirable effect of these techniques is the early recognition of the effects of stress factors (for example, cold weather, heat, dryness) before visible symptoms appear at a time where damage is already inevitable. In a more recent work, Nedbal and others (2000) demonstrated the potential for using rapid imaging of chlorophyll fluorescence in postharvest fruit to develop an automated assorting device capable of removing poor quality fruit long before damage becomes visible. The measurement of chlorophyll fluorescence of greenhouse-grown cucumber (Cucumis sativus L. cv. Mustang) fruit can be a useful tool in monitoring senescence, temperature stress, and desiccation during storage. Under some circumstances, some fluorescence parameters may be used as quality indicators for postharvest handling procedures of greenhouse cucumbers subjected to various storage treatments (Lin and Jolliffe 2000).

Chlorophyll fluorescence was also reported to be a possible means to nondestructively establish the lowest acceptable O_2 concentration for CA-stored chlorophyll containing plant products. Kim and others (2004) used a laboratory-based hyperspectral imaging system capable of both reflectance and fluorescence measurements and a multispectral laser-induced fluorescence imaging system to determine from the spectral and spatial information several optimal wavebands that can be implemented to a multispectral imaging system for rapid automated safety inspection of food, for example, detection of invisible fecal residues on fruit. Sikorska and others (2005) tested luminescence and synchronous scanning fluorescence spectroscopy techniques as regards their ability to characterize and differentiate edible oils, including soybean, sunflower, rape-seed, peanut, olive, grape-seed, linseed, and corn oils. Both methods provided very good discrimination between the oil classes with low classification error.

Near-Infrared Spectrophotometry (NIRS)

Since the late 1980s, NIRS had been examined as a nondestructive method for the determination of firmness, freshness, Brix value, acidity, color, and other characteristics of many fruits and from the results achieved, NIRS could be judged as an appropriate method for these applications (Cho 1996; Kawano 1999). While early applications began to become accepted in agri-food analysis with the work of Karl Norris (in the 1960s), today NIRS is increasingly examined, tested, and used within all fields of food science and technology. Applications range from grains over potatoes and potato chips to meat and prepared meals as well as fruit juice and wine production where the contents of materials such as fat, water, protein, total nitrogen, sugar, and alcohol are assayed using this technique. Beyond that, the procedure has long been used also in the chemical industry (for example, petroleum chemistry, plant protection agents) and pharmaceutical industry for process control and quality control and also in polymer analysis. The near-infrared range covers the wavelengths from 750 to 2500 nm, equal to the wave number range of 4000/cm to 12500/cm. NIRS is a method well suitable for the determination of chemical compounds containing OH-, CH-, and NH- groups. This is particularly due to the overtone bands of these functional groups, which are to be observed within the short wavelength range of near-infrared, which is rather poor of bands. In relation to the middle-infrared range, where the pervasive water absorbs strongly its absorption in the NIR range is far less pronounced, but still clearly present with a broad peak of about 980 nm. The absorption is smaller, so that according to the dependence between layer thickness and the extent of absorption, the sample diameters can be larger. Another advantage is that by using fiber optics, measurements from nearly any position may be conducted. Overtone bands can interact variously with one another, strengthen or extinguish thus; they interfere which leads to the so-called combination oscillations, which inherit an additional identification potential. The interpretation of the spectra may take place via direct spectrum identification using data bases or increasingly by applying procedures of high-speed chemometrics. The complex spectral data are often pretreated by statistical procedures, to facilitate the handling.

Fundamentals of near-infrared and the instrumentation are given, for example, in Osborne and others (1993) or in a more recent shorter review by Barton (2002). Well-known work on the field of NIRS has been done by Kawano and others (1992), for example, who determined the sugar content of peaches in the "Interactance" mode, which means by registration of the reflected light, which is changed due to absorption in the fruit. For this a fiber-optic probe (2-way for illumination and detection) is brought into contact with the sample. The wavelength band around 906 nm could be assigned for sucrose, as for high, middle, and low Brix values clear spectral differences (in the 2nd-derivative spectra) were determined. The highest correlation coefficient of 0.97 was received by means of linear regression, where spectral data received at 4 different wavelengths were processed. The standard error of calibration (SEC) amounted to 0.48° Brix, the corrected standard error of prediction, SEP, amounted to 0.50° Brix with a bias of 0.01° Brix. These results show the high exactness of the method. Similarly, good results were published by Kawano and others 1 y later (1993) for the determination of the sugar content in Satsumas. In this measurement, the Brix value was examined from the registered transmitted after a correction on the size of the fruits. A further use of fiber optics was proposed by Slaughter (1995) who could predict with good success the content of soluble solids, different sugars, and of chlorophyll in peaches and nectarines using wavelengths from visible light and NIR. Kawano and others (1995) found a possibility of compensating an obvious temperature influence on the spectral data of peach fruits by application of a special calibration equation. A review focusing on NIR analysis of apples with special emphasis on the developments in Japan has been given by Kupferman (1997), available also online. Quilitzsch and Hobert (2003) reported a fast determination method of apple quality by spectroscopy in the near infrared. The Italian company Sacmi markets a quality-control system with large transportation bowls for sugar melons, watermelons, and pineapple as well as a version for medium-sized fruits such as citrus, apples, pears, peaches, tomatoes, mangoes, and others. The devices measure in transmission mode and determine sugar and acidity and sort according to ripeness, glassiness, and internal breakdown with a transportation speed of 18 fruits per min. Pineapple and mango were objects of investigations by Guthrie and Walsh (1997). Despite the expected problems regarding the epicarp structure of pineapple and the large core of mango fruit, good results could be achieved by means of reflection measurement and fiber optics, whereby further work was considered necessary for the calibration development. In an investigation of Schaare and Fraser (2000), 3 spectroscopic procedures were accomplished in the range VIS/NIR: reflection, transmission, and interactance Kiwi fruit (*Actinidia chinensis*) were used for the determination of the content of soluble solids, density, and pulp color. The spectral data were transformed and the efficiency of the calibrations was examined. Each method delivered good calibration results, thus the application of NIRS as fast and nondestructive method for the determination of the internal quality of fruits was confirmed. In each case, the interactance mode supplied the best prediction models. Expectations that the transmission method would supply better results due to smaller influences of the fruit surface was not confirmed because for that mode, only a relatively low light intensity and thus a more unfavorable signal-noise ratio were perceived. Using a more intensive light source or a more sensitive detector for the transmission measurement could have led to better results. Butz and others (2002) applied a multi-wavelength NIR diode laser array as stronger light source for transmission measurements in apple, peach, and tomato. Tungsten halogen light sources as NIR radiation source develop thermal broadband radiation, which leads to strong heating of the fruits, whereby the stability of the material is questioned. Besides, most of the radiation does not penetrate very deeply into the sample. To remedy the situation, laser diodes were used, which are more efficient. These radiation sources exhibit somewhat broader line widths than conventional lasers. Thus, sufficient spectral information can be received by using only 6 to 10 diode lasers in the range between 750 and 1100 nm where the spectra are usually composed of a multitude of broad overlapping peaks. The individual beams of the array were focused on the fruits to be measured, and a fast diode array spectrometer was used as detector. The spectral information from transmission measurements of apple, peach, and tomato was chemometrically set into the relationship with the results of analysis by the reference method for the constituent of interest, that is, Brix degree or firmness, and in all cases, good or acceptable correlation was reached. Using a 45° arrangement for lasers and detection also internal damage in apples could be detected and quantified noninvasively (Butz 2004). The method is to be regarded as promising. Another sophisticated technique was reported by Lu (2004). It was shown that near-infrared multispectral scattering measurements enable the prediction of apple fruit firmness; with 3 ratios of spectral profiles involving only 4 wavelengths, a neural network gave firmness predictions with the correlation of 0.76 and the standard error of 6.2 N for the validation samples.

Topics of general interest still are standardization, sample presentation, and developments in the field of handheld NIRS devices. Dardenne and others (2002) studied the influence of the calibration methods and the size of the cloning set in standardization of near-infrared instruments using 10 different NIRS instruments. They concluded that only calibration transfer to standardized "slave" instruments enables acceptable results to be received and that the data sets have to be large and robust. Standardization was performed using special single-sample and multi-sample standardization process software. Kawano (2002) reports on the optimization of sample presentations for near-infrared analysis of intact fruits, single grains, vegetable juice, milk, and other agricultural products, concluding that while recording of useful spectra requires many parameters to be monitored, the selection of the most appropriate sample holder (cell) is absolutely essential. McClure (2002) reports about the future of hand-held NIR meters (HHNIR). While "normal" spectrometers are getting more and more compact, there is a lack of commercial HHNIR meters. This is due to difficult miniaturization, energy problems, and small profit margins. It is speculated that the problems could be overcome soon and that HHNIR meters would appear within a few years. An interesting quite unfamiliar application of near-infrared reflectance spectroscopy was recently reported by Ko and others (2004). Because the application of relatively high levels of heavy metals in the compost poses a potential hazard to plants and animals, the content of heavy metals in the compost with animal manure is important to know if it is as a fertilizer. The study showed that NIRS is a feasible analytical method for prediction of heavy metal contents in compost: Coefficient of simple correlation (r) and standard error of prediction (SEP) were Cr (0.82, 3.13 ppm), As (0.71, 3.74 ppm), Cd (0.76, 0.26 ppm), Cu (0.88, 26.47 ppm), Zn (0.84, 52.84 ppm), and Pb (0.60. 2.85 ppm), respectively.

Terahertz Radiation

Terahertz radiation, also called T-Rays, is situated in the far-infrared region (millimeter and sub-millimeter wave) in the final "gap" in the electromagnetic spectrum between microwaves and the infrared. Compared with microwaves, terahertz frequencies bring wider bandwidths, smaller antennas, and wavelengths appropriate to the resolution of everyday objects. Molecules emit characteristic rotational transition lines at terahertz frequencies, whereas substances show markedly different opacities to those at other wavelengths. Research is performed by several groups, for example, by electrical engineers at the Univ. of Leeds and their collaborators at the Univ. of Cambridge to exploit the potential uses of this new technology (e-mail: r.e.miles@leeds.ac.uk) or at the Terahertz Laboratory, a part of the Instrumentation & Signal Processing Research Group (ISP) at the Dept. of Cybernetics, Univ. of Reading, which is active in the development of instrumentation and techniques for the generation, detection, and analysis of terahertz radiation (http://www.cyber.rdg.ac.uk/terahertz/). Applications include earth remote sensing (meteorology, oceanography, greenhouse gas, and ozone mapping) and passive imaging used mainly in medical diagnosis (noninvasive detection of breast cancer or skin cancer). Unlike X-rays, terahertz waves are not harmful, so there are no exposure worries for practitioners or patients. But also noninvasive food applications are possible: determination of fat in meat, ripeness of tomatoes, and so forth. A major breakthrough was reported recently (Carr and others 2002): A new approach, based on synchrotron radiation from accelerated electrons, has been used to generate broadband THz radiation with an average power of 20 Watts, 100000 times more intense than the best existing sources. This could enable various new applications, in particular, many materials have distinct absorptive and dispersive properties in this spectral range, so that THz imaging could reveal interesting features, for example, the distribution of specific proteins or water in food tissues. The Kawase Initiative Research Unit at RIKEN (2004), Japan, has developed a widely tunable (0.7 to 2.4 THz, 125 to 430 μm, 23/cm to 80/cm) injection seeded THz-wave parametric generator (IS-TPG) that operates at room temperature. The spectral resolution (<100 MHz, 0.003/cm) is the Fourier transform limit of the nanosecond THz wave pulses. The continuous scanning and the narrow spectral bandwidth of the ISTPG are verified in absorption spectra of low-pressure water vapor. The output has a high peak power (>200 mW) and a small beam divergence, which are suitable for applications such as spectroscopic imaging (see http://www.riken.go.jp/lab-www/THz/21pjt.pdf). Kawase (2004) showed applications of THz imaging for drug detection and LSI inspection (large-scale integrated circuits): Terahertz imaging can be used to noninvasively detect drugs hidden in envelopes and other containers, an application that may one day help law enforcement officials thwart traffickers. In another application, LSI are being inspected noninvasively for faults by means of laser-THz emission microscopes. A breakthrough of this technique in the field of noninvasive food analysis may be expected soon.

Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)

Some nuclei of atoms, for example, ^{1}H, ^{13}C, ^{31}P, have a magnetic moment and are able to absorb resonance energy when placed in a strong magnetic field and irradiated with a proper radio frequency. For food applications, ^{1}H MRI is most interesting. The proper radio frequency will rotate its magnetic moment by 90°. After removal of the radio frequency energy relaxation induces a signal in a receiver. The energy loss is dependent on the environment surrounding the nucleus, leading to different but characteristic relaxation times. By applying magnetic field gradients in 3 directions, 2- and 3-dimensional images can be created (MRI). One of the most important applications of NMR is to measure water content and water distribution because especially hydrogen nuclei show high response to magnetic fields. NMR instruments require high magnetic fields and sophisticated electronics so that generally they are large and may be very expensive, but recently also low-cost, low-field proton MRI sensors have been developed, allowing the rapid sensing of internal browning in whole apples. The results indicate that it should be possible to use the MR sensor and conveyor system for online sorting of apples with internal browning at conveyor speeds below 100 mm/s if precise control of the conveyor speed and apple position at the time of interrogation can be maintained. Good performance at faster conveyor speeds may be possible if improvements such as better pre-magnetization are implemented (Chayaprasert and Stroshine 2005) [D18]. The unique advantage of NMR is the detection of variations in concentration and state of water and of fat in fruits and vegetables, which is very useful for the assessment of ripeness, defects, or decay. High-resolution images of these internal characteristics can contribute to the evaluation of maturity and quality parameters but they can also help the understanding of physiological processes, for example, water transport (Faust and others 1997). Mealiness in apples was assessed by Barreiro and others (1999) using MRI techniques. Small samples of Top Red apples stored 6 mo under controlled atmosphere (expected to be non-mealy) and 2 °C (expected to be mealy) had been used for MRI imaging. Multi-slice multi-echo MRIs (64*64 pixels) had been recorded with an 8-ms echo time. Three of 4 apples corresponding to the sample maintained under controlled atmosphere did not develop mealiness, whereas 3 of 4 fruits corresponding to the sample stored at 2 °C became mealy after 6 mo of storage. The minimum T-2 values obtained for the mealy apples were shown to be significantly lower ($F = 13.21$) compared with non-mealy apples, suggesting that a more desegregated structure and a lower juiciness content leads to lower T-2 signal. Also, there was a significant linear correlation ($r = -0.76$) between the number of pixels with a T-2 value below 35 ms within a fruit image and the deformation parameter registered during the Magness-Taylor firmness test. Finally, all T-2 maps of mealy apples showed a regional variation of contrast, which was not shown for non-mealy apples. Significant differences ($F = 19.43$) between mealy and non-mealy apples were found in the histograms of the T-2 maps as mealy apples showed a skew histogram combined with a "tail" in their high T-2 extreme, which was not shown in the histograms of non-mealy apples. These histogram features were also shown for an apple showing internal breakdown, indicating that in mealy apples there is a differential water movement that may precede internal breakdown. An overview of the multiplicity of publications concerning NMRI is given the review article of Clark and others (1997). MRI was also compared with X-ray CT imaging when both techniques were applied by Lammertyn and others (2003) to study the development of core breakdown disorder in 'Conference' pears. This disorder, which is characterized by brown discoloration of the tissue and development of cavities, is induced by elevated CO_2 and 548 decreased O_2 levels during controlled atmosphere storage. Both X-ray and MRI were able to differentiate between unaffected tissue, brown tissue, and cavities. It was concluded that MRI is the most appropriate technique to study the development of core breakdown disorder 551 during postharvest storage. Cho and Chung (1997) designed their own equipment, in which they successfully measured soluble solids of apples, peaches, and kiwi fruits. Mealiness (woolliness in peaches) is a negative attribute of sensory texture that combines the sensation of a desegregated tissue with the sensation of lack of juiciness. In a study by Barreiro and others (2000), 24 apples cv. Top Red and 8 peaches cv. Maycrest, submitted to 3 and 2 different storage conditions, respectively, have been tested by mechanical and MRI techniques to assess mealiness. In peaches, MRI techniques were found useful to identify woolly fruits. Not all the changes found in the histograms of woolly peaches were similar to those observed in mealy apples, pointing to a different underlying physiological change in both disorders. Magnetic resonance imaging was also studied by Hernandez and others (2005 and 2004) to identify seed-containing oranges and also freeze injury under an online strategy. Axial FLASH images (780-ms acquisition time) have been analyzed to identify seed-containing oranges conveyed at 50 and 100 mm/s through a 4.7 Tesla spectrometer. Developed algorithms enabled an automated identification of oranges with more than 1 seed, though axial images under motion conditions suffered from significant blurring artifacts. To overcome this hindrance, coronal FLASH images have been acquired (279-ms acquisition time), developing algorithms for motion correction with encouraging results for quality improvement of dynamic images. The objective of an article by Mariette (2004) was to show how complementary studies including both NMR relaxometry and MRI have expanded the number of applications of MRI in food research. An important step toward lower cost and more convenient sample handling was introduced by Hills and others (2005). A working prototype of a novel low-cost Halbach-array-based NMR system was described. The new design provides open access to the sample relative to conventional NMR magnet designs, and this facilitates the simultaneous use of multi-sensor techniques on the same sample, in which NMR/MRI can potentially be combined with other spectroscopic techniques such as impedance spectroscopy, laser scattering, and also rheological measurements.

X-ray Analyses

X-ray and gamma-rays were examined for their suitability for quality assessment of horticultural products. Both kinds of radiation penetrate material bodies and the shorter the wavelength, the larger is the penetration strength. Following a law of absorption, the intensity of the measured light after passing the sample is dependent on the initial intensity as well as on density and sample thickness of the absorber substance and its absorption coefficient (wavelength and material dependent). The high water content of vegetable products accounts for the largest portion of the absorption. Some internal disorders with negative effects on quality that should be detectable by X-ray techniques include cork spot, bitter pit, water core, and brown core for apple, blossom and decline, membranous stain, black rot, seed germination, and freeze damage for citrus, and hollow heart, bruises, and perhaps black heart for potato. Because the method is primarily dependent on the density of the tissue, not the chemical composition, the selectivity is limited (Tollner and others 1994). Three techniques for quality control are used: the 2-dimensional radiography well-known from medicine, the line scan method producing images when the product passes though a vertical plane of X-rays (known from baggage control at the airport), and Roentgen CT, which is also used in medicine. This method produces a 3-dimensional image, from which 2-dimensional information can be computed. Commercial routine is the detection of hollow heart in potato tubers (Nylund and Lutz 1950). The discovery of remaining pits in processed cherries or olives is important for the processing industry and has been the subject of investigations (Tollner and others 1994). Other publications cover the water content in apples (Tollner and others 1992), density changes during the ripening of tomatoes (Brecht and others 1991), and insect infestation of pistachio nuts (Keagy and others 1996). For separating out freeze-damaged citrus fruits, x-ray units are used in packaging facilities (Abbott and others 1997). Sonego and others (1995) published a comparative study on woolly breakdown in nectarines using NMR imaging and X-ray CT. Woolly breakdown was detectable by NMR imaging as dark areas corresponding to low proton density. However, the development of woolliness did not affect the mobility of water in the tissues. X-ray CT indicated that the lower proton density of injured tissues observed with NMR corresponded in fact to the presence of gas spaces. The method is therefore ideal for the analysis of modern food products with complex aerated microstructures, which determine to a large extent the mechanical and aesthetic properties of these products. Such new materials require noninvasive techniques for visualization and measurement of the internal microstructure. The visualization and analysis of the 3-dimensional (3D) cellular microstructure of a number of food products (aerated chocolate, mousse, marshmallow, and muffin) using X-ray micro-CT was reported by Lim and Barigou (2004), and quantitative information was obtained on a number of parameters including spatial cell size distribution, cell wall-thickness distribution, connectivity, and voidage.

Analyses of Mechanical Characteristics

Texture characteristics such as firmness of fruits relate to their mechanical properties. A large number of devices and techniques have been developed to determine the firmness of fruits and vegetables; most of the tests are based on puncture, compression or response to shear stress, creep, or impact. But also sonic and ultrasonic vibration as well as the density of horticultural products are used as indicators of texture characteristics. Reviews on these techniques are available, for example, by Sarig (1993), Abbott and others (1997), and Abbott (1999). Mechanical force/deformation techniques applying compression or penetration often are not very suitable for online sorting of fruits and vegetables because they are of low speed or destructive. But there are also fast techniques based on responses to only sub-destructive deformations, vibrations, air puffs, and impacts. A nondestructive laser air-puff firmness detector has been demonstrated to be effective in sensing the firmness of fruits and a variety of food products (Hung and Prussia 1995). This technique is based on the principle that a small puff of air at a regulated pressure can be made to impinge on a fruit surface, depressing it by a measurable amount. The deformation, which is measured by a laser displacement sensor, is taken as an indication of the firmness of the fruit. Because the measurement is nondestructive, the laser air-puff technique can be used on a very large fruit population (or even online) without loss of product, unlike the destructive Magness–Taylor test, which is limited to only a very small fraction of the fruit batch.

Recent research also concentrates on impulse response and on ultrasonic techniques. Mechanic or acoustic impulses applied to fruits produce acoustic responses, for example, resonance, which are related to elasticity, internal friction or damping, shape, size, and density. Thus, sonic vibration measurements represent the mechanical properties of the entire fruit (Lu and Abbott 1996). For ultrasonic waves their propagation velocity, attenuation, and reflection are the important parameters used to evaluate tissue properties of fruits and vegetables (Upchurch and others 1987; Galili and others 1993). In the following, some examples of related recent research are listed: Jancsok and others (2001) investigated the effect of the shape of pears on their acoustic response (= resonant frequencies) using finite element (FE) modal analysis. The results of this study may help in the development of a nondestructive firmness sensor for non-spherical fruits. De Ketelaere and De Baerdemaeker (2001) investigated the use of tomato vibration analysis after impact excitation as a nondestructive physical quality measurement. They found that the resonant frequency of the 1st elliptical mode of the tomato is related to its firmness and that due to the non-homogeneity of a tomato, the measurements at the bottom were more reliable. Flitsanov and others (2000) used nondestructive ultrasonic tests to elucidate the influences of storage temperature and time on the softening process of avocado fruit. The attenuation of the ultrasonic waves transmitted through the fruit tissue changed as the fruits passed through the various softening stages during and after low-temperature storage. A system and method based on ultrasonic energy absorbance was suggested by Mizrach and others (2003) and by Bechar and others (2005) for rapid nondestructive measurement of mealiness in apples. This method is based on a patented development, which enables the fruit quality attributes to be observed by measuring the changes in ultrasonic sound waves passing through the fruit tissue over a short distance across the peel (Mizrach and others 1994). A system based on ultrasonic energy absorption technique was evaluated as a possible means for rapid nondestructive measurement of mealiness in intact apples. Ultrasonic energy transmitted through the fruit tissue and the load applied on the transducers was simultaneously measured. Linear equations were calculated between the ultrasonic energy and the load applied for each color side of each apple. The slope of the linear plot of each equation was extracted as a measure of the mealiness of the sample. The comparison between the results of the ultrasound measurements and the confined-compression tests showed good matching (probability 0.05) with the slopes for the fresh and the overripe mealiness levels for Cox apples (for example, for measurements on the red side, the average slope for overripe fruits was higher by 88% than that for fresh fruits). The ultrasound results obtained for Jonagold apples did not correlate well with the mealiness levels; the differences were found to be minor and statistically insignificant (Bechar and others 2005). The ultrasonic method was also used to determine the maturity and sugar content of plum fruits during storage. Experiments were carried out at intervals throughout the storage period. The measured attenuation, the firmness, and sugar content were found to decrease during shelf life. A link between the attenuation and the firmness could be observed from 78 h in shelf life until the end of the softening process (Mizrach 2004). The density (specific weight) of horticultural products is a characteristic, which changes during the process of ripening and also after harvest. These processes comprise changes in the cell structure, the soluble solids content, and thus also water content. Moreover, tissue diseases like glassiness and insect infestation among other things contribute to density deviations (Throop and others 1989). Therefore, in some cases, one can use this property as a quality index. However, the assessment of density is to be understood rather as a rough orientation in the sorting process (for example, separating foreign bodies or unripe fruits), than a quality measurement (Wolfe and others 1975). Common is the computer-aided classification by means of a camera that measures fruit size. From this, the volume is estimated and put in relation with the result of the automatic weighing. This principle was tested as an online procedure with apples, tangerines, and oranges (Miller and others 1988). Partially high correlation between estimated value and actual volume could be found. However, in citrus frost damage, drainage and different grades of ripeness cause deviations in density. Upchurch and others (1994) reported on the employment of automatic density sorters in ten Florida packing houses. Irregular fruit shape and large size distribution limit the success of such a plant. Density in combination with measurement of the transmitted light level by a high sensitivity camera is reported to be advantageous for melons. There was a correlation between fruit density and softening rate measured by fruit pressure tester and the transmitted light level increased when the fruit soften. Therefore, the ripeness level at the time of shipment can be estimated using, and the softening rate can be estimated using the fruit density measured nondestructively in packinghouse (Kato and Matuda 2004). Even mass loss and shrinkage may be used for predicting firmness in apples under regular atmosphere (RA) storage conditions. The relationship between firmness and mass loss or shrinkage was dependent on apple cultivar. Firmness was significantly and linearly related to mass loss and to shrinkage in 'Delicious' apples (Link and others 2004).

A novel approach for performing discriminative test in food quality control is based on the use of an electronic nose, see for example, Llobet and others (1999) or Sarig (2000), equipped with Metal Oxide Semiconductor Field Effect Transistor (MOSFET) sensors, Metal Oxide Semiconductor (MOS) sensors, and humidity sensors. The pattern of the sensor responses generated by the electronic nose has been used for performing "objective" triangle tests in several food products. The results were compared with the data obtained by using standard methodology (triangle test) of sensory analysis (UNI ISO 4120 Norm). The e-nose is able to classify correctly all the samples under study, while the sensory panel is able to correctly perform the test only in 50% of the cases. Compared with the sensory test, the electronic nose methodology is simple and rapid, and results suggest that it can be useful tool for performing discriminative testing (Benedetti and others 2004). Another recent review by Deisingh and others (2004) additionally examines the applications of electronic tongues in food analysis. While arrays of gas sensors are termed electronic noses, arrays of liquid sensors are called electronic tongues. The former are used in quality control and process operations in the food industry, whereas the latter are widely used in taste studies. Applications described include identification and classification of flavor and aroma and other measurements of quality using the electronic nose. The uses of the electronic tongue in model analyses and other food, beverage, and water monitoring applications are also discussed. The review concludes that each technique, electronic nose and tongue, is still being developed but the advantages are already clear. Strengths of the electronic nose include high sensitivity and correlation with data from human sensory panels for several applications. An electronic tongue can perform as an intelligent sensor to reproduce the taste sense, which is a complex, comprehensive sense. It is, therefore, able to transform molecular information into taste qualities. However, there are several problems with the technology. In both devices, sensor drift is a major problem, which leads to the inability to provide proper calibration. For the electronic nose, in particular, there is loss of sensitivity in the presence of water vapor and high concentrations of single components. Even with the integrated electronic nose–tongue systems, there is the major issue of combining data of different origins. Finally, sensor arrays tend to predict the quality of a sample without providing hard data with respect to composition and concentration. Regardless of these concerns, the future for both the electronic nose and tongue appears to be promising as they can fulfil niche analyses.

Miscellaneous

In conclusion, some noninvasive methods of minor dispersal are briefly mentioned. The dielectric constant, for example, of a material is physical dimension indicating the change in capacity of a capacitor, if the gap between its plates is filled with this material instead of air. Ripening and/or decay change the electrical characteristics of vegetable cells (Kato 1993). In addition, temperature damage may be responsible for changes. Harker and Forbes (1997) published an investigation of frost damages of persimmons; however, they used isolated tissue samples instead of whole fruits. Frequency- and temperature-dependent permittivities of fresh fruits and vegetables from 0.01 to 1.8 GHz were assessed by Nelson (2003), providing new information useful in understanding dielectric heating behavior and evaluating dielectric properties of such agricultural products for quality sensing applications. A study of Nyanjage and others (2001) of mango fruits could not clearly show a connection between stage of ripeness and apparent electrical impedance. Hot water treatment (for hygienic purposes) and different storage temperatures were the variable factors, whose effects on gloss, color, and soluble solids were examined in regular intervals. The lowering of impedance, for example, correlated well with reduced gloss at 22 °C storage, but not at 13 °C. The researchers indicated that further work is necessary for revealing the relationship of impedance and quality parameters. There is another noninvasive method dealing with "bio-photons," the weak light emission from biological systems.

This was described as an integrated procedure in the sense of retarded luminescence, where a continuous spectrum from at least 220 to 850 nm is measurable (Popp 1999). Hellebrand and others (2001) reported about measurements of the thermal radiation from horticultural products, which offers a possibility for the study of the influence of ripeness and other criteria. Gas analysis was applied by Willging and Weichmann (1999) who performed breathing and transpiration measurements with radish, beans, spinach, and cucumbers to study the influence of variations in temperature during storage. The water content of air was determined by infrared absorption and with a pyro-electric detector. After elimination of the water vapor CO_2 was determined in the same way. The water potential of carrots and radish was measured by Herppich and others (2004) by using a pressure bomb for the investigation of the water status as an indicator of freshness.

Research Needs

All noninvasive methods described in this review or elsewhere have their strengths and weaknesses and special aptitudes for special applications, but the ideal method covering all requirements of today's and future applications in production, storage, and retail has not yet emerged and probably will not be found in the foreseeable future. The authors think that future developments will deal with synergistic combinations of already existing constituents that have to be improved and adapted to each other. An example could be the combination of MRI with ultrasound techniques. Both have been applied to noninvasively measuring, for example, on mealiness in apples (see, for example, citations of Barreiros and others) delivering useful data, each with strengths and weaknesses, but the combination might result in synergy. The possible combination of both technologies was made feasible only recently through the development of low-cost, low-field proton MRI sensors (see chapter on MRI). The tendency to synergistically combining data delivering techniques will also conquest the optical methods. Hyperspectral cameras, e.g., already deliver combined information from the ultraviolet, the visible, and the near-infrared spectral region. To enhance that information, suitable powerful low-cost light sources will have to be utilized, probably diode lasers. There will be no danger that too many data might be compiled because the efficiency of information technology will continue to grow exponentially. The development of future research will also be governed by the question of where to put resources for the best return on the investment. Consequently, costly methods will only be applicable where a corresponding profit is to be expected. The margin for sophisticated expensive equipment will certainly be larger in online assorting applications than in handheld devices. Also safety considerations will be of importance for future research, especially in cases where high-energy radiation is involved. In general, developments with research and technology in quality and use of agricultural products will be focused on 3 areas: basic agricultural sciences including consumer research, automating of as many aspects of production as possible, and advancing the capabilities in the fields of storage, packing, and shipping. Future research on fruit quality and functionality in terms of genetics, metabolic processes, product composition, molecular structure, physical state, and consumer acceptability will cause the necessity of new technologies and techniques to better measure quality attributes. Future shifts in consumer lifestyles and attitudes will influence eating and food-purchasing behaviors. For example, it is to be expected that marketing food products with special functionality for disease prevention and treatment will be commonplace (Sloan 1998), which will require novel methods of analysis and also the study of consumer acceptability of these novel foods. In the world of fruit and vegetable quality, the most significant changes have been the introduction of fresh-cut products with many more prepackaged items, the promise and lack of adoption of irradiation and GMOs in the marketplace, and a much more consumer-driven market. Shewfelt and Henderson (2003) predict that the next 10 to 20 y will see less total consumption of fresh fruits and vegetables with less emphasis on fresh and natural products, less emphasis on extended shelf life and low prices, fewer bulk items, and less interest in postharvest physiology and low-cost crop production. During this time there will be a similar emphasis on convenience of fruit and vegetable products and purchase quality. They also expect to see more emphasis on the quality of products, particularly consumption quality and value, with more local production and technological innovations to deliver fuller flavor, and research emphasizing preharvest factors in postharvest quality as well as sustainable production to lessen undesirable impact to the environment. Integrated sensor technologies will have to be developed or adapted to enable real-time quantitative assessment of fruit quality during growth and all postharvest operations. For example, according to the long-term technology roadmap of the Washington Tree Fruit Research Commission (2004), the aim is an intelligent, automated system controlling most orchard manipulations including remote and automated sensing to estimate crop quantity and quality assisted by GPS technologies (http://www.treefruitresearch. com/index.html). Research needs defined by the Agricultural Research Service (ARS, USDA) point in the same direction. The Natl. Program 306 "Quality and Utilization of Agricultural Products" highlights the need for rapid, nondestructive methods for detection and measurement of physical/chemical quality attributes and quality defects as a basis for automated, high-throughput online grading, sorting, and packaging systems for agricultural products. Those systems should use, for example, multispectral and hyper-spectral techniques, imaging and image analysis, and methods incorporating information technology and artificial intelligence for further improvement of processing and grading (ARS Strategic Plan: 2003 to 2007 (http://www.ars.usda. gov/research/programs/programs.htm?NP_CODE = 306). Speakers at the 12th Intl. Conference on Near-Infrared Spectroscopy, April 2005, Auckland, New Zealand, pointed out that today's needs for tomorrow's instruments include improved sensitivity and dynamic range, spectral range and reproducibility, measurement speed, portability, ruggedness, and reduced cost (Stark 2005). The integration of tuneable optical filters based on micro-electro-mechanical systems (MEMS, enabling technology for light-wave communication systems, multi/hyper-spectral imagers and sensors) with broadband detectors was presented as an obvious development path, allowing micro-spectrometers with various levels of performance to be achieved. Scanning speed and robustness are key issues where the technology is required for high-throughput applications such as food production lines (Keating and others 2005).

Conclusions

During the past year, much progress has been made in developing nondestructive techniques for the assessment or inspection of quality parameters of fruits including internal disorders but also taste, sugar content, and so forth. As already emphasized in the research needs section, the ideal method covering all requirements of today's and future applications in production, storage, and retail has not yet emerged and probably will not be found in the foreseeable future. As sensors often only measure a single constituent or quality property, combined techniques will have to be optimized to measure overall quality. Commercial application of these techniques will be beneficial for the consumer as well as the grower and trade. The risk of buying poor-quality products will significantly decrease, the income of fruit growers will correspond to the quality of their products, and merchants will be able to comply with consumer demands for uniform high-quality products. However, even if fresh fruits and vegetables of uniform quality were readily available around the world at any time of year, which is an underappreciated triumph of postharvest pysiology and technology, many consumers may still be dissatisfied: Management decisions during handling and distribution can lead to a sacrifice of flavor to maintain appearance and extend shelf life. Future advances in fruit and vegetable quality are likely to come from developing a better understanding of consumer expectations (Shewfelt 2000). New technologies will always open brilliant opportunities to measure some parameters very well, but because the consumer is who buys the product and is willing to pay the price, one should keep in mind that "it is better to measure something which is really important for the consumer than to believe something is important because you measure it really well" (Shewfelt and Phillips 1996). Jordan (1990) summarized that even though much research effort has been devoted to the problems of how to produce and measure quality, it is not sufficient to simply measure quality. Consumers' decisions and satisfaction are determined by how product quality is perceived. For this reason, the measurement of consumer perception and the analysis of the determinants of the perception process are an essential and integrated part of all research. The aim, of course, is the improvement of product quality and consumer satisfaction—a necessary precondition for a good position in international competition.

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