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Nondestructive internal quality assessment of kiwifruit using near-infrared spectroscopy

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A nondestructive optical method for determining the internal quality of intact kiwifruit was investigated. The method, based upon near-infrared spectrophotometric techniques, was found to be capable of predicting the fructose content ($r = 0.96$, SEC = 1.96%), glucose content ($r = 0.97$, SEC = 1.68%), soluble solids content ($r = 0.99$, SEC = 0.78°Brix), and dry weight ($r = 0.97$, SEC = 0.61%) of kiwifruit.

Keywords: nondestructive measurements; near-infrared spectroscopy; internal quality; kiwifruit

Introduction

California kiwifruit are harvested in the fall when they are mature but before they are fully ripe. The timing of the harvest is an important factor in the subsequent postharvest shelf-life and fruit quality. If the fruit is harvested too early, the quality will be inferior owing to low levels of total carbohydrate in the fruit; if harvested too late, the fruit may soften prematurely, reducing shelf-life. and there is an increased risk of mold if seasonal rains are early.

Several researchers have attempted to use optical techniques to develop a non-destructive means of assessing fruit quality. In some commodities the stage of ripeness is well correlated with fruit color and since the initial purchase decision by consumers is often based upon appearance most commercial sorting systems have been developed to sense the visible light characteristics associated with these attributes (e.g. Worthington *et al.* 1976; Nattuvetty and Chen, 1980). Unfortunately color is not a good indicator of internal quality in kiwifruit.

Mitchell and co-workers (Mitchell and Mayer, 1987; Mitchell, 1990; Mitchell *et al.*, 1989) found a strong relationship between final soluble solids content measured on ripe kiwifruit and consumer taste acceptance. They found that the soluble solids level in kiwifruit at the time of harvest was not a reliable method for predicting the soluble solids content in the ripe fruit because a large portion of the total carbohydrates are still in the starch form at harvest. Reid *et al.* (1982) observed that kiwifruit soluble solids continue to increase for several weeks after commercial harvest, that simultaneous increases in the concentrations of fructose, glucose, and sucrose were correlated with the increase in soluble solids, and that the fall in starch content after harvest accounted for half the rise in sugar content during that time. Mitchell *et al.* (1989) found that the total solids content of kiwifruit could be used to predict the ripe soluble solids content and consumer acceptance.

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However, early attempts to develop a quick total solids testing procedure were not successful.

Near-infrared (NIR) spectroscopy has been used as a rapid and nondestructive technique for measuring the soluble solids content (SSC) and moisture content of several commodities. Dull *et al.* (1989) and Dull and Birth (1989) used NIR light to determine the SSC in cantaloupe and honeydew melons. When the NIR measurement was made on intact cantaloupes the correlation to SSC was −0.60 with an SEC 1.67°Brix and for honeydew melons the correlation was −0.87 with an SEC of 1.6°Brix. The authors attributed the lower correlation in cantaloupes to light losses passing through the rind. Slaughter (1995) and Slaughter *et al.* (1996) used a nondestructive NIR technique to predict the SSC of intact peaches and nectarines with a correlation coefficient of 0.92 and an SEC of 0.87°Brix and intact tomatoes with a correlation coefficient of 0.92 and an SEC 0.27°Brix. Kawano *et al.* (1993) used a calibration equation with four terms to predict the SSC of intact satsuma mandarins with a correlation coefficient of 0.989 and an SEC of 0.28°Brix. Dull *et al.* (1991) used NIR transmission to measure the moisture content of whole dates with a correlation coefficient of 0.977 and an SEC of 0.89%.

Objective

The objective of this research was to study the feasibility of using a nondestructive optical technique based upon NIR spectroscopy to determine the internal quality of intact kiwifruit.

Materials and methods

A preliminary study was conducted using simple sugars (fructose, glucose, and sucrose) in aqueous solution to indicate the feasibility of distinguishing one from another using optical absorbance information in the 700–1100 nm NIR region. Ten different mixtures of sugar solutions were prepared using distilled water and pure dry crystalline samples of fructose, glucose, and sucrose. All ten mixtures consisted of 35g of distilled water and 15g of sugar resulting in a total sugar content of 30% (w/w). Each of the three sugars were present in each of 0, 5, 10, or 15g amounts such that the 15g of sugar in each mixture was either all one type, a combination of two, or a combination of three simple sugars. The ten mixtures provided a factorial design where all possible combinations of each simple sugar (i.e. 0, 10, 20, and 30%) were represented and yet the total sugar content of all mixtures was held constant at 30%. This experimental design was selected to minimize the influence of water content (which has strong absorbance bands in the NIR region studied) on the calibration process. The samples were placed in 1 cm pathlength quartz cuvettes and the optical absorption spectrum from 400 to 1100 nm was measured in direct transmission for each solution using a spectrophotometer (Model 6500, NIRSystems, Silver Spring, MD, USA). The average of 250 individual optical scans for each sugar solution was stored for later use. An air-filled cuvette was used as the optical reference standard for the system. This process was replicated three times for a total of 30 observations.

A partial least squares (PLS) regression analysis (Martens and Naes, 1989) was conducted on the optical data using the NSAS software package (version 3.18, 1990, NIRSystems, Silver Spring, MD, USA) (NSAS, 1990). A trial and error process was used to determine the portion of the spectral region scanned which would provide the best

prediction of sugar content using the PLS multivariate calibration technique. PLS calibrations resemble principal component regression models in that regression factors are linear combinations of optical absorbance at each wavelength in the spectral region studied (e.g. 800–1000 nm). The correct number of regression factors for the PLS model was determined by the minimum mean square error of cross validation, where the calibration data set was split into four subsets of equal size (Martens and Naes, 1989).

Hayward kiwifruit were hand harvested in California over a 4 month period beginning 2 months prior to and ending 2 months after typical commercial harvest dates to guarantee a wide range of maturities. The kiwifruit were stored at 1°C after harvest until ready to test and were equilibrated to room temperature (24°C) prior to evaluation.

The optical absorption spectrum from 400–1100 nm was measured for each fruit using a fiber optic interactance probe (Figure 1). The fiber-optic probe consisted of a central bundle of Schott glass fibers 7.6 mm (0.3 in) in diameter surrounded by a 0.64 mm (0.025 in) wide concentric ring of Schott glass fibers which had an outside diameter of 19 mm (0.75 in). The outer ring of fibers was separated from the central bundle by a 5.1 mm (0.2 in) thick metal barrier. A rapid scanning (1.8 scans/s) spectrophotometer (Model 6500, NIRSystems) configured for interactance mode was interfaced to the fiber-optic probe. At the spectrophotometer interface the fibers in the probe corresponding to the outer ring were reconfigured to align with the exit slit of the monochrometer and those corresponding to the inner bundle were reconfigured to align with the silicon detector.

The use of a fiber-optic probe such as that shown in Figure 1 to collect the optical absorption spectrum has been called 'interactance' (Conway *et al.*, 1984) rather than transmittance or reflectance and is similar to the 'body transmittance' technique used by Chen and Nattuvetty (1980), Birth *et al.* (1984), and Dull *et al.* (1989). Conway and others used the term interactance because monochromatic light enters the fruit and 'interacts' with the tissue inside. Some of the nonabsorbed light is internally reflected and exits the fruit on the same side as the entrance beam. The interactance configuration allows the

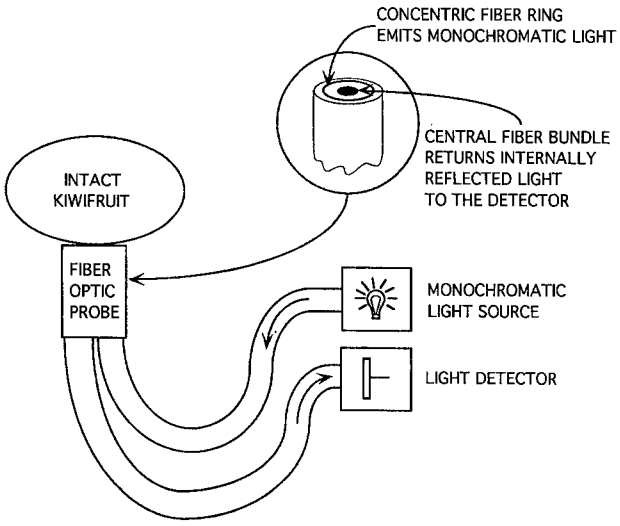

Fig. 1. Fiber-optic configuration for light interactance measurements of intact kiwifruit.

optical absorption spectrum to be collected from intact optically dense biological specimens of irregular size such as kiwifruit.

To measure the optical absorption spectrum, each fruit was hand placed on the probe so that the fruit was centered on and in direct contact with the probe. The fruit were not washed prior to measurement but foreign material adhering to the skin was removed. The average of 250 individual optical scans of each fruit was stored for later use. A 20.8 mm (0.82 in) thick Teflon block was used as the optical reference standard for the system.

Following optical measurement, the kiwifruit was sliced in half longitudinally (from sepals to styles) with the knife held parallel to the major diameter of the 'elliptical' cross-section of the fruit and the unscanned half was discarded. The fresh weight of the scanned half kiwifruit was then determined using an electronic balance (Sartorius Model A200S). The fruit half was then sliced into hemielliptical 'wedges' approximately 5 mm (0.2 in) thick. A hemielliptical slice near the center of the fruit was compressed by hand to express two or three drops of juice on to a temperature compensated refractometer (American Optical) for soluble solids determination. All the slices from the scanned half were placed in a vacuum oven and dried at 55°C according to AOAC Official Method 22.018 (1980) and the dry weight was recorded. The dried samples were then ground and stored in Zip Lock polyethylene film bags until analyzed for sugar and starch content. The dried fruit samples were analyzed for fructose, glucose, and sucrose content by high-performance liquid chromatography according to the method described by Richmond *et al.* (1981) and for starch content according to AOAC Official Method 3.120 (1980). The numbers of kiwifruit analyzed were 180 for total solids content, 90 for soluble solids content, and 70 for sugar and starch content.

The optical and internal quality data were then merged and a PLS regression analysis was conducted using the NSAS software package (NSAS, 1990). The correct number of regression factors for the PLS model was determined by the minimum mean square error of cross validation, where the calibration data set was split into four subsets of equal size.

Since the optical measurement was based upon light entering and exiting the same side of the fruit, a study was conducted to determine the total solids distribution laterally across the fruit. For this study, 30 Hayward kiwifruit were hand harvested at each of three dates approximately 2 weeks apart for a total of 90 fruit. The fruit were sliced longitudinally (from sepals to styles) through the locule with the knife held parallel to the major diameter of the 'elliptical' cross-section of the fruit into three approximately equal portions (Figure 2) so that the two outer portions (A and C) contained outer pericarp (outer wall tissue) while the inner portion (B) contained the columella (central core) and outer pericarp. The total solids content of each portion was determined using the method described previously.

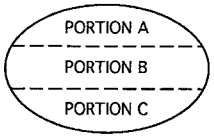

Fig. 2. Diagram showing the three portions of kiwifruit tissue used to determine the total solids distribution within the fruit.

Results

PLS analysis of the sugar solutions indicated that the 800–1000 nm subset of the 700–1100 nm NIR region was best suited for determining the glucose and sucrose content. Cross validation indicated that five-factor PLS calibration models were appropriate, providing a correlation coefficient of $r = 0.9997$ and an SEC of 0.123% for glucose and $r = 0.9998$ and an SEC of 0.117% for sucrose. For fructose ten PLS factors were required in the 800–1000 nm range whereas the 850–1050 nm range required only seven PLS factors. The seven-factor PLS model had $r = 1.0000$ and an SEC of 0.039%. Similar to that observed by Dull and Giangiacomo, examination by eye of the raw absorption spectra does not indicate that there is sufficient character to use this data to distinguish one sugar solution from another, however post-processing the spectra with a second-derivative treatment enhances the subtle differences present. Williams and Norris (1987) reported that sucrose in aqueous solution has absorption bands at 838, 888, and 913 nm. Figure 3 shows the second derivative spectra in this region for pure water and the three 30% simple sugar solutions. These results indicate the feasibility of distinguishing these simple sugars when present in mixtures using a full spectrum optical technique such as PLS in the 800–1050 nm NIR region.

The absorbance spectra of typical unripe and ripe kiwifruit measured intact in the interactance mode (as shown in Figure 1) are shown in Figure 4. PLS analysis of the kiwifruit spectra indicated that 800–1000 nm was the best subset of the 700–1100 nm NIR region scanned for predicting fructose and glucose content. No calibration model could be determined for sucrose content in intact kiwifruit, possibly owing to the small range of sucrose content in the samples studied. For example, the fructose content ranged from 0.6% fresh weight (FW) to 4.1% FW while the sucrose content ranged from 0% to 1.4% FW. Cross validation indicated that a six-factor PLS calibration model was appropriate for determining the fructose content of intact kiwifruit, providing $r = 0.96$ and an SEC of 2.0% dry weight (DW). Similarly, a six-factor PLS model was found to be sufficient for determining the glucose content of intact kiwifruit, providing $r = 0.96$ and an SEC of 1.9% DW. The calibration results are shown in Figures 5 and 6.

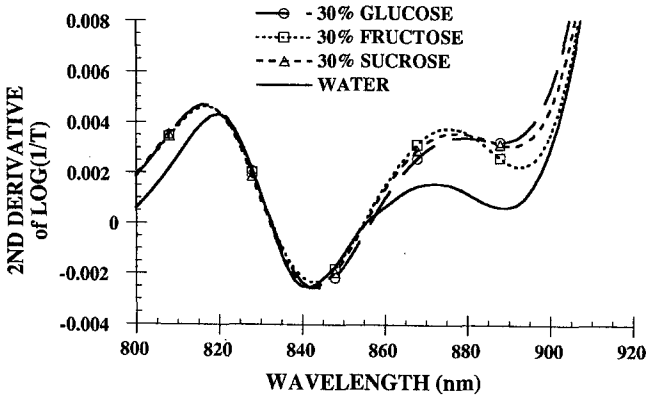

Fig. 3. Second-derivative spectra of water and three 30% (w/w) aqueous sugar solutions.

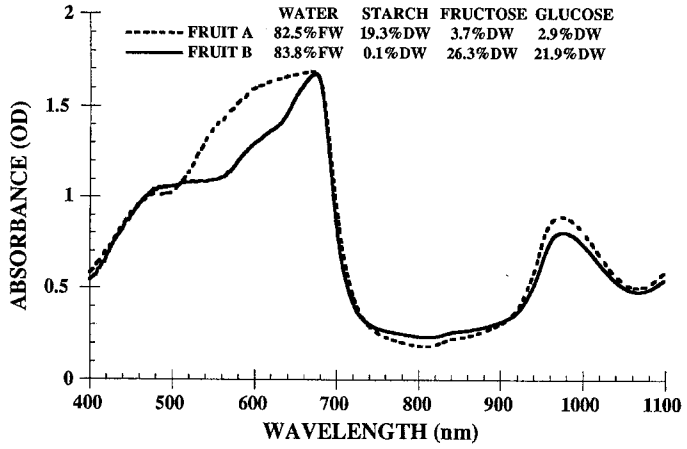

Fig. 4. Absorbance spectra for (A) unripe and (B) ripe intact kiwifruit measured in the interactance mode as shown in Figure 1.

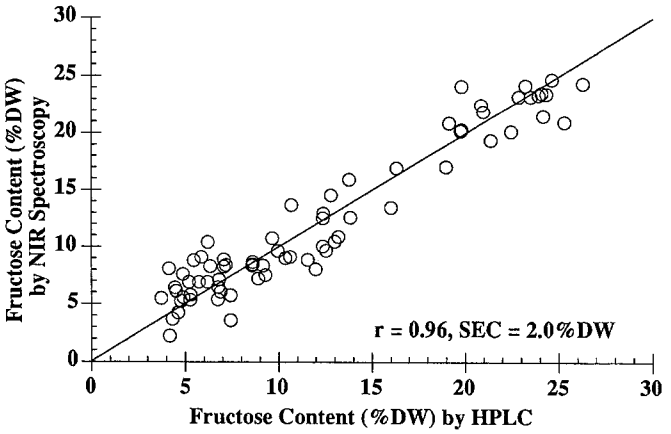

Fig. 5. Calibration results for fructose content in intact kiwifruit using NIR spectroscopy.

PLS analysis of the kiwifruit spectra indicated that 850–950 nm was the best subset of the 700–1100 nm NIR region scanned for predicting total solids content and soluble solids content. Cross validation indicated that a seven-factor PLS calibration model was appropriate for determining the total solids content of intact kiwifruit, providing $r = 0.95$ and an SEC of 0.68% FW. Similarly, an eight-factor PLS model was found to be sufficient for determining the soluble solids content of intact kiwifruit, providing $r = 0.99$ and an SEC of 0.72°Brix. The calibration results are shown in Figures 7 and 8.

PLS analysis of the kiwifruit spectra indicated that 750–1050 nm was the best subset of the 700–1100 nm NIR region scanned for predicting starch content. Cross validation indicated that a seven-factor PLS calibration model was appropriate for determining the

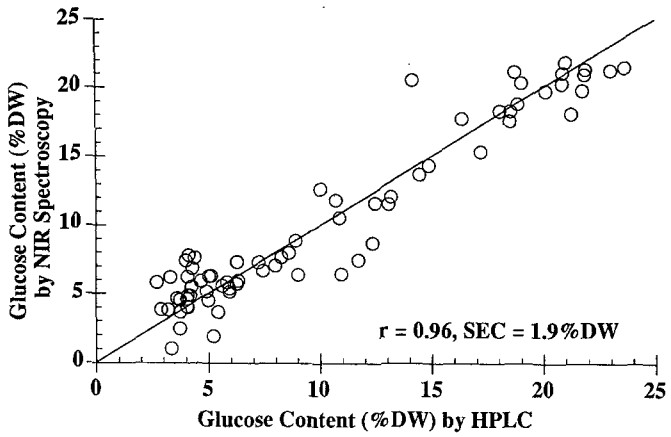

Fig. 6. Calibration results for glucose content in intact kiwifruit using NIR spectroscopy.

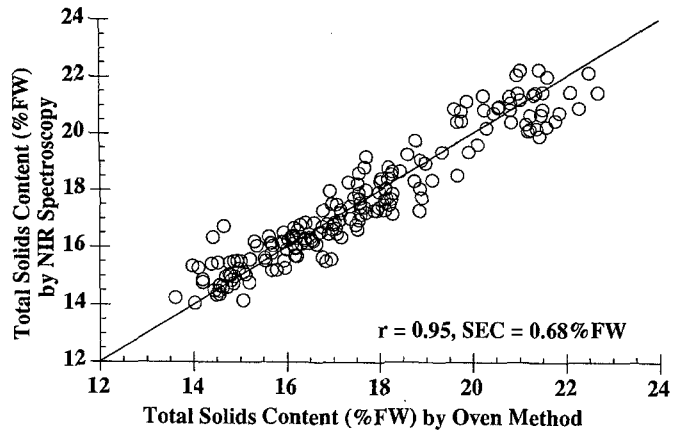

Fig. 7. Calibration results for total solids content in intact kiwifruit using NIR spectroscopy.

starch content of intact kiwifruit, providing $r = 0.93$ and an SEC of 3.7% DW. The calibration results are shown in Figure 9.

An analysis of variance was conducted on the total solids content for each of the three portions (A, B, and C) of the kiwifruit tissue with each fruit set as a blocking variable. This analysis indicated that both the total solids content between fruit as well as between regions in the fruit were significant at the $\alpha = 0.01$ level. A Fisher's protected LSD test indicated that the two portions (A and C) containing the outer pericarp were not significantly different ($\alpha = 0.05$) while the portion (B) containing the columella had a significantly higher total solids content than the others (Table 1). The correlation between the total solids content of the central portion (B) and the average of the two outer portions (A and C) was $r = 0.81$. These results indicate that measurement of the total solids content

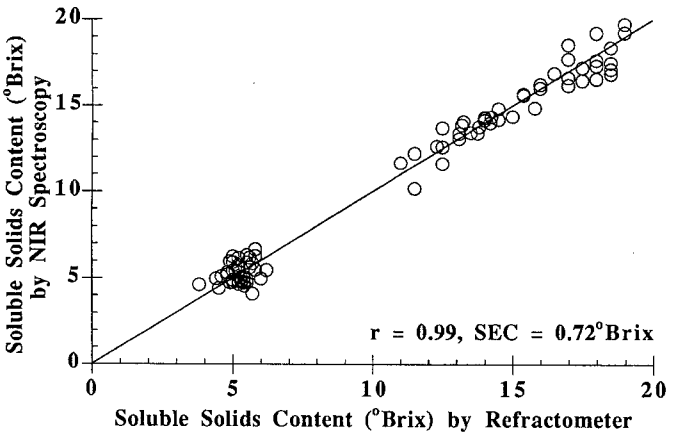

Fig. 8. Calibration results for soluble solids content in intact kiwifruit using NIR spectroscopy.

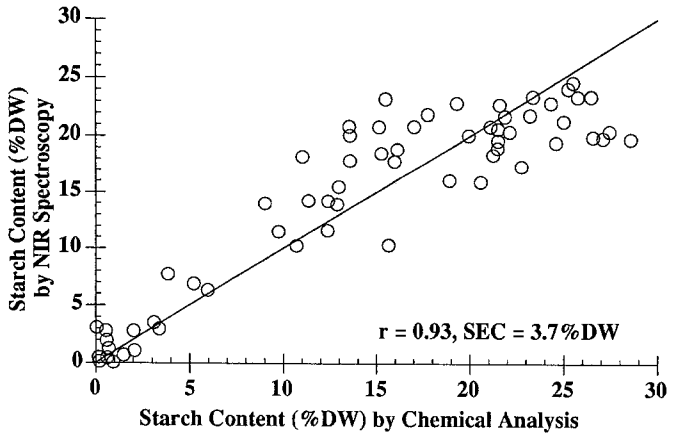

Fig. 9. Calibration results for starch content in intact kiwifruit using NIR spectroscopy.

Table 1. Distribution of Total Solids Content for Three Lateral Regions in Kiwifruit.

Fruit portion	Average total solids content (%FW)*
A	15.5b
B	17.2a
C	15.4b

* Means with the same letter are not significantly different at the $\alpha = 0.05$ level.
LSD = 0.2, df = 58, MSE = 0.15, N = 30 fruit for each portion.

optically on one side of the fruit should give a reasonable estimate of the total solids of the whole fruit since the total solids distribution is fairly consistent from side to side and the total solids content of the center is well correlated with that in the sides.

Conclusions

The results showed that NIR spectroscopic techniques can be used to determine non-destructively several indices of internal quality in kiwifruit. The ability to sense both the soluble and insoluble carbohydrates in an intact kiwifruit indicate that an NIR technique may be suitable for determining kiwifruit quality at harvest. Because of it potential for high-speed measurement, this optical technique may be suitable for packing shed or vineyard use if robust NIR equipment can be developed.

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