PREDICTING FIRMNESS AND SUGAR CONTENT OF SWEET CHERRIES USING NEAR–INFRARED DIFFUSE REFLECTANCE SPECTROSCOPY

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ABSTRACT. The objective of this research was to study the potential of near–infrared (NIR) reflectance spectroscopy as a means for nondestructive measurement of the firmness and sugar content of sweet cherries. NIR spectral data were collected from Hedelfinger and Sam sweet cherries in the spectral region between 800 nm and 1700 nm. Statistical models were developed using the partial least square method to predict the firmness and sugar content of sweet cherries. The models gave relatively good predictions of the firmness of both Hedelfinger and Sam cherries, with corresponding r values of 0.80 and 0.65 and standard errors of prediction (SEP) of 0.55 N and 0.44 N. The NIR models gave excellent predictions of the sugar content of the sweet cherries, with SEP values of 0.71 °Brix and 0.65 °Brix for Hedelfinger and Sam, respectively. NIR reflectance spectroscopy can be used to predict the firmness and sugar content of sweet cherries.

Keywords. Near–Infrared, Spectroscopy, Fruit, Cherry, Quality, Firmness.

Firmness and sugar content are two important quality attributes that not only determine the consumer acceptance and shelf life of sweet cherries but also influence their susceptibility to bruising and pathogenic invasion. A common, subjective method for assessing the firmness of sweet cherries is to squeeze the fruit between fingers, which is practiced by growers to make harvest decisions and by consumers when purchasing fresh sweet cherries. As the sweet cherry ripens, its skin color generally changes, for instance, from light red to mahogany or fully black. Researchers have developed color charts as a guide to make harvest decisions (Timm et al., 1995). However, the correlations of skin color with firmness, sugar content, or other attributes (such as acid and specific gravity) are unreliable and generally low (Mitcham et al., 1998).

In the past, numerous nondestructive or minimally destructive techniques have been reported for measuring the firmness of sweet or sour cherries. Parker et al. (1966) compared four techniques, including two dropping and two compression techniques, for measuring the firmness of sour cherries. They found that only the dial gauge compression technique, which measures the deformation of the cherry under a constant load, was acceptable. Younce and Davis (1995) reported a nondestructive cherry firmness device based on measuring the momentum generated from impacting the fruit onto the disc of an audio speaker. Timm et al. (1993) developed a portable instrument for measuring cherry firmness by compressing the fruit between two parallel plates. Armstrong et al. (1995) reported a laboratory cherry firmness instrument that measures the force–deformation relation of individual cherries as a firmness index. Chen and Ruiz–Altisent (1996) reported on a firmness device based on measuring the acceleration characteristics of a low–mass impactor upon impacting the fruit. Mitcham et al. (1998) evaluated the performances of three nondestructive devices (Armstrong et al., 1995; Chen and Ruiz–Altisent, 1996; Younce and Davis, 1995) and a destructive penetrometer. They compared the results of these four devices with the Instron compression method, which uses a 9–mm diameter ball bearing to compress the fruit for 1 mm of deformation. Mitcham et al. (1998) reported that the device of Armstrong et al. (1995) provided the most consistent measurements among the four compared.

Recently, several studies have been reported on using near–infrared (NIR) spectroscopy techniques in the spectral region between 700 nm and 1100 nm to measure the sugar content of fruits including apples, kiwifruits, melons, peaches, pears, and tangerines (Dull et al., 1992; Kawano et al., 1992, 1993; Slaughter, 1995; Ventura et al., 1998). Others (Choi et al., 1997; Lammertyn et al., 1998; Moons et al., 1997) used both visible and NIR regions from 400 nm up to 2500 nm to assess the firmness and sugar content of apples. Since NIR spectroscopic measurements are affected by many factors such as sensing technique and detector type, direct comparisons of these studies, to determine which spectral regions are most appropriate for sugar content and firmness measurement, are often difficult. However, a greater spectral region beyond 1100 nm appears to give improved prediction results in sugar content and other quality attributes (Moons et al., 1997; Lu et al., 2000). Lu et al. (2000) conducted a study to predict the firmness and sugar content of apples in the spectral region between 800 nm and 1700 nm with the use of an InGaAs detector. They found that the technique gave
good predictions of the apple’s sugar content, with the standard errors for prediction (SEPs) ranging from 0.5° to 0.7° Brix. NIR reflectance was related to fruit firmness (with an r value as high as 0.65), but the NIR predictions were not good enough for practical purposes.

So far, no studies have been reported on using NIR techniques for measuring the firmness and sugar content of cherries or other small deciduous tree fruits. The objective of this research was, therefore, to investigate the NIR diffuse reflectance spectroscopy technique as a means to predict the firmness and sugar content of sweet cherries. The specific objectives were:

1. To measure the diffuse reflectance of sweet cherries over the spectral region between 800 nm and 1700 nm.
2. To develop statistical models from the diffuse reflectance data to predict the firmness and sugar content of sweet cherries.

MATERIALS AND METHODS

MATERIALS

Two varieties of sweet cherries, Hedelfinger and Sam, were hand picked at Michigan State University’s Clarksville Horticultural Experiment Station for four harvest dates between 26 June and 12 July 2000. Hedelfinger cherry fruit are round to ovoid in shape. The skin is thick and brown–red in color, and the flesh is firm. Sam cherry fruit are heart–shaped, medium firm, and fully black. All fruit were visually inspected, and defective and misshapen cherries were removed. The cherries were placed in cold storage at 40° F prior to testing to minimize the physiological changes, particularly softening, in the fruit because the experiments were normally conducted within four days after each harvest. The test cherries were removed from cold storage 12 h before tests were conducted so that the fruit would be in equilibrium with room temperature. A total of 724 cherries were measured in this study, 374 for Hedelfinger and 350 for Sam.

NIR INSTRUMENT SETUP AND MEASUREMENTS

NIR diffuse reflectance measurements were performed using an Oriel spectrophotometric system (Oriel Instruments, Stratford, Conn.). The system consisted of a DC light source with the control unit, an MS 257 monochromator, and a thermal electric cooled InGaAs detector connected to an Oriel controlling/amplifying unit, which in turn was connected to a computer. A 250 W quartz tungsten halogen lamp was used to provide broadband light, which was modulated by a chopper at 60 Hz. The light was delivered to the fruit through a liquid guide cable and an imaging collimator. The diffuse reflected light was acquired by a fiber optic detector and sent to the Oriel monochromator, where the light was dispersed according to wavelength. The dispersed light at different wavelengths was sensed by the InGaAs detector and converted into electronic signals. In this study, the light delivery probe was oriented 45° from the sensing probe.

Each test cherry was placed in the sample holder with a 12.7–mm diameter hole. The cherry was positioned with the distal side, opposite to the fruit suture, facing down towards the light delivery probe. One scanning was performed for each fruit between 800 nm and 1700 nm at an interval of 2 nm. For every four samples, one spectrum was also obtained from a Spectrolon disc (Labsphere Inc., North Sutton, N.H.) with 98% or higher reflectance for the spectral region measured. This spectrum was used as a reference to calculate the relative reflectance of individual fruit.

FIRMNESS AND SUGAR CONTENT MEASUREMENTS

Although numerous techniques have been reported for measuring the firmness of cherries, a standard technique has not been established. After reviewing various techniques mentioned earlier, we decided to use a 6–mm diameter Magness–Taylor probe to measure the cherry firmness. The probe was attached to a TA.TX2 Texture Analyzer (Texture Technologies Inc., Scarsdale, N.Y.), and the speed of the loading head was set at 0.5 mm/s. The fruit was placed with the suture side down in a wooden indenter. Firmness measurements were taken from the same location where NIR measurements had been taken. The force–deformation data were collected from each fruit that was compressed to 3 mm deformation and then unloaded.

Figure 1 shows a typical force–deformation relation of sweet cherries during loading and unloading. The initial portion of the force–deformation curve in loading was highly linear, but the overall trend was nonlinear. There was considerable energy loss during the loading and unloading cycle, as indicated by the area encompassed by the loading and unloading curves. This is because sweet cherries, like many other fruits, exhibited a highly viscoelastic or inelastic behavior. In this study, three quantities were extracted from the force–deformation curve of each fruit. They are the slope of the curve from the origin to 2 mm deformation (point A in fig. 1), peak force at 3 mm deformation (Point B in fig. 1), and the area encircled by the loading and unloading curves.

DATA ANALYSES AND MODEL DEVELOPMENT

The NIR spectral data were analyzed using a commercial software package, GRAMS/32, with an add–on application tool, PLSplus/IQ (Galactic Industries Corp., Salem, N.H.). First, the relative reflectance of each cherry was calculated as the ratio of the difference in the absolute reflectance between the sample and the dark (no light) to that between the spectra.
standard reference material and the dark. This relative reflectance (R) was then expressed as log(1/R). Each spectral curve was smoothed using the Savitzky–Golay method with a gap of 11 data points (or 22 nm). This gap was chosen after trial of several different gap sizes and was found to be adequate.

Two standard data preprocessing methods, multiplicative scatter correction (MSC) and area normalization, were tried to remove the variations in spectra caused by unknown sources that tend to increase errors in the calibration models. The MSC method is mainly used for removing the effects of light scattering on spectra. The normalization method, on the other hand, is often used to correct the spectra for indeterminate pathlength when it cannot be measured. It was found that the normalization method gave slightly better prediction results and led to fewer factors in the statistical models. Therefore, only the results from the normalization method are reported in this article.

After completing the above preprocessing procedures, the partial least squares type I (PLS–I) method was used to develop calibration models for predicting the firmness and sugar content for the two cherry varieties. The calibration models were developed using one half of the measured cherries from each variety, and the remaining half was used to validate the models.

RESULTS AND DISCUSSION

Table 1 summarizes the means and standard deviations (SD) of four measured quantities (maximum force, slope, area, and Brix reading) for both Hedelfinger and Sam sweet cherries. On average, Hedelfinger cherries were firmer than Sam, as measured by the average maximum force (4.8 N vs. 3.4 N) and the slope of the force–deformation curves (1.5 N/mm vs. 1.2 N/mm). Hedelfinger cherries had greater variations in the sugar content than Sam (SD = 2.3° vs. 1.4°), although the average values for the two varieties were not statistically different. Table 2 is a summary of the correlation coefficients among the three firmness indexes and sugar content for the two cherry varieties. The three firmness indexes (force, slope, and area) were highly correlated with each other, with the correlation coefficients equal to, or greater than, 0.95 for Hedelfinger and between 0.87 and 0.96 for Sam. Because of the high intercorrelations among the three firmness indexes, further discussion of the results will focus on the maximum force. Table 2 also shows that the sugar content of sweet cherries was negatively correlated to the firmness indexes for both varieties, but the correlations were low, ranging between ∼0.23 and ∼0.28 for Hedelfinger and between ∼0.22 and ∼0.25 for Sam.

**Table 1. Summary of the means and standard deviations of three firmness indexes (force, slope, and area) and Brix readings for sweet cherries.[a]**

<table>
<thead>
<tr>
<th>Variety</th>
<th>Force (N)</th>
<th>Slope (N/mm)</th>
<th>Area (N-mm)</th>
<th>Brix (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hedelfinger (n = 374)</td>
<td>4.8 (1.3)</td>
<td>1.5 (0.4)</td>
<td>4.0 (1.1)</td>
<td>14.7 (2.3)</td>
</tr>
<tr>
<td>Sam (n = 350)</td>
<td>3.4 (1.4)</td>
<td>1.2 (0.2)</td>
<td>3.7 (0.6)</td>
<td>15.0 (1.4)</td>
</tr>
</tbody>
</table>

[a] The values in parentheses are the standard deviations.

**Table 2. Correlations among the measured firmness indexes and sugar content of sweet cherries.[a]**

<table>
<thead>
<tr>
<th></th>
<th>Force</th>
<th>Slope</th>
<th>Area</th>
<th>Brix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hedelfinger</td>
<td>1.00</td>
<td>0.99</td>
<td>0.95</td>
<td>−0.22</td>
</tr>
<tr>
<td>Sam</td>
<td>0.95</td>
<td>1.00</td>
<td>0.98</td>
<td>−0.24</td>
</tr>
<tr>
<td></td>
<td>0.87</td>
<td>0.96</td>
<td>1.00</td>
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</tr>
<tr>
<td></td>
<td>−0.22</td>
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<td>−0.25</td>
<td>1.00</td>
</tr>
</tbody>
</table>

[a] The italic numbers in the upper right triangle are for Hedelfinger, and the bold numbers in the lower left triangle are for Sam.

FIRMNESS PREDICTIONS

Figure 2 shows the average absorption spectral curves for three firmness classes (low, medium, and high) of Hedelfinger sweet cherries. Each class of cherries was determined based on the maximum force measured with the Texture Analyzer. The fruit were considered low if the maximum force was less than 3.5 N, medium between 3.5 N and 6.0 N, and high if the force was greater than 6.0 N. This firmness classification is solely for gaining some qualitative understanding about the light absorption of sweet cherries as affected by fruit firmness, and it should not be considered a standard practice.

The absorption curves of sweet cherries were rather smooth across the entire spectral region and had three broadband peaks around 994 nm, 1186 nm, and 1462 nm (fig. 2). These absorption peaks are rather close to the three absorption wavelengths of pure water (958 nm, 1153 nm, and 1460 nm) and, therefore, are related to the water in the cherry fruit. The overall pattern of the absorption curves for sweet cherries is similar to that for apples (Lu et al., 2000), but the former have higher absorption than the latter. As shown in fig. 2, the absorption of light decreased with fruit firmness. The firm fruit reflected more light (or absorbed less light) than softer fruit. The “low” firmness class of fruit had the highest average absorption, and the “high” class had the lowest average absorption across the entire spectral region between 800 nm and 1700 nm. Each spectral curve did not cross over the other curves (fig. 2). The same pattern of light absorption with fruit firmness was also observed for Sam cherries.

Figure 3 shows the calibration and prediction results of firmness from the PLS models for Hedelfinger and Sam cherries. The correlation of calibration between NIR measurements and the maximum force for Hedelfinger was as high as 0.89, with the standard error of calibration (SEC) of 0.53 N. When the model was used to predict the other half of the data, prediction results were also good (r = 0.80 and SEP = 0.79 N). The PLS model appeared to be robust since only five factors were used in the calibration model. Similar results were obtained when NIR spectral data were used to predict the slope and area of the force–deformation curves.

For Sam cherry fruit, the calibration model for firmness had only four factors. The correlations of calibration and prediction between NIR spectral data and the maximum force were 0.75 and 0.65, respectively, which are lower than those for Hedelfinger. The SEC and SEP for Sam were 0.39 N and 0.44 N, respectively, which are better than those for Hedelfinger. If the coefficient of variance (CV) was used as a measure of calibration and prediction errors, then the differences between the two varieties were small. These

**Table 2. Correlations among the measured firmness indexes and sugar content of sweet cherries.[a]**

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[a] The italic numbers in the upper right triangle are for Hedelfinger, and the bold numbers in the lower left triangle are for Sam.
results indicate that NIR diffuse reflectance can be used to predict the firmness of cherry fruit with reasonable accuracy.

**SUGAR CONTENT PREDICTIONS**

Figure 4 shows three average absorption spectral curves for Hedelfinger cherries grouped into three classes based on their Brix readings. A cherry was considered “low” if its Brix reading was less than 12°, “medium” between 12° and 17°, and “high” greater than 17°. Again, the grouping method was solely for helping us in gaining some qualitative understanding of the overall trend of the light absorption in fruit as affected by its sugar content. A consistent pattern of the light absorption in fruit with respect to sugar content is observed from fig. 4. The average light absorption in fruit increased with its sugar content; the “high” class of Hedelfinger cherries had the highest average absorption of light and the “low” class had the lowest absorption for the spectral regions between 800 nm and 1400 nm. The absorption spectrum for the “low” class crossed over the spectrum for “medium” class between 1400 nm and 1700 nm, and the difference between the three classes was smaller in the
Figure 4. Average absorption spectra of Hedelfinger sweet cherries for three sugar content levels: low (Brix < 12.0°B), medium (12°B < Brix < 17°B), and high (Brix > 17°B). There were 61 fruit for the low class, 250 fruit for medium, and 63 fruit for high.

vicinity of 1460 nm than in the rest spectral region. This could be because the absorption of light by the water in fruit at
around 1460 nm was so predominant that it greatly diminished the absorption of light by the sugar. The same pattern of light absorption was also observed in Sam cherries.

The calibration models gave excellent fits to the Brix data for both Hedelfinger and Sam sweet cherries (fig. 5). The correlation for the calibration model for Hedelfinger cherry fruit was 0.97 and the SEC was 0.52° Brix. When the model was used to predict the sugar content of the prediction data set for Hedelfinger cherries, the prediction errors increased slightly, with r = 0.95 and SEP = 0.71° Brix. For Sam, the correlation of prediction was 0.89 and the SEP was 0.65° Brix. These results indicate that the sugar content of sweet cherries can be accurately predicted using NIR reflectance spectroscopy.

CORRELATION SPECTRA

In the above discussion of the prediction results from the PLS models, no consideration was given to the contributions of individual wavelengths to the prediction results. This is because the PLS method first applies linear transform to the entire spectral data. As a result, it is often difficult to ascertain how individual wavelengths are directly related to the quantities to be predicted. However, it would be helpful to examine

Figure 5. NIR calibration and prediction results from the partial least square models for the sugar content of (a) Hedelfinger and (b) Sam sweet cherries.
how firmness and sugar content are simply related to individual wavelengths so that a better understanding of NIR diffuse reflectance may be obtained. Figure 6 shows the simple correlation spectrum of Magness–Taylor maximum force for Hedelfinger cherry fruit. The firmness of Hedelfinger cherries was negatively correlated with the absorption of light across the entire spectral region, which is consistent with the findings presented in figure 2. The correlation remained nearly constant at ~0.50 between 800 nm and 1400 nm, which was much lower than the one for the calibration model (r = 0.89, fig. 3). The absolute correlation decreased dramatically above 1400 nm and reached the minimum of ~0.25 around 1460 nm, which corresponded to the water absorption band. This is also true for the correlation spectrum between the sugar content and light absorption by cherry fruit across the entire spectral region (see further discussion at fig. 7).

As discussed earlier, the low correlation around 1460 nm could be due to the fact that water absorption in cherry fruit had such a dominant effect on light absorption that the effect of sugar and firmness was diminished greatly. These results indicate the difficulty of selecting one or a few wavelengths for accurate prediction of the firmness of sweet cherries and the necessity to use a wider spectrum or even an entire spectrum for firmness prediction. This was further justified when several narrower spectral regions were used to develop the calibration models; the prediction results were not as good as those using the entire spectral region (results are not presented here). A similar pattern of correlations between firmness and light absorption was found for Sam cherry fruit, but the correlations were consistently lower across the entire spectrum.

Figure 7 shows the correlation relation between the sugar content and wavelength for Hedelfinger cherry fruit across the entire spectral region between 800 nm and 1700 nm. Unlike that for firmness, the sugar content was positively correlated with light absorption for the entire spectrum, which confirms an early observation that cherries with high sugar content absorbed more light than those with lower sugar content. The correlations were relatively constant, ranging between 0.50 and 0.60 for the spectral region from 800 nm to 1300 nm. Once again, the minimum correlation occurred around 1460 nm. The fact that no single wavelengths were strongly correlated with firmness or sugar content suggests the necessity to use a wider range of spectrum than selected wavelengths to predict either firmness or sugar content of sweet cherries.

CONCLUSIONS

The results of this study showed that there were relatively good correlations of prediction between NIR measurements and firmness for the two varieties of sweet cherries, with a correlation of 0.80 and standard error of prediction (SEP) of 0.55 N for Hedelfinger, and r = 0.65 and SEP = 0.44 N for Sam. The NIR model based on the partial least square method gave good predictions of the sugar content of cherries (r = 0.97 and SEP = 0.71° Brix for Hedelfinger, and r = 0.89 and SEP = 0.65° Brix for Sam). These results are very encouraging and indicate that NIR diffuse reflectance between 800 nm and 1700 nm can be used to predict the firmness and sugar content of sweet cherries with reasonable accuracy. This study also showed that no single wavelengths were strongly correlated with the firmness and sugar content of sweet cherries, which indicates the difficulty of using selected wavelengths or bands to accurately predict the firmness and sugar content of cherries.

Further research is needed to study different sensing techniques and/or light delivery methods to improve firmness predictions. Studies should also be conducted to investigate the effect of such factors as crop growth condition, location, and season on predictions of the firmness and sugar content of sweet cherries.

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REFERENCES


