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Nondestructive Techniques for Quality Inspection of Fruits and Vegetables

-Review-

Young J. Han, Yong-Jin Cho*†, Wayne S. Rial and Wade E. Lambert

Dept. of Agricultural and Biological Engineering, Clemson University, SC29634-0357, USA
**Korea Food Research Institute, Songnam 463-050, Korea*

Abstract

Various nondestructive technologies for quality inspection of fruits and vegetables were reviewed through published literatures and selected agricultural databases. These technologies were grouped into nine categories, including acoustic response, dielectric response, impact response, machine vision, magnetic response, mechanical vibration response, microwave response, optical properties, and other possible sensing technologies. Their principles and characteristics were investigated and these technologies were presented with their current and potential applications. The link of appropriate nondestructive technologies with common principal quality parameters of fruits and vegetables was summarized.

Key words: nondestructive techniques, quality inspection, fruits and vegetables

INTRODUCTION

Quality control is becoming increasingly important in the agriculture and food industry because the consumer expects competitively priced foods with consistently high quality. Agricultural products and foods have to be safe, wholesome and attractive in appearance, taste and texture. To promise such agricultural products and foods, optimum quality assurance should be applied.

The on-line measurements using nondestructive testing technologies can be considered as very attractive quality assurance method to inspect agricultural products and foods At present, many nondestructive technologies are available for their quality evaluation. Also, there are many potential applications which will be able to be utilized in industrial production line in the future.

In this study, principles and characteristics of various nondestructive techniques(NDT) used in evaluation of quality parameters of fruits and vegetables were investigated through published literatures and selected agricultural databases. These techniques were grouped into the following nine categories: 1) acoustic response, 2) dielectric response, 3) impact response, 4) machine vision, 5) magnetic response, 6) mechanical vibration response, 7) microwave response, 8) optical properties including light reflection, transmission and emission, and 9) other possible sensing technologies including X-ray.

NONDESTRUCTIVE TECHNIQUES

Acoustic response

Acoustic response is usually thought to be a field of ultrasonics. Ultrasonics is widely used in the foods industry for process control measurements such as liquid level, suspended solids concentration, interfaces between liquids, interfaces in solids, and density of liquids and solids.

When longitudinal sound waves propagate through a medium, periodic displacement of the medium particles occurs Some of the main factors affecting such sound wave propagation through different media are particle size, particle distribution, density of the material versus frequency, refractive indices of interfaces, temperature, frequency of the wave, and energy in the wave. Kress-Rogers(1) further described a number of factors affecting propagation of ultrasonic signals through a medium as follows: 1) transit time for the transmission of a pulse through a material, 2) attenuation of the signal transmitted through the sample, 3) reflected and transmitted proportions of a signal meeting an interface, and 4) amplitude, phase, and frequency of the scattered ultrasound signal at specific angles.

As to the frequency ranges, about 500 MHz is the approximate limit of usefulness for ultrasound. In the process control industry, the upper limit of frequency is about

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[†] Corresponding author

10 MHz. Sound waves do not behave in the same way as electromagnetic waves do when passing through a medium. Since standard electromagnetic theory cannot be applied to ultrasound, a special branch of physics(the physics of sound propagation) is required for its application. As is required in most high resolution work where good special resolution is a necessity, short wavelengths of the impinging energy compared to the particle size are required. To achieve directional characteristics at any frequency, the transducer face diameter should be at least ten times the ultrasonic wavelength; this is why low frequency transducers are usually large in diameter.

Frequently, instruments designed for use at low frequencies, such as between 10 and 100kHz, are designed to transmit acoustic energy beams to the material being tested without requring a coupling medium(couplant). Generally, for an application using frequencies above 100 kHz, a couplant(coupling gel or material) is required to provide good acoustic coupling for efficient energy transfer between the transducer and the medium.

Ultrasonics have been explored for detecting bruises in apples at 1 and 5 MHz but without significant success. The acoustic impedance of apples is very high and the ultrasonic power spectrum that is reflected from the apple varies greatly between sites, making bruised and unbruised tissue difficult to detect(2). A number of studies on melons have been made using ultrasonics with some excellent success for internal breakdown(3). Potatoes have been tested for hollow heart by density measurements with ultrasonics. The density of the whole potato could be correlated with the observed volume of hollow heart although the accuracy was considered too low for production use. The maximum frequency that could be used was 150 kHz for the hollow heart measurements. Fast Fourier Transform (FFT) techniques have been used for the frequency analysis of the transmitted ultrasonic signal. Power spectrum moment differences have also been used for detecting hollow heart with high accuracy(4).

Dielectric response

One of the fundamental properties of most electrically non-conducting materials is its dielectric constant. This property is usually associated with the ability to hold an electronic charge for some period of time after removal of the electrical excitation. Kent(5) stated that dielectric materials have no loosely bound or free electrons that may drift through the material. In the presence of an applied electric field, a displacement of charge occurs through rotation of the dipoles. The positive charges within the dielectric are displaced minutely in the direction of the electric field and negative charges are displaced oppositely. This slight displacement of the centers-of-charge polarizes or effectively reduces the electric field within the dielectric material. This general effect is called polarization of the dielectric material. He also reported that when the applied electric field was removed, the polarized dipoles reoriented themselves and returned to their equilibrium state. This reorientation takes time which is referred to the "relaxation time". In a time varying electric field(i.e., an alternating current), the time lag to equilibrium exhibits an effect similar to conduction loss in a circuit with moving charges(i.e., a current). As their frequency of oscillation is increased, it becomes increasingly difficult for polarization and relaxation to be completed. As this occurs, the dielectric constant starts to decay. This is known as dielectric dispersion(with frequency). The rates of change of the dielectric constant and of the loss factor versus frequency are not the same, causing a peak response in the effective dielectric constant at some particular frequency for each dielectric material. Water is easily detected at around 17GHz by this method. Different molecules have specific peak responses although they are not so pronounced as those of water.

The dielectric constant is the ratio of the response of the material to that of vacuum at the same frequency. Dielectric constant is sometimes called relative permittivity. Several methods have been used to assess the dielectric constant by means of attenuation measurements (using Beer's law), by the resonant method, and by using the dielectric material as a termination in an RF waveguide system and analyzing the reflections.

Bulk density and moisture content have been studied frequently at microwave frequencies. Also, sugar(solute) and soluble solids have been studied at medium RF and microwave frequencies. These methods applied below microwave frequencies appear to have limited production line use at this moment(except for water concentration) for assessing fruit and vegetable quality-parameters. At microwave frequencies while assessing dielectric constant, density and internal disorders act similarly to the material behavior under X-ray exposure. Microwave energy is absorbed more efficiently in regions of high fluid or material density(6).

Soluble solids relates to sweetness, or sugar concentration. Firmness can be related to water content. Generally, water comprises over 70% of fresh weight of most fruits and vegetables. Also, total carbohydrates account for greater than 70% of the dry matter except in avocado and asparagus. Sugar often correlates well with soluble solids measurements. During ripening, changes occur in the dielectric properties. Nelson(7) reported that the dielectric properties of some fruits and vegetables measured at 2.45GHz and 23°C show no difference between mature-green and full-ripe in peaches. The dielectric constant correlated with moisture content and tissue density. No correlation existed between dielectric constant and soluble solids as was verified by refractometer measurements. More studies are needed in this area. Nelson et al.(6) performed microwave measurements taken on 23 kinds of fresh fruits and vegetables with plots of dielectric constant and loss factor at 41 different frequencies from 200 MHz to 20 GHz. The dielectric behavior of the fruits and vegetables tissue appeared to be influenced by ionic conductivity and bound relaxations at lower frequencies and by free water relaxation at higher frequencies.

Impact response

One of the most important parameters to the consumer in buying most fresh fruits and vegetables is the commodity's firmness. This parameter ranks high along with color, shape, and cleanness. Some fruits and vegetables are naturally soft, like tomatoes, and some others may be quite firm like lemons. During their maturation, citrus fruits lose water content and thereby become firmer, whereas tomatoes naturally become softer as the ripening process advances. Over the years, many different techniques and devices have been developed to determine the firmness of fruits and vegetables. Most of these have been mechanical in nature, most of which cause measurable deformation of the skin or peel. There have been other technologies used such as acoustic wavefront, air blast deformation, driving point mechanical impedance, deformers, and a "mechanical thumb sensor". These techniques are an attempt to measure the elasticity of the peel and the supporting flesh inside the peel.

The desirable impact tester is a completely nondestructive measuring device that will not show evidence of testing, will not develop a bruise later in time, and will give a reliable indication of the firmness, and will be fast enough to use in processing lines. Considerable work has been done by Perry(8) on such measurements and in the development of a nondestructive firmness tester(NDF). His device consisted of a pressure cell to hold the commodity, such as peaches, and mechanical displacement dial-gauges to measure the deformation. Compressed air was used as the driving force. In comparing this method with other known methods of evaluating firmness in peaches, fairly high correlation coefficients were observed and the procedure developed did not damage the fruit when the fruit was in an advanced stage of maturity.

Mizrach et al.(9) have developed a spring-loaded "mechanical thumb sensor" for sorting oranges and tomatoes by firmness. A 3mm diameter probe loaded with a calibrated spring was used to engage the peel of the fruit, causing elastic deformation of the peel. They used a predetermined load for the spring stiffness, which allowed a Go-No-Go test sequence to be conducted for acceptance and rejection of the fruit based on peel deformation. The spring stiffness was determined experimentally and adjusted beforehand for each test condition or commodity. Sorting results showed that it was possible to sort with errors less than 5% for some commodities. This technique is applicable to processing line use if it can be developed further.

Another method that has been investigated by Brusewitz et al.(10) was to drop the commodity onto a rigid flat plate and measure the impact parameters as a function of firmness. The result would be more related to bruise resistance, but are applicable to firmness considerations as an indication of maturity.

Acoustic techniques are very appealing to use for firmness testing because minimum contact or no contact between the transducer and the commodity. No contact would be ideal for hygienic reasons and for possibly fast measurements on a processing line. Studies of acoustic elastic moduli in apples have been done by Armstrong et al.(11). They used mechanical impact to excite the apple, and acoustic microphones to detect acoustic response such as resonant frequencies and acoustic spectra.

Machine vision

Machine vision system is an electro-optical sensing system for obtaining a digital image of an object suitable for further processing by computer. The machine vision technology holds a great potential for applications in agricultural and food industry because many aspects in these areas rely on visual ratings and interpretation. Identifying these areas and applying the emerging technology can reduce intensive labor with less human error, encourage nondestructive measurement and inspection, and stimulate an automated mass production/processing system. In fruit sorting and packing operation, producers and consumers will both benefit from higher duality and uniformity of marketed fruit at a reduced cost.

A machine vision system is more than just a camera and a computer. Image capturing environment plays an important role in the system, since no image processing technique can enhance the details that were never captured. Proper illumination of the object can eliminate shadows and specular reflection while preserving well-defined edges. It is also important in a spectral point of view. Since a camera has a certain spectral response, a combination of proper illumination and optical filters can greatly enhance the image.

One apparent application of machine vision system is measuring color, physical size and shape of fruits and vegetables for sorting and grading(12,13). Sistler et al.(14) developed a video analyzer for measuring the surface areas, volumes, and centroids of anomalous shapes. The measured parameters were based on a series of digitized video images of the object rotated about its longitudinal axis. Sarkar and Wolfe(15,16) developed classification algorithms using digital image analysis and pattern recognition techniques for sorting tomatoes. Maturity was classified into two stages: Light Red and Red tomatoes were considered to be ripe, and the other ripeness stages were considered as green.

Color is one of the most important factors associated with the quality evaluation of fruits and vegetables. There are many color models in use today, which include RGB (Red, Green, and Blue) model for television industries and color video cameras; CMY(Cyan, Magenta, and Yellow) model for color printers; YIQ(Luminance, Inphase, and Quadrature) model for TV broadcast standard; and HSI (Hue, Saturation, and Intensity) model for easy color manipulation. The color models most often used for image processing applications are RGB, YIQ, and HSI models. Among these models, the HSI model is very useful in color machine vision, because it closely resembles the way human beings perceive color. Humans discern the color of an object in terms of its hue(dominant color), saturation(chroma, relative purity, or lightness), and intensity(brightness) by integrating some very complex signals into these three components. Another advantage of the HSI model is that the intensity is decoupled from the other color information in the model, which can minimize the effect from variations in illumination intensity.

Wiggers et al.(17) used a color image processing system to detect and classify fungal-damaged soybeans with the hue and the ratios of the red, green, and blue signals. They reported that the color ratio was more reliable than the hue method for detecting color differences. Miller and Delwiche(18) developed a color computer vision algorithm to inspect and grade fresh market peaches. Machine and manual classification agreed with only 54% of the samples. Large differences between machine and manual results occurred mostly on peaches with portions of surface area that were speckled with red color but not fully blushed. Shearer and Payne(19) investigated machine vision for sorting bell peppers by mapping the RGB values to hues and statistically classifying the frequency distribution. Varghese et al.(20) developed a computer vision system to inspect and assess fresh apples by color, defect, shape, and size. Apples were classified for color with very high accuracy using a hue histogram and its linear discriminant analysis. Choi et al.(21) developed a color image analysis procedure to classify fresh tomatoes into six maturity stages according to the USDA standard classification Green, Breakers, Turning, Pink, Light Red, and Red. Classification was based on the aggregated percent surface area below certain hue angles. They proposed a Tomato Maturity Index(TMI) to indicate the degree of maturity within each stage and to provide a continuous index over the complete maturity range.

The Fourier Transform is extremely useful in a variety of signal processing applications and can be readily computed for one-dimensional signals by digital computer. Qiu and Shearer(22) applied one-dimensional Fast Fourier Transform(FFT) to one-dimensional images of broccoli to assess maturity. Frequency response magnitudes were averaged over 8 frequency ranges to form the classification variables. Using a generalized squared distance function, they reported the classification accuracy between 77 to 86.3%. Han and Feng(23) studied the feasibility of frequency domain inspection using two dimensional FFT. This procedure was applied to egg shell inspection, and demonstrated an 88% success ratio. They concluded that while the frequency domain analysis was suitable for inspecting overall appearances with ambiguous criteria, conventional morphological analysis had to complement the frequency domain analysis when an application required specific dimensional measurement or precise location of the object.

Unlike industry inspection applications, where parts are all same shape, size and color under the same environment, objects in agricultural applications are different in shape and size, and color of the object varies. The precision tolerances needed in automotive or electronic inspection are usually not required in food processing, but agricultural and food products are basically difficult to inspect because they are ambiguous. There is high variation in the appearance of acceptable objects and defective objects. Fortunately, the machine vision technology is rapidly growing in processing power, and the equipment cost is steadily declining with cheaper components, more integration of circuits, and higher sales volumes Combined with the state-of-the-art recognition software with artificial intelligence, a low-cost but powerful machine vision system may lead us to solve the issues of 100% inspection for the agricultural and food processing industry.

Magnetic resonance

Magnetic Resonance usually refers to Nuclear Magnetic Resonance(NMR), which involves resonance absorption by the nuclei of atoms when immersed in a quadrature pair of magnetic fields. One of the fields is an intense static field and the other is an alternating radio frequency field. Most light nuclei have specific resonances at some particular frequency and magnetic combination which defines its resonance constant which is characteristic of that element. When resonance is achieved by the nucleus, it absorbs considerable energy compared to nuclei of other chemical species in the same environment(24).

Whenever nuclei absorb energy, their equilibrium with their environment is changed and the absorbed energy is exchanged exponentially with the surroundings. Two time constants are involved during relaxation of the applied energy to the material. One is called spin-spin time constant, involving the energy exchange between neighboring resonating nuclei, and the other is called spin-lattice time constant, involving the energy exchange between the resonant nuclei and the surrounding environment These time constants occur during relaxation after removal of the RF energy and vary from tens of microseconds to several seconds. These relaxation times are unique to each light nuclei species, allowing identification of species. Also quantitative information can be detected as to the quantity of energized nuclei of that species(24).

The hydrogen nuclei in particular exhibits strong response to these magnetic fields which can provide very specific identification of the hydrogen nucleus(the proton) and also of the water molecule. Instruments have been devised to measure specifically the water content of objects. Due to the intense magnetic field required plus other necessary electronics, NMR instruments may be bulky and very costly, depending on their complexity and capability. In spite of these limitations, NMR can measure physical properties not measurable by other techniques, and can detect variations in concentration and state of water and fat in fruits and vegetables, useful for assessing maturity, damage, and/or decay. Pulsed NMR techniques are already widely used in quality control in the food industry for the determination of water and lipid content and of the solid/liquid ratio of fat(1).

NMR Imaging(NMRI or MRI) can provide high resolution images of internal structures of fruits and vegetables, and detect many types of defects easily, such as seeds, pit, and other density changes. The use of Fourier Transforms further enhances image contents. Some modern NMR instruments are designed as FT-NMR(Fourier-Transform Nuclear Magnetic Resonance) instruments. Wang et al.(25) investigated water-core in apple using NMRI which was studied in the early stages of development of the apple and then studied at later stages of its development toward maturity. They concluded that the water content could be correlated with the water core defect.

Chen et al.(26) investigated identification of quality factors like bruises, seeds, pits, worm damage, and stage of maturity, and reported that NMR imaging of fruits and vegetables resulted in high resolution images of the internal structure of the samples. When a defect or an abnormal condition was present, it often showed up quite clearly in the image. They also observed that a bruise in a fruit or vegetable resulted in massive cell rupture and redistribution of free water, which can readily be observed using NMR. Stroshine et al.(27) has shown that proton NMR can be used to measure firmness of fruits and vegetables. In fruits and vegetables, the majority of the protons are found in the water and sugar molecules. Physiological changes that take place during softening of the fruits or vegetables can affect the state of water content, which can be correlated to firmness.

Mechanical vibration response

Nondestructive methods for determining the elastic properties, shear modulus, self-resonance frequency, bandwidth of the resonances, shape of the resonance curves, and other related mechanical parameters of fresh fruits and vegetables may characterize quality-parameters that will allow quality grading and selection(28-30).

Free vibration data have been collected on many objects. Abbott et al.(31) studied sonic techniques for measuring texture of fruits and vegetables and identified the principle peaks of self-resonances for apples. Finney(32) studied the mechanical resonance properties of apples as a means of evaluating textural quality and attempted to correlate force-deformation results with taste panel evaluations. Further, Finney(29) concluded that Young's modulus and shear modulus of fresh apples were highly correlated with frequency squared times mass of the intact fruit and reflected the elastic properties of apples.

The frequency ranges used for many investigations were in the 20 to 4000 Hz range. Not only did fruits and vegetables exhibit resonances but also showed modal deformations at particular frequencies. From this magnitude, shear modulus could be calculated. These characteristics have been studied rather theoretically, assuming ideal shapes(e.g., spherical) with some difficulty relating them to fresh fruits and vegetables. Different investigators reported widely different values for Young's modulus, shear modulus, and modal definition. From these reports, it may be concluded that such measurements may not be generally useful in evaluating firmness of whole fruit and vegetable commodities, especially fruits like apples and peaches. Shear modulus can be determined nondestructively for various fruit and vegetable commodities, though with some questionable degree of usefulness(28).

Microwave response

Microwave electromagnetic radiation has been used since at least 1960 for determining water content and some other parameters of various materials. This radiation covers a broad frequency range between 100MHz and 100 GHz(about 0.3cm to 300cm wavelengths). Power levels used for microwave measurements are usually below the levels that cause permanent damage to biological tissue. At these frequencies, the wavelengths lie within the 0.3 to 300cm range which can result in severe scattering and interference problems due to the similarity in dimensions between the corresponding wavelengths of the microwave energy and the dimensions of the features or discontinuities of the material. Most commercial instruments operate in the "S" and "X" frequency bands of 2~4GHz and 8~12GHz, respectively, or wavelengths of 7~15cm and 3~4cm, respectively(5).

Before approximately 1980, very few applications of using microwave measurements techniques were reported in the food industry journals. Since the early 1980's, many new applications in food industry have utilized microwave technology. The proper choice of microwave frequencies to fit the application is necessary because a poor choice of frequency can result in poor measurement results due to absorption of dissolved ions and also to the fact that transmission decreases with water content instead of the contrary as might be expected. Correct choices of frequency can be made by using the work of Kent(33) or by empirical laboratory measurements.

Another factor of interest is the dielectric dispersion. In polar materials that have a dipole moment, microwave energy tends to align the dipoles, causing an orientation of the molecules of the material. When the microwave energy is removed, the dipoles return to their random configuration after some period of time which is called "relaxation time". This property can be useful in defining some soft tissue parameters. Energy lost in the process of "polarizing" molecules and the phase angle of the dipoles is related to the dielectric constant of the material. The net effects of polarization at low frequency with low losses and higher losses at higher frequencies is known as dielectric dispersion. Another parameter found in using microwave frequencies is that of permittivity which relates to the energy storage ability of the dielectric(5).

Water content is easily measured using these techniques. Water in solution may have different relaxation times due to the properties of the solute(sugar content applications). The most easily measured parameter using microwave energy through material is its attenuation. In the case of fruits and vegetables, the distance through the measuring plane can be measured separately by machine vision or ultrasonics, and thus the attenuation coefficient can be calculated. This can then be correlated with known references for determination of density possibly being related to maturity, voids, water content, and other parameters(33).

At present, microwave techniques are difficult to implement for whole-food items like apples or strawberries, because these items normally require fast assessment of parameters in a processing line. In addition, whole-food commodities would have to be evaluated one-at-a-time. Bulk materials like jams, jellies, sandwich spreads, etc., are being measured now in real-time while the product is continuously flowing in a closed conduit. These bulk material applications use horn-shaped antennas for interfacing between the input and output signals, where the microwave energy passes through the commodity. Also, these same bulk material methods are generally not applicable to whole-food items at present.

Optical properties

Optical response is concerned mainly with the behavior of reflected, absorbed, and scattered electromagnetic radiation in the near infrared, visible, and near ultraviolet portions of the electromagnetic spectrum. These wavelengths can be in the 100 to 2000 nanometer range. The analysis of the behavior of such light is called the field of spectrophotometry. When light of these wavelengths impinges upon objects, some of the light energy may be absorbed, reflected, scattered, or some combination of these effects occurs. This phenomenon is well known and understood, and it is in widespread use throughout the world for analysis of various chemical species.

Selection of fruits and vegetables by the consumer is often based on visual perceived-quality parameters like peel color, shape, texture of the surface, bruises, etc. Many of these external parameters are manifested as reflected light in the visual spectrum. Reflections in the non-visual spectrum in the near infrared and near ultraviolet regions may also have considerable information content that is useful for quality assessment by surface reflections from fruits and vegetables.

The reflectance characteristics indicative of maturity in apples, peaches, and pears were investigated by Bittner and Norris(34). Detectors sensitive in the 400~500nm region were suitable for detecting bruises and peel on processed apples. The magnitude of reflectance at 390 or 458nm could distinguish bruised apple tissue from non-bruised ones(35). Brown et al.(36) investigated the reflectance properties of unpeeled apples in the 700~2200nm range with results indicating that bruised areas can be positively identified. Surface blemishes have been shown to be difficult to detect and differentiate from bruised areas with computer vision by Rehkugler and Throop(37).

The shape of the reflectance spectra can indicate early frost damage in apples in the 610 to 680nm range. The similarities between the results of frost damage and non-blemished areas make separation very difficult at a single wavelength. Spectrophotometric studies have shown that a difference between bruised and non-bruised tissue can be detected for the visible through infrared wavelengths by Brown et al.(36). Another study showed that reflectance in the 720 to 840nm range produced the best models for differentiating bruised and non-bruised apples(38). Howarth et al.(39) investigated carrots with 486 to 1043 nm wavelengths and concluded that three kinds of defects could be identified between 535 and 722nm. They found significant differences in reflected response at specific wavelengths which could be correlated with dry rot, soft top, and black crown.

In addition to real-time light reflectance and transmittance, maturity of some fruits and vegetables can be classified by measuring the light emitted from the commodity several seconds after the excitation by a light source. This technique is called Delayed Light Emission (DLE). DLE refers to the measurement technique of exposing a commodity to some portion of the electromagnetic spectrum for a specified period of time and subsequently measuring the spectral emission some time after the removal of the electromagnetic stimulus.

Abbott et al.(40) have described DLE as the excitation by back-reactions along the photosynthetic pathway, that is, light energy in, then partial completion of photosynthesis, then reverse chemical reactions, then re-excitement of chlorophyll, then light energy out. Directly related phenomena are classed as Refreshed Delayed Light Emission(RDLE) and Fluorescence(FLU). These three DLE techniques require that the item under test have functional chloroplasts. DLE and RDLE have much longer response durations than FLU and are detectable in the dark following a single illumination exposure for times ranging from milliseconds to many minutes. The output response signals are detectable only in the dark, yield low energy output, and decay exponentially(40).

Chlorophyll alone is not sufficient in plant tissue to be used with DLE. The complex chlorophyll and related compounds in plant material jointly contribute to DLE phenomenon(41). An interesting property of DLE demonstrates that beyond a certain saturation level of illumination, increasing the illumination further will not improve or degrade the quantitative output of DLE even if the illumination is considerably above the saturation value. Saturation involves a two dimensional relation(time-intensity) whereby high values of illumination are required to achieve saturation in a short period of time.

Speed of the measuring process may be a serious pro-

Table 1. The summary of nondestructive techniques linked with common principal quality parameters

Quality Parameters	Applicable Nondestructive Techniques
Maturity	
Firmness	Acoustic response(ultrasonic transmission)
	Impact response(indentation property)
	Gas evolution detection
	Mechanical vibration response
	Microwave response(dielectric, structure, density)
Sugar content	Magnetic response(NMR, sugar refractometer)
	Dielectric response
	Optical response(delayed light emission)
Shape	
Geometry	Machine vision, compared with geometry algorithm
Appearance	Machine vision with artificial intelligence
Size	
Diameter	Machine vision
Length	Machine vision
Cross section	Machine vision
Weight	Electronic weighing
Density	Microwave response
Color	
Color hue range	Optical properties(spectrometer in visual spectrum)
	Machine vision as a spectrophotometer
Hue identification	Optical properties(spectrophotometer)
	Machine vision as a spectrophotometer
% of discoloration	Machine vision
% of surface color	Optical properties(spectrophotometer)
	Machine vision
Decay and disease	
Molds, decays	Visible and UV spectrum machine vision
	Optical properties(UV spectroscopy)
Rot	Visible and UV spectrum machine vision
Black-rot	X-ray imaging
	Acoustic response(ultrasonic)
Defects	
Cracks, splits	Visible and UV spectrum machine vision
	Ultrasonic and NMR imaging
Mushy, puffiness	Density measurements
Split pits	X-ray imaging
Roots	Machine vision
Pealing	UV spectrum machine vision
Stems	Machine vision and image recognition software
Thick skins	Acoustic response(ultrasonic reflections)
	Optical properties(delayed light emission)
Moisture	Optical response(IR, UV and visible light reflection)
	Magnetic response(proton resonance, NMR)
Seeds, cores	X-ray machine vision
	Acoustic response(ultrasonic)
Damage and injury	
Cuts	Visible and UV spectrum machine vision
Worm holes	Machine vision
Indentations	Machine vision
Scars	Machine vision
Freezing	Visible and UV spectrum machine vision
Sunburn	UV spectrum machine vision
Hail damage	UV spectrum machine vision
Insects and worms	Machine vision
Ammoniation	Gas evolution detector
Peel injury	Optical properties(delayed light emission)
Bruises	Machine vision
	Acoustic response(ultrasonic reflection)

Table 1. (continued)

Quality Parameters	Applicable Nondestructive Techniques
Internal quality	
Spongy, puffiness	Acoustic response(ultrasonic response)
Woodiness	X-ray machine vision
Water content	Magnetic resonance Microwave response
Lipid content	Magnetic resonance
Internal breakdown	Acoustic response(ultrasonic transmission)
Open spaces	X-ray machine vision Acoustic response(ultrasonic transmission)
Softness	Optical response(light transmission) Acoustic response(ultrasonic reflection) Density measurement
External quality	
Dirt	Visible and UV spectrum machine vision
Shriveled	Visible and UV spectrum machine vision
Smoothness	Optical response(visible and UV light reflection)
Skin texture	Optical response(light reflection) Visible and UV spectrum machine vision Mechanical vibration

blem for sorting applications when using these techniques. For example, FLU measurement can take as long as 3 seconds, and such long measurement times may be required to determine maximum rate of rise of induced FLU. DLE may require at least 7 seconds after a single illumination exposure. By surveying the literature up to the end of 1993, there did not appear to be any commercially available equipment for using DLE, RDLE, or FLU for fruit or vegetable sorting on production lines.

Other possible sensing technologies

Some other nondestructive technologies can measure pH, surface moisture, chemical composition, gas evolution, and detailed analysis of the type of pathological defect observed(e.g. fungi) as measured at the surface of the commodity. Also, some of the other nondestructive measurements like weight, buoyancy, center of gravity, centroid of mass, etc., can be measured in the bulk state of the commodity.

Aroma sensors are being developed which measure the gases that are important to the consumer's perception of acceptable aroma. The gases that allow us to differentiate between acceptable and non-acceptable commodities evolve from the surface of the commodity. For example, at present it appears that detectors are available for methane detection that are capable of resolving possibly a few parts per billion concentration. These new detectors are often based on a fuel-cell technology and can be very gas specific(that is, can detect one specific molecular species of gas). This technology is very slow at present for production line use.

Taste sensors are also being developed in the USA and in England, based strictly on measuring chemical composition of the item. Chemical analysis is well established in other industries for most materials. These techniques are being looked at for the fresh fruit and vegetable industry. Also, these techniques are generally destructive in that a sample of the internal tissue is required. Since our perception of taste often involves aroma, a combination of gas evolution, sugar concentration, and chemical measurements may lead to a satisfactory taste sensor technology. At present, taste sensors that are suitable for production line inspection applications are not available on the market.

Methods to determine fruit quality according to Finney(42) are visible radiation, infrared techniques, ultrasonic, NMR, and X-ray. Of these techniques, X-ray is the only method sensitive enough to detect structural discontinuities(voids and cracks) and density differences or variations for fresh fruit and vegetables(43). X-rays are very energetic electromagnetic radiations with very short wavelengths which have enough energy to excite the inner shell electrons of the material being radiated, as opposed to lower frequency electromagnetic radiations like infrared, visual and ultraviolet lights, which excite only outer shell electrons of the atoms of the material.

These X-ray frequencies range from approximately 10^{16} to 10^{19} Hz, with wavelengths of approximately 10^{-6} to $5x10^{-9}$cm. The use of these very energetic radiations allows deep penetration into or through dense material at high energy levels(up to about 200 keV) and also allows penetration into or through soft material at lower X-ray energies(below 25 keV). X-ray energies below about 25 keV are called soft X-rays(because of their energy level) and X-rays above about 25 keV are called hard X-rays.

These X-ray radiations lose energy and are attenuated in varying amounts in their encounter with atoms of the material, depending greatly on the density of the material and the elements involved as they pass through the object being examined. A signal pickup device that is responsive to X-ray radiation is required for detecting these attenuated signals that have passed through the material. In medical and material science work, radiation sensitive photographic media have been used for a long time. Today, in many industrial applications, it is common to use an X-ray sensitive vidicon or CCD camera for two dimensional X-ray image analysis. Since these wavelengths are so short, quite high image resolution can be achieved. With the use of CCD cameras and filters for image acquisition, X-ray imaging systems that operate in real time can be easily assembled. Such systems can then be used in real-time for on-line examination of soft material, such as fruit and vegetable tissues.

SUMMARY

Nondestructive technologies being used for the inspection of agricultural products and foods were reviewed. To successfully evaluate their quality, a certain quality parameter should be linked with appropriate sensing technologies. Table 1 is the summary of previously reviewed nondestructive techniques linked with common principal quality parameters.

Though, at present, all the technologies reviewed in this study are not available for the industrial production line, many equipments using nondestructive technologies are being used in the food industry. The potential of their applications to food industry is so great.

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