14 Applications in Analysis of Fruits and Vegetables

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We begin with background and a brief history of optical measurements of fruits and vegetables from the 1920s to the 1970s. The optical properties of fruits and vegetables have always been important characteristics in the assessment of their quality, with much of the work done prior to 1950 being conducted in the visible region. Kramer and Smith (63) identified ripeness and color as "the most important factors of quality in peaches [*Prunus persica* (L.) Batsch] and apricots (*Prunus armeniaca* L.) as well as other fruits," noting that color and ripeness are closely associated with many fruits losing their green color due to a reduction in the chlorophyll content as they ripen. Bittner and Stephenson (12) noted that, in the evaluation of agricultural commodities such as fruits, appearance tended to dominate the evaluation and that, in government inspection of quality, 40 to 60% of the grade value was derived from color alone.

Prior to MacGillivray's (79) initial spectral analysis of tomato (*Lycopersicon esculentum* Mill.) pulp in 1937, much of the study of produce quality was conducted using subjective assessment. For example, MacGillivray (78) used Munsell color matching disks to evaluate the color of tomato fruit. In using this subjective system MacGillivray noted that it is critical to know the color sensitivity of the operator judging the color matching. In the late 1930s and early 1940s researchers began to investigate the spectral reflectance of fruits and vegetables. For example, Lott (71, 72) investigated the use of spectral reflectance from 400 to 700 nm of apple [*Malus sylvestris* (L.) Mill.] flesh and skin in an attempt to accurately describe color changes in the flesh with changing maturity. Lott noted that all apple samples tested, from immature to overmature, had a reflectance minimum at 675 nm. Although Lott did not identify the chemical constituent associated with this optical characteristic (i.e., chlorophyll), he concluded that the 675-nm region offered the most promising avenue for further study. Rood (119), in a similar study on peach flesh and skin reflectance, also determined that color and chlorophyll content were useful indices of fruit maturity. Francis and Clydesdale (41) reviewed several early optical instruments used to measure the color characteristics of tomatoes and tomato products.

In the 1950s and 1960s a group of researchers at the United States Department of Agriculture Instrumentation Research Laboratory in Beltsville, MD began to develop instrumentation for measuring the optical transmission of intact agricultural commodities (4, 6, 7, 8, 127, 154, 156). Birth (5) observed that with optical transmission, the absorbance of intact produce at a single wavelength is influenced by several factors, including sample size. To reduce the influence of variations in sample size on optical measurements of intact fruits and vegetables the optical-density difference at two wavelengths was used by early researchers. Birth's dual-monochrometer version of the basic instrument design described by Norris (99) was developed to facilitate easy use of the optical-density difference type measurements. Example applications of this technique include the prediction of peach chlorophyll content by $\Delta OD_{695\text{–}725\ nm}$ (5), green tomato ripening time by $\Delta OD_{510\text{–}600\ nm}$ (154), and detection of internal discolorations in potato (*Solanum tuberosum* L.) using $\Delta OD_{800\text{–}710\ nm}$ (4). Norris and Hart (101) developed a high efficiency spectrophotometer using a wedge interference filter for the monochrometer to allow direct NIR transmission measurements on dense light scattering materials such as intact peanuts (*Arachis hypogaea* L.) and lima beans (*Phaseolus lunatus* L.) and were able to predict moisture content using $\Delta OD_{970\text{–}900\ nm}$.

IMPACT OF COMPUTER-BASED NIR TECHNIQUES ON OPTICAL MEASUREMENTS

Prior to the development of computerized spectrophotometers and advanced spectral analysis software in the early 1970s, the full potential of NIR measurements on produce was not realized. In their 1968 study of the reflectance of apples, peaches, and pears (*Pyrus communis* L.), Bittner and Norris (11) concluded that the NIR reflectance values change very little as fruit grows and matures, with water being the main absorber evident in the spectra. They found no significant relationships between picking date and NIR reflectance values. Unlike the NIR research on agricultural commodities such as grains, oilseeds, and forage (e.g., 153, 100) in the early 1970s, the impact of these computer-based techniques and the related development of NIR methods were not evident in produce until the 1980s. Birth et al. (9, 10) conducted some of the earliest studies using derivative math pretreatments and multivariate statistics on NIR spectra of produce, predicting pigments and soluble solids content (SSC) in papaya (*Carica papaya* L.) and soluble solids and dry matter contents in onion (*Allium cepa* L.). Since Birth et al.'s early application of computer-based NIR techniques, considerable research has been conducted on their application to fruits and vegetables. A listing of NIR research on produce can be found in Table 14–1. Work has been conducted to develop NIR calibrations for determining the concentration of a wide range of constituents including:

carotenoids	firmness	malic acid	soluble solids (°Brix)
chlorophyll	fructose	moisture	starch
citric acid	glucose	N	sucrose
ethanol	ketose	sorbitol	total solids (dry matter)

Table 14–1. Near-infrared applications in analysis of fruits and vegetables.

Sample	Parameter	Reference
Almond		
*Prunus dulci*s (Mill.) D.A. Webb	internal defects	107, 108
Apple		
Malus sylvestris (L.) Mill.	acid, malic	16, 129
	acidity	73, 94, 96, 113, 114, 129
	alcohol insoluble solids	73
	bruised tissue	15, 42, 92, 98, 147, 145
	color, external surface	11
	dry matter	73, 94
	firmness	24, 73, 94, 113, 114
	fructose	16, 23, 43, 129
	glucose	16, 23, 43, 129
	maturity	114
	moisture	96
	N	62
	pH	65, 73, 94
	saccharose	129
	soluble solids	2, 13, 23, 24, 30, 66, 65, 73, 77, 94, 113, 114, 118, 135, 148
	sorbitol	23,
	stiffness	65
	sucrose	16, 23, 43
	sugar	23, 67, 96, 129
	water core	8
Apricot		
Prunus armeniaca L.	maturity	63
	soluble solids	20, 21
Banana		
Musa acuminata Colla	firmness	141
	glucose	141
	sucrose	141
	sugar	141
Cantaloupe		
Cucumis melo L.	soluble solids	36, 102
Carrot		
Daucus carota L.	carotenoids	126
	fructose	126
	glucose	126
	saccharose	126
	sugar	126
Cherry		
Prunus avium L.	firmness	74
	pit detection	68
	scald	156
	soluble solids	20, 74
Citrus oil		
Citrus	identity	136
	limonene	136
Cocoa bean		
Theobroma Cacao L.		
	quality	31
Cucumber		
Cucumis sativus L.	bruised tissue	91

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Table 14–1. Continued.

Sample	Parameter	Reference
Date		
Phoenix dactylifera L.	moisture	37, 124
	soluble solids	124
Fig		
Ficus carica L.	defects	18
Honeydew		
Cucumis melo L.	soluble solids	34
Kiwifruit		
Actinidia deliciosa C.S. Liang	density	123
& A.R. Fergusson	dry matter	85, 105, 106, 133
	firmness	27, 85, 84
	fructose	133
	glucose	133
	rupture force	84
	soluble solids	27, 85, 105, 106, 123, 133
	starch	133
Lemonade		
Citrus limon (L.) Burm.	sugar	67
Mandarin		
Citrus reticulata Blanco	acid, citric	87
	soluble solids	59, 88
Mango		
Mangifera indica L.	acid, malic	16
	acidity	125
	dry matter	46
	firmness	125
	soluble solids	125
	storage period	125
	sucrose	16
Melon		
(see honeydew or rockmelon)		
Mushroom		
Agaricus bisporus (J.E. Lange) Pilát	moisture	120
Mushroom		
Ganoderma lucidum (Curtis:Fr.)		
P. Karst.	glucosamine	137
Olive oil		
Olea europaea L.	purity	151, 152
Onion		
Allium cepa L.	dry matter	10
	soluble solids	10
Orange		
Citrus sinensis (L.) Osbeck	acid, citric	70
	acid, malic	70
	fructose	67, 70
	glucose	67, 70
	identity	40
	purity	144
	sucrose	67, 70
	sugar	67
Papaya		
Carica papaya L.	carotenoids	9
	chlorophyll	9
	maturity	44
	soluble solids	9, 132

(continued on next page)

Table 14–1. Continued.

Sample	Parameter	Reference
Pea		
Pisum sativum L.	flavor	61, 80
	texture	61, 80
Peach		
Prunus persica (L.) Batsch	chlorophyll	130
	color, external surface	11
	identity	104
	maturity	63, 127
	soluble solids	3, 58, 60, 110, 130
	sorbitol	130
	sucrose	130
Pear		
Pyrus communis L.	color, external surface	11
	fructose	139
	glucose	139
	sorbitol	139
	sucrose	139
Persimmon		
Diospyros virginiana L.	soluble solids	102
	phenol, total	102
Pineapple		
Ananas comosus (L.) Merr.	soluble solids	46, 47, 48
Plum		
Prunus × *domestica* L.	acidity	103
	firmness	103
	soluble solids	103
Potato		
Solanum tuberosum L.	bruised tissue	39
	discoloration	4
	dry matter	50, 122
	fructose	50
	glucose	50
	N	158
	protein	50
	specific gravity	122
	starch	50
	sucrose	50
	sugar	86
Potato (sweet)		
Ipomoea batatas (L.) Poir.	amylose	54
	moisture content	56
	soluble solids	56
	starch	56
Prune		
Prunus × *domestica* L.	defects	17
	dry matter	134
	soluble solids	134
Pumpkin		
Cucurbita pepo L.	carotenoids	55
	vitamin E	55
Raisin		
Vitis vinifera L.	density	53
	moisture	53
Rockmelon		
Cucumis melo L.	soluble solids	45, 48, 149

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Table 14–1. Continued.

Sample	Parameter	Reference
Sugarbeet		
Beta vulgaris L.	dry matter	32, 52, 121
	marc	52
	N	32, 52
	soluble solids	38, 52
	sucrose	25, 32, 38, 121
Tangerine		
Citrus reticulata Blanco	drying score	109
Tomato		
Lycopersicon esculentum Mill.	acidity	51, 157
	color, external surface	51
	maturity	93, 97
	soluble solids	51, 111, 131, 157

Near-infrared spectroscopy research has also been conducted to develop prediction models for detection of defects in produce such as bruises, impurities, internal discoloration, pits, scald, and water core.

Approximately half the NIR research on fruits and vegetables has been conducted using nondestructive measurements. Near-infrared reflectance has been used in about half of the NIR research on fruits and vegetables, with transmission and interactance evenly divided between the remaining studies. Multiple linear regression (either on raw absorbance values or absorbance derivative values) has been used for calibration development in about half of the studies listed in Table 14–1, with about a third using partial least squares regression. Of the research listed in Table 14–1, approximately 75% has been conducted on fruits, with apples being the most commonly studied commodity.

UNIQUE REQUIREMENTS IN MEASURING INTACT PRODUCE

One of the most commonly touted advantages on NIR spectroscopy is the avoidance of elaborate sample preparation procedures. In many cases the measurement is noninvasive and the samples are measured in a natural intact state or after a simple grinding procedure. Unfortunately most agricultural produce is nonhomogeneous in its natural, intact state, frequently having a thick rind or skin. Considerable light scattering occurs inside produce tissues, and the scattering and/or absorption of light transmitted directly through whole intact produce can easily exceed 6 OD (19, 154), making accurate transmission measurements of intact produce difficult. Prior to Norris' pioneering work in the 1950s, much of the research on the optical properties of fruits and vegetables was conducted using reflectance techniques. The optical measurement techniques used prior to this time required destructive sample preparation for studies evaluating the optical characteristics of internal tissues.

In the 1950s Norris (14, 99) developed an optical instrument to detect blood in intact chicken (*Gallus gallus* L.) eggs. Norris adapted the instrument to measure the spectral absorption characteristics of intact fruits and vegetables. The in-

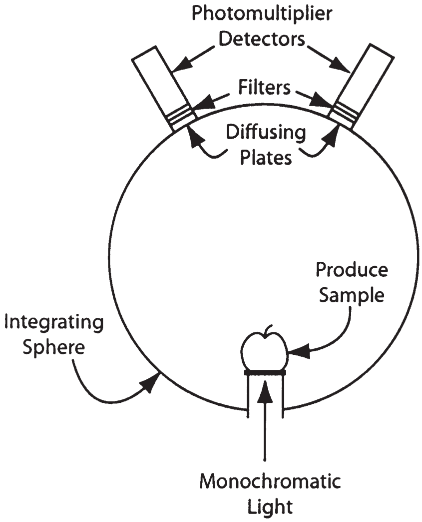

Fig. 14–1. Schematic of Norris (99) instrument enclosing a sample inside an integrating sphere to measure the transmission of intact produce.

strument enclosed the sample at the incident irradiation port of an integrating sphere and used photomultiplier tubes to detect transmitted light in the 350- to 1100-nm region (Fig.14–1). Birth et al. used this early instrument to measure the transmittance of whole tomatoes from 500 to 1000 nm and found that the ratio of transmitted light at 620 and 670 nm gave a good indication of internal color of tomatoes of various ripeness levels. Birth (4) used this instrumentation to detect hollow heart in potatoes nondestructively. Sidwell et al. (127) used this instrument and a dual monochrometer version developed by Birth (5) to estimate (r = 0.957) the chlorophyll content of intact Elberta peaches.

Energy Distribution of Light Transmitted Through Intact Fruit

Birth et al. (7) measured the distribution of transmitted light emitted at the surface of an intact tomato when the fruit was illuminated at the blossom end (Fig. 14–2a). As the distance along the surface, d (Fig. 14–2b), between the incident light and the detector increases, the intensity of the transmitted light dramatically decreases. Chen and Nattuvetty (22) reported similar findings for apple, orange [*Citrus sinensis* (L.) Osbeck], and tomato in the 500- to 750-nm region. Dull et al. (35) conducted a similar study on a ripe Honeydew (*Cucumis melo* L.) melon (15-cm diameter) in the 600- to 1100-nm region and observed that the optical density (OD) increased approximately 2 OD (from about 2.7 OD to about 4.7 OD at 800 nm) when the detector was moved 23° along the melon's surface (the angle α of the detector relative to the incident beam was changed from 22 to 45°). Chen and Nattuvetty (22) also studied the internal path that light travels from point of incidence by inserting a metal knife at various depths, h (Fig. 14–2b), midway between the incident light and the detector. They defined the light "penetration depth" as the depth to which the knife had to be inserted to block 90% of the light transmitted before the knife was inserted (i.e., ΔOD = 1).

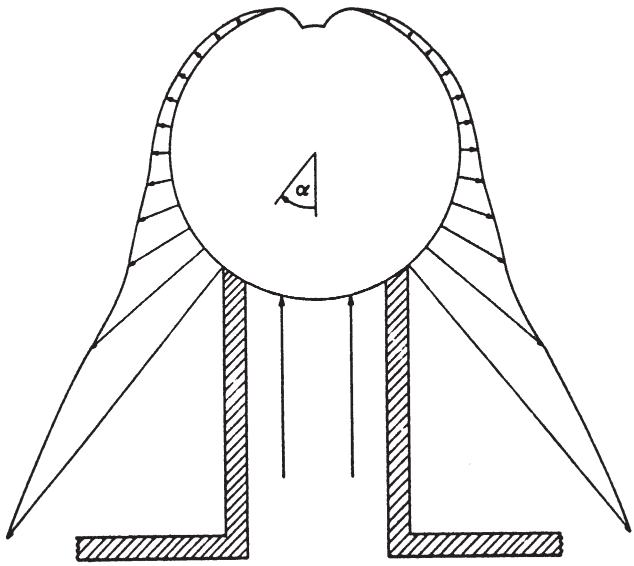

Fig. 14–2. (a) Distribution of light (640 nm) emitted at the surface of an intact tomato when illuminated at the blossom end. Emitted line lengths are proportional to their intensity (7); (b) typical method of measuring the pattern of light transmission through portions of intact produce.

Their studies of green tomatoes, apples, and oranges showed that penetration depth increased as the distance along the surface, *d*, increased. Other studies confirm the need for highly sensitive instrumentation when attempting to make direct transmission ($\alpha = 180°$, Fig. 14–2b) measurements on intact produce. Worthington et al. (154) observed that the absorbance of intact green tomatoes exceeded 6 OD when illuminated using direct transmission in the 500- to 650-nm range. Birth (5) observed that the absorbance of the chlorophyll absorption band (675 nm) in green peaches exceeded the 6 OD maximum sensitivity of the dual-monochrometer spectrophotometer he designed for transmission measurements on intact produce.

Nondestructive Measurement Techniques for Intact Produce

Traditionally, spectrophotometric methods use either direct transmission or diffuse reflectance geometries. These techniques are applicable where the optical path can be adjusted to minimize the sample's OD or the composition of the sample surface is either of interest or the same as its interior (or the skin is sufficiently thin as to pose negligible optical absorbance). In nondestructive applications, the sample is used in its natural, intact state, frequently resulting in a high OD.

As an alternative to placing the sample inside an integrating sphere, Norris developed a spectrophotometric technique termed *interactance* (26). The term interactance was used because with this technique monochromatic light enters the fruit and "interacts" with the tissue inside; some of the unabsorbed light is internally reflected and exits the fruit on the same side as the entrance beam. Figure 14–3 shows

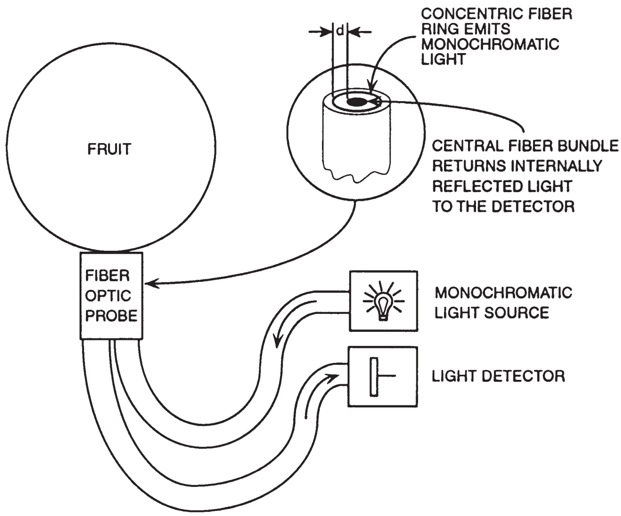

Fig. 14–3. Fiber optic probe used for interactance measurements of intact produce.

the type of interactance probe developed by Norris, where the light from the monochrometer is emitted onto the fruit from an outer ring of optical fibers concentric to a central bundle of optical fibers that collect the unabsorbed light internally reflected from the fruit. The interactance configuration allows the optical absorption spectrum to be collected from intact, optically dense biological specimens of irregular size, such as papayas, and, unlike direct transmission measurements, does not require any correction for pathlength differences between fruits of different sizes. The configuration of the fiber optic probe can be optimized for a specific commodity by adjusting the thickness of the optical barrier and the diameter of the central fiber optic bundle and outer ring. The thickness of the optical barrier, *d*, affects the penetration depth defined by Chen and Nattuvetty (22). The diameter of the central fiber optic bundle should be as large as possible to maximize the amount of internally reflected light detected, but not too large to prevent the majority of these fibers from directly contacting the fruit in order to minimize surface reflectance reaching the detector. Several researchers have successfully used this probe design to measure the soluble solids content of intact fruits (e.g., 69, 60, 130). The interactance technique is similar to the "body transmittance" technique used by Birth et al. (9), Dull et al. (35), and Chen and Nattuvetty (22).

Birth et al. (9) compared traditional diffuse reflectance measurements with interactance measurements using the fiber optics configuration shown in Fig. 14–4. They found that the reflectance measurements could be used to separate the papayas into maturity stages ranging from color break to ripe, but could not distinguish immature from mature green fruit. Using the interactance measurement geometry they were able to distinguish immature from mature-green papayas in addition to the color break to ripe stages.

Schaare and Fraser (123) compared the performance of diffuse reflectance, interactance, and direct transmission measurements in predicting soluble solids con-

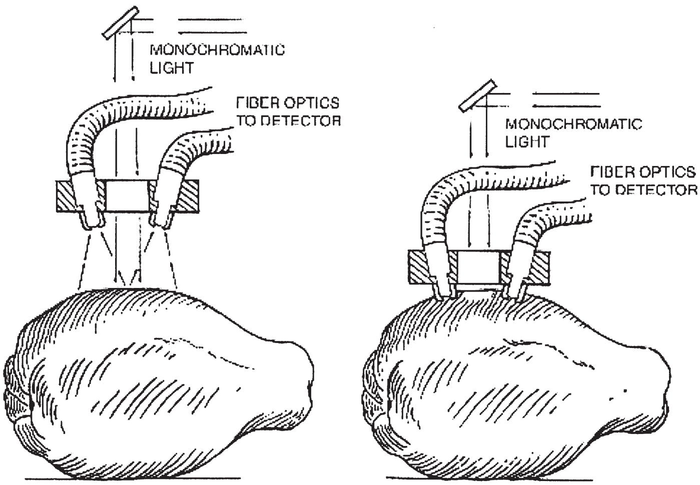

Fig. 14–4. Measurement geometries evaluated by Birth et al. (9) for nondestructive measurement of internal constituents of intact papayas.

tent, density, and internal flesh color of intact kiwifruit (*Actinidia deliciosa* C.S. Liang & A.R. Fergusson). They found that interactance had the greatest accuracy in predicting all three constituents and concluded that interactance was superior to reflectance because interactance was less dominated by the peel and that it had a superior signal/noise ratio when compared with direct transmission through the entire fruit.

Using direct transmission measurements on cylindrical cantaloupe (*Cucumis melo* L.) tissue "slices" with no rind, Dull et al. (36) showed the feasibility of using a second derivative NIR absorbance ratio (913/884 nm) to predict the soluble solids content ($r = -0.97$, SEP = 1.56 °Brix, study's SSC range: 4.8–15.5 °Brix). When the body transmittance or interactance technique was used on intact cantaloupe they found that the correlation to soluble solids content dropped to $r = -0.60$, with an increased SEP = 2.18 °Brix (study's SSC range: 4.8–15.5 °Brix). They attributed the decreased performance to constituents in the rind that are not found in the edible tissue and to light scatter due to the rind surface netting, illustrating some of the challenges encountered when attempting to use NIR techniques on intact produce.

OPTICAL SORTING

The suitability of NIR techniques for nondestructive determination of internal quality has led to the development of on-line optical sorting systems that can evaluate the quality of each piece of fruit. Although based on reflectance in the red region (not NIR), one of the earliest optical fruit sorters was developed by Powers

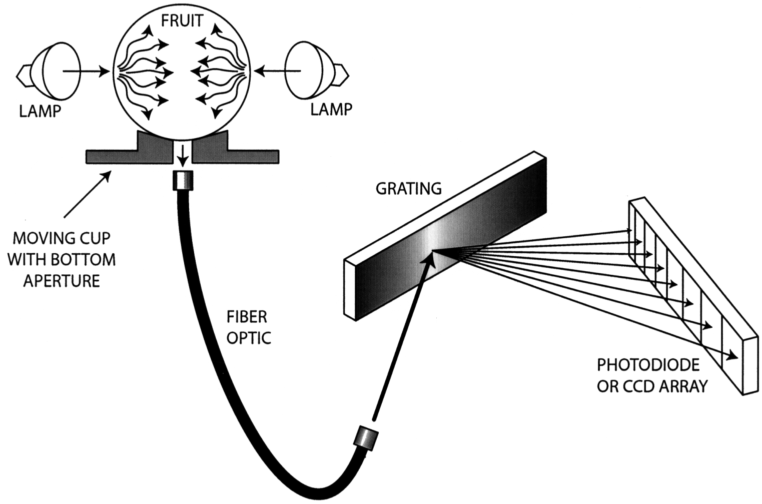

Fig. 14–5. Schematic illustrating the use of the interactance measurement technique for on-line NIR determination of the internal quality of intact fruit.

et al. (116) for lemon [*Citrus limon* (L.) Burm.]. This early experimental sorter operated at a rate of 4 fruit s^{-1} and used the reflectance ratio

$$\frac{R_{720\ nm} - R_{678\ nm}}{R_{678\ nm}}$$

to sort fruit into one of five ripeness categories.

One of the first commercial sorters to use NIR measurements for sorting fruit by internal quality was developed in 1988 by Mitsui Mining and Smelting, Co. Ltd. of Japan (49). Kawano (57) reported on a 1989 version of this sorter that illuminated the fruit with "white" light and used a postdispersive diode array sensing technique called the MPS (multi-purpose sensor) to measure the NIR reflectance of each fruit. A sorting rate of 3 fruit s^{-1} was achieved in sorting apples, peaches, and Japanese pears [*Pyrus pyrifolia* (Burm.) Nak.] for sweetness.

Kupferman (64) noted that the use of reflectance in the MPS design limited the depth of penetration to about 5 mm, which can be a source of error when measuring the spectra of nonhomogeneous materials like intact produce. A commercial fruit sorter was developed by Fantec Research and Development Co. (Osaka, Japan) using an on-line interactance type measurement technique to allow sweetness sorting of thick skinned fruits like oranges, Fig. 14–5. In this configuration, the fruit is placed in a cup with an aperture in the bottom, white light illuminates the fruit from the side and the interactance measurement is made at the bottom where a fiber optic transfers the unabsorbed light to a postdispersive diode array type sensor. A similar NIR spectrometer design for on-line measurement of the sugar content of fruit was developed by Bellon et al. (3). Commercial companies that have developed or have NIR produce sorters at an advanced state of development include Autoline Inc. (Reedley, CA), AWETA BV (Nootdorp, the Netherlands), Colour Vision Systems Pty. Ltd. (Bakersfield, CA), Fantec Research and Development Co. (Osaka, Japan), Kubota Co. (Osaka, Japan), Maki Co. (Japan), Mitsui Mining and Smelting Co. Ltd. (Tokyo, Japan), Saika Co. (Japan), Sumitomo Co. (Tokyo, Japan), and Taste Technologies Ltd. (Onehunga, New Zealand).

While the interactance measurement technique allows rapid, on-line spectral measurements to be conducted on the internal tissue of optically dense items like fruits, its localized nature may not accurately predict the average internal quality of the fruit because of spatial variability within. For example, Slaughter et al. (132) observed differences in soluble solids content as high as 5.3 °Brix (study's SSC range: 4.5 to 16 °Brix) between tissue from the "sunny side" vs. tissue from the "shady side" of the same papaya.

Peiris et al. (112) studied the spatial variability of soluble solids content and dry matter in several commodities. They observed that radial and proximal to distal variation was generally greater than circumferential variation, but that the level of variability depended on the commodity. For example, they observed that the coefficient of variation in soluble solids content along the proximal to distal locations was 3% in apple samples but 13.4% in honeydew. Their observation that the circumferential variation in soluble solids content in tomato was one-fifth that in the proximal to distal direction agrees with Slaughter et al.'s (131) observation that a calibration developed at a location along the equator of a tomato had lower SEP values (0.37–0.43 °Brix, study's SSC range: 3.5–7.5 °Brix) when used at another equatorial location than when applied to the blossom end of the fruit (SEP: 0.53–0.87 °Brix, study's SSC range: 3.5–7.5 °Brix).

Massie and Norris (83) developed a high-intensity, low stray light spectrophotometer designed to measure the direct transmission of intact produce, reducing the errors associated with spatial variability. While this system had a useful range in excess of 13 OD, the double monochrometer design used two rotating filter wheels and a light-tight seal around the fruit exterior to reduce stray light, features which are difficult to incorporate into on-line systems.

IMAGING TECHNIQUES

To date, NIR-based imaging techniques have had limited application in produce. Near-infrared imaging techniques can be classified into three methodologies:

- Single waveband, typically implemented with a camera using a single interference filter
- Small number of wavebands, typically 2 to 10 and implemented with a single camera and a filter wheel, or a set of cameras each with its own filter
- Multispectral (or hyperspectral) systems, typically a continuous sequence of wavebands >10 and implemented with a single camera and a liquid crystal tunable filter (LCTF), an acousto-optic tunable filter (AOTF), or a grating spectrometer

Some NIR imaging techniques have primarily investigated the area of on-line defect detection in produce. Imaging techniques for bruise detection in apples are based on research (e.g., 15, 147) showing that the NIR reflectance of the bruised apple tissue is lower than the reflectance of nonbruised tissue when measured 1 d after bruising. Brown et al. (15) found that the NIR reflectance of the bruised tissue in McIntosh, Jonathan, and Golden Delicious apples continued to decrease for 28 to 42 d after bruising. Upchurch et al. (147), however, observed that the NIR reflectance of the bruised tissue exceeded that of nonbruised tissue for Delicious and Golden Delicious apples when measured 28 to 42 d after bruising, depending on bruise severity. Rehkugler and Throop (117) and Upchurch et al. (147) both developed line scan imaging systems with a single long-pass optical filter to record the apple reflectance from 750 to 1000 nm for bruise detection. Rehkugler and Throop (117) were able to predict bruise area with a correlation ranging from $r = 0.63$ to $r = 0.84$. Using the same imaging system as Upchurch et al. (147), Throop et al. (143) developed a NIR image processing algorithm to detect both 24-h-old and 2-mo-old bruises in apples. The percentage of correctly identified bruises in the Throop et al. (143) study varied from 48 to 93% depending on bruise severity and age. Throop and Aneshansley (142) reported the development of a multispectral image-based sorting system for defect detection in apples that acquired four images of each apple at 540, 650, 750, and 950 nm, although no assessment of the performance was reported. Lu et al. (76) used a hyperspectral imaging system, where each image consisted of 55 wavebands (every 3.74 nm from 700 to 900 nm) to detect bruises in Delicious apples. They were able to correctly detect bruises in 19 of 20 bruised apples studied. Lu (75) developed a hyperspectral imaging system with 186 wavebands (every 4.3 nm from 900 to 1700 nm) to detect bruises in Delicious and Golden Delicious apples. Lu (75) determined that the optimal number of wavebands needed for bruise detection was between 20 and 40, corresponding to a spectral resolution between 8 and 17 nm. Lu (75) also observed that the NIR region between 1000 and 1340 nm was most appropriate for bruise detection. The system was able to detect both new and old bruises, with a detection rate of 62 to 88% and 59 to 94% for Delicious and Golden Delicious apples, respectively.

Miller and Delwiche (89) studied the surface reflectance of undamaged or damaged (scarred, bruised, cut, damaged by scale, brown rot, or worm holes) peaches. Their findings were similar to the observations by Brown et al. (15) in apple in that most peach defects had a lower reflectance in the 700- to 1200-nm NIR region than peaches without defects. They determined that a sorting criterion based on the spectral reflectance at 650, 720, and 815 nm showed feasibility for sorting defective peaches. Miller and Delwiche (90) used an on-line imaging system with a single bandpass filter centered at 750 nm (40 nm half-power bandwidth) to detect peaches with defects. They were able to predict the area of scar, bruised, cut, worm hole, and brown rot with correlations of $r = 0.91$, 0.75, 0.61, 0.91, and 0.92, respectively. The overall error rate for the imaging system in defect identification was 31%. About 25% of the time the stem cavities were misclassified as defects. They also determined that the system was ineffective in detecting peaches with scale. Using a similar NIR imaging system Singh and Delwiche (128) developed improved machine vision techniques better suited for pipeline image processing hardware, reducing the overall error rate of defect identification to 28.6%. They were able to predict the scar area and bruised area in peaches with correlations of $r = 0.72$ and $r = 0.75$, respectively.

Burkhardt and Mrozek (17) studied the surface reflectance of dried prunes in the 600- to 2200-nm region and determined that the reflectance in this region of prunes (*Prunus* × *domestica* L.) with scab damage, exposed pits, or side cracks was greater than that of undamaged prunes. Delwiche et al. (33) developed a line-scan imaging system to distinguish prunes with surface defects such as mold, scab, or cracks from undamaged prunes. The system used a silicon-based line scan camera with no optical filter to provide an image covering the 400- to 1100-nm region in a single waveband. A spatial gradient was applied to detect defect boundaries that had a greater spatial rate of change in reflectance than was found in undamaged prunes. The imaging system was able to detect 98.2% of defective fruit and 100% of undamaged fruit correctly.

The typical configuration for automatic visual inspection of produce positions the camera(s) above a multilane horizontal conveyor carrying the produce to be inspected. Due to their size and spheroidal shape, the diffuse reflectance from the surface of produce like apples or peaches will vary from location to location across the fruit surface unless the illumination system is carefully designed (1). For visual defect detection methods like those discussed for apples and peaches, where the defect has a different NIR reflectance level than the undamaged tissue, the detection algorithm will be less complex and more robust if the surface reflectance from undamaged produce is uniform. Singh and Delwiche (128) developed a visual inspection chamber using a spherically shaped optical diffuser and four lamps placed in a circle around the exterior of the diffuser to produce an image in which the surface reflectance from the fruit was uniform across the fruit. They reported a coefficient of variation in gray level intensity of about 5% from point to point across a sphere. Crowe and Delwiche (28) reported that their use of multiple lamps around the exterior of a cylindrically shaped optical diffuser provided sufficient uniformity in image intensity that additional image preprocessing for uniformity of image intensity was unnecessary. Tao and Wen (140) developed an adaptive image transformation algorithm to compensate for the diffuse reflectance gradient on curved three-dimensional objects like apples when an elaborate illumination chamber is not available. The algorithm used an adaptive spherical object transformation as a preprocessing step to compensate for image gray level variation due to both shape and size when attempting to detect defects with lower reflectance values than healthy tissue.

One of the problems encountered when attempting to implement a NIR-based imaging system for bruise detection is that the “shadow” caused by the stem cavity, suture, or the calyx for some fruit orientations can have a similar reflectance to bruised tissue. For example, Miller and Delwiche (90) observed that stem cavities were misclassified as defects about 25% of the time when using their NIR imaging system to detect defects in peaches. Crowe and Delwich (28, 29) developed an on-line NIR imaging system using structured illumination at 780 nm to detect the stem cavity, and reflectance at 750 nm to detect defects in apples and peaches. This system had a throughput of 5 fruit s^{-1} and theoretical error rates of 25, 38, 38, and 33% for detecting good, bruised, cracked, and cut apples, and 25, 9, 3, and 30% for detecting good, bruised, scared, and cut peaches. Yang (155) also applied structured lighting techniques to distinguish stem cavity and calyx regions from dark patch type defects in apples using machine vision in the visible region. Yang achieved an accuracy of 95% in distinguishing stem cavity and calyx regions from defects that appear as dark patches in the visible. Wen and Tao (150) used multispectral imaging based on an image in the NIR (single waveband from 700 to 1000 nm) and a second image in the mid-infrared (single waveband from 3.4 to 5 μm) to distinguish between bruised apple tissue and the stem cavity or calyx. Only 0.91% of apple stem cavities and calyxes were misclassified as defects in this study.

There have been a few research studies investigating the feasibility of using multispectral imaging techniques for other produce sensing tasks. For example, Martinsen et al. (81, 82) studied the spatial distribution of soluble solids content across the cut face of a kiwifruit using a hyperspectral imaging system, where each image consisted of waveband resolution better than 5 nm from 650 to 1100 nm. They discussed the challenge of calibrating a NIR imaging system on produce due to the spatial variability in the constituent of interest (i.e., soluble solids content) and the difference in spatial resolution between the imaging system and the standard method (i.e., refractometry). They also observed high levels of specular reflectance due to free juice on the cut surface. Muir et al. (95) reported the development of a multispectral imaging system for detecting defects in potatoes using six wavebands, but no assessment of the performance was reported. In a preliminary study of four tomatoes, Polder et al. (115) used a hyperspectral imaging system with 80 wavebands (every 5 nm from 450 to 850 nm), to classify tomatoes into different ripeness stages based on the surface reflectance. Upchurch and Thai (146) used a multispectral imaging system with 32 wavebands (every 10 nm from 1100 to 1420 nm) to study the feasibility of distinguishing pecan weevil (*Balaninus caryae* Horn) larvae from pecan [*Carya illinoinensis* (Wangenh.) K. Koch] nutmeat. They observed that the 40-nm bandwidth of the LTCF reduced the spectral resolution of the imaging system and impaired its effectiveness in weevil detection. Sugiyama (138) observed that the chlorophyll absorbance at 676 nm had a strong inverse correlation with sugar content in melon flesh. He used an imaging system with a single bandpass filter centered at 676 nm to develop a method of mapping the spatial distribution of sugar within the flesh of cut melons using reflectance.

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