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Apple mealiness detection using hyperspectral scattering technique☆

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ABSTRACT

Mealiness is a symptom of fruit physiological disorder, which is characterized by abnormal softness and lack of free juice in the fruit. This research investigated the potential of hyperspectral scattering technique for detecting mealy apples. Spectral scattering profiles between 600 and 1000 nm were acquired, using a hyperspectral imaging system, for 'Red Delicious' apples that either had been kept in refrigerated air at 4 °C or undergone mealiness treatment at 20 °C and 95% relative humidity for various time periods of 0–5 weeks. The spectral scattering profiles at individual wavelengths were quantified by relative mean reflectance for 10 mm scattering distance for the test apples. The mealiness of the apples was determined by the hardness and juiciness measurements from destructive confined compression tests. Prediction models for hardness and juiciness were developed using partial least squares regression (PLS); they had low correlation with the destructive measurement ($r \leq 0.76$ for hardness and $r \leq 0.54$ for juiciness). Moreover, PLS discriminant models were built for two-class ('mealy' and 'nonmealy'), three-class ('mealy', 'semi-mealy' and 'fresh') and four-class ('mealy', 'soft', 'dry', and 'fresh') classification. The overall classification accuracies for the two classes of 'nonmealy' and 'mealy' apples were between 74.6% and 86.7%, while the overall accuracies in the three-class classification ranged between 60.2% and 71.2%. Much better results (≥93% accuracy) were achieved for the two-class classification of 'mealy' apples that had undergone longer time of mealiness treatment (i.e., 4–5 weeks of storage at 20 °C and 95% relative humidity). Hyperspectral scattering technique is potentially useful for nondestructive detection of apple mealiness; however, improvements in classification accuracy are needed.

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1. Introduction

Mealiness in apples is characterized by the sensation of a deteriorative texture and lack of juiciness. It results from pectin degradation in the middle lamellae (Gross and Sams, 1984; Von Mollendorf et al., 1993). Mealiness degrades the quality of apples and reduces their commercial value. Apple mealiness is influenced by such factors as harvest date, fruit size, long-term storage and storage conditions including air composition, temperature and relative humidity (Fisher, 1943; Barreiro et al., 2000; Harker and Hallett, 1992; Von Mollendorf et al., 1992; De Smedt, 2000). Mealy apples can be induced using room temperature (20 °C) and high relative humidity (95%) (Barreiro et al., 1998).

Mealiness in apples can be assessed by sensory panels with sensorial descriptors (Harker et al., 2002; Bignami et al., 2003). However, the sensory panel method is subjective and time consuming, and it is only suitable for testing a small number of fruit. Instrumental methods for apple mealiness measurement are thus preferred because they tend to be more objective and efficient and because they correlate reasonably well with sensory evaluation (Harker et al., 1997; Barreiro et al., 1998; De Smedt, 2000). Barreiro et al. (1998) established a new instrumental mealiness scale based on the combination of instrumental parameters like loss of crispness, hardness and juiciness, which was related to the mealiness perceived by sensory panelists. De Smedt et al. (2002) developed a mathematical model relating the textural attributes of apples (i.e., juiciness, tensile strength and hardness) to the cell turgor and middle lamella.

A number of nondestructive methods for mealiness detection have been investigated and evaluated against destructive instrumental measurement for apple, peach, and tomato. They include magnetic resonance imaging (Barreiro et al., 1999), acoustic impulse response (De Smedt, 2000), nuclear magnetic resonance (Barreiro et al., 2002), impact (Arana et al., 2004), near-infrared spectroscopy (Ortiz et al., 2001), ultrasonic (Bechar et al., 2005) and time-resolved reflectance spectroscopy (Valero et al., 2005). Despite all these efforts, a nondestructive technique that is rapid, noninvasive, and suitable for online sorting and grading still needs to be developed (Valero et al., 2005).

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Optical techniques hold great promise for mealiness detection and classification because they usually are rapid and nondestructive or noninvasive and, more importantly, they can provide a large amount of information about the condition or status of a sample. When a light beam impinges upon a fruit, most of the light will enter the fruit tissue — some of the light will be absorbed, some will scatter back from the region close to the beam incident point, and some may pass the entire fruit and reemerge from the opposite side. Chemical constituents in the fruit tissue, like chlorophylls, soluble solids and water, directly influence light absorption, while fruit density and tissue structures including cells, middle lamella, and extracellular matrices are known to affect the scattering properties (Birth, 1986). Hence, spectral absorption and scattering properties could be useful for determining the mealiness of apples. Hyperspectral scattering is a promising technique that acquires spatially resolved diffuse reflectance from a sample at contiguous wavelengths over a spectral range (Lu, 2007; Qin and Lu, 2008). The technique can provide better quantification of scattering properties about the fruit, compared to conventional near-infrared spectroscopy. Moreover, the technique is simpler, faster and relatively easier to measure the optical properties, compared to other emerging optical techniques such as time-resolved, frequency-domain, and spatial frequency-domain (Cubeddu et al., 2001; Anderson et al., 2007). Hyperspectral scattering technique has been applied for evaluation of internal quality of fruit including the soluble solids content and firmness of apples and peaches (Lu, 2003, 2007; Lu and Peng, 2006; Peng and Lu, 2008). Since mealiness results from changes in the structural and physiological properties of apples, hyperspectral scattering could potentially be useful for detecting or differentiating mealy apples.

Therefore, the overall objective of this research was to use hyperspectral scattering technique for detecting apple mealiness. The specific objectives were to:

- acquire hyperspectral scattering images from apples that either had been kept in refrigerated air or undergone mealiness treatment (i.e., high temperature/relative humidity), over the spectral region between 600 and 1000 nm;
- establish quantitative prediction models relating the hyperspectral scattering features to apple flesh hardness and juiciness measured by confined compression; and
- develop and validate discriminant models for apple mealiness classification.

2. Materials and methods

2.1. Fruit samples

Five hundred and eighty 'Red Delicious' apples obtained from two different sources were used in the experiment. One hundred eighty apples were harvested from the orchard of Michigan State University (MSU) Horticultural Teaching and Research Center in Holt, Michigan, USA during the 2008 harvest season, and these apples were kept in controlled atmosphere storage (2% O_2 and 3% CO_2 at 0 °C) for about four months prior to the experiment. The remaining 400 apples were obtained from a commercial packinghouse in Sparta, Michigan. The apples were separated into two groups: the first group of 240 apples (180 from the commercial packinghouse and 60 from the MSU orchard) was kept in a cold room at 4 °C, and the second group of 340 fruits (220 from the commercial packinghouse and 120 from the MSU orchard) was kept at 95% relative humidity and 20 °C to accelerate the development of mealiness (Barreiro et al., 1999). Apples that were kept at the high humidity condition were expected to develop various degrees of mealiness at various times during the course of storage, while

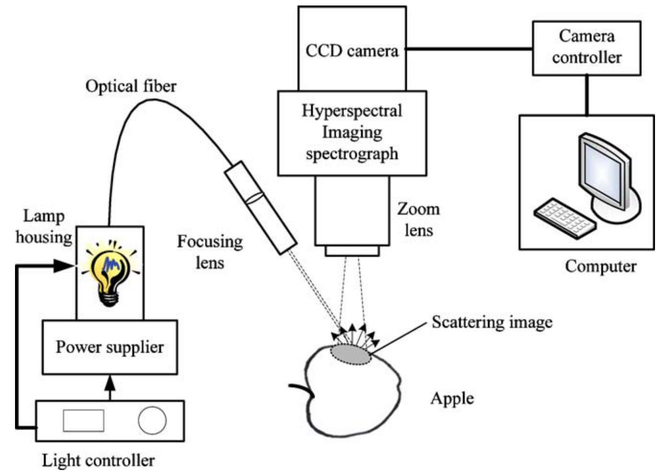

Fig. 1. Schematic of the hyperspectral imaging system for acquiring scattering images from apples.

mealiness was not expected for those apples stored at 4 °C. However, not all fruits in the second group would become mealy after they had undergone the mealiness treatment. Hence there were more fruits for the second group than for the first group.

The mealiness of apples was determined by destructive confined compression tests (see details in Section 2.3). For the first group (cold storage), 60 samples each for 0, 2, 3, and 4 weeks of storage were tested, while 85 samples from the second group (high temperature/high humidity storage) were used for 2, 3, 4, and 5 weeks. For each test, the samples were kept at room temperature (~24 °C) for at least 15 h before the experiment was started. The equatorial diameter of each sample was measured by a digital caliper in two perpendicular directions and then averaged; this information was later used for correcting the spectral scattering profiles. The averaged sample diameter ranged between 60.7 mm and 89.0 mm.

2.2. Hyperspectral scattering images acquisition

An in-house developed line-scan hyperspectral imaging system was used to acquire hyperspectral scattering images from 'Red Delicious' apples (Fig. 1). This system mainly consisted of a hyperspectral imaging unit, a DC regulated light source and a sample handling unit. The hyperspectral imaging unit was made up of a back-illuminated 512 × 512-pixel CCD (charge-coupled device) camera (Model C4880-21-24A, Hamamatsu Photonics Systems, Bridgewater, NJ, USA), an imaging spectrograph (ImSpector V10, Spectral Imaging Ltd., Oulu, Finland) covering an effective range of 400–1000 nm connected with a zoom lens, and a computer for controlling the camera and acquiring images. The DC light source was composed of a 250-W quartz tungsten halogen lamp housing (Oriel Instruments, Stratford, CT, USA) with a feedback controller (Spectra-Physics, Mountain View, CA, USA), and a single optic fiber coupled with a microlens for delivering a circular beam of 1.0 mm diameter to the sample with the divergence angle less than 15°. The sample handling unit consisted of one vertical motorized stage, one horizontal motorized stage and a through-beam photoelectric sensor. Each test fruit was placed onto the sample cup; the fruit was such oriented that its stem-calyx axis was kept horizontal and also perpendicular to the scanning line of the hyperspectral imaging unit. The two motorized stages automatically moved the fruit to the pre-determined initial position. The vertical stage was used to position the sample at the pre-determined height, so that the distance between the camera and the light spot on the fruit would be kept constant. The horizontal stage then started to move horizontally in synchronization with the camera's acquisition of hyperspectral

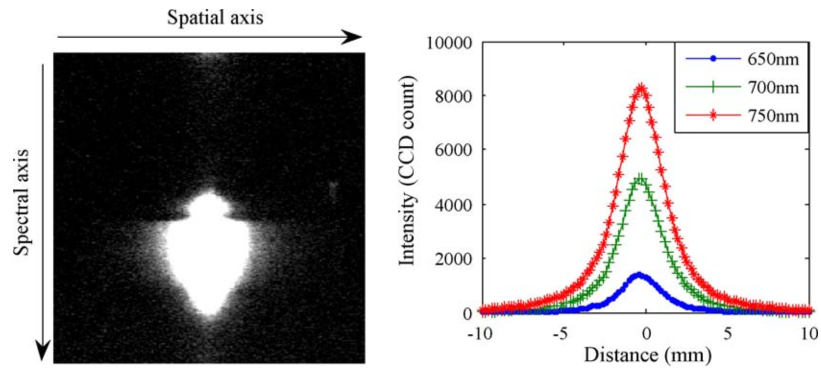

Fig. 2. Hyperspectral scattering image of an apple (left), and raw spatial scattering profiles at three wavelengths (right).

scattering images from the fruit. The system was calibrated both spectrally and spatially by following the procedures described in Qin and Lu (2007).

For each test fruit, 10 scans covering 9 mm distance were acquired on the equator of the fruit at an exposure time of 200 ms for each scanning image. These scanning images were then averaged to obtain the mean image for each fruit. Only the mean images were saved for future analysis. After 2×2 binning operations, the resultant hyperspectral scattering images had 4.54 nm spectral resolution per pixel and 0.20 mm spatial resolution per pixel. For correcting the light source effect, reference scattering images were also acquired from a white Teflon disk for every 10 apples.

A typical raw hyperspectral scattering image is shown in Fig. 2 (left), where the horizontal axis represents a spatial dimension and the vertical axis shows the spectral dimension. Each scattering image in effect consisted of more than 100 spatial scattering profiles, each representing a specific wavelength. The region of interest covering the spectral region of 600–1000 nm and the total spatial distance of 20 mm was selected from each image for further processing and analysis.

2.3. Destructive instrumental tests

After the acquisition of hyperspectral scattering images, confined compression tests were performed, using a specially built fixture with a Texture Analyzer (model TA.XT2i, Stable Micro Systems, Inc., Surrey, UK), for measuring the hardness and juiciness of the apples to determine fruit mealiness. Cylindrical fruit specimens of 16 mm in length and 18 mm in diameter were excised from the outer part of the fruit in the radial direction from the same area where the hyperspectral scattering images had been taken. The specimens were placed into the hole of a stainless steel block of 25 mm height and of the same diameter as the fruit specimens. The probe used for compression test was 17 mm in diameter, one mm smaller than the diameter of the hole, to avoid any contacts between the probe and the sample holding block during the compression test. The maximum deformation of 3 mm was applied to the specimens at 20 mm/min deformation rate. After the probe reached the maximum deformation, it returned immediately at the same speed in the opposite direction (Barreiro et al., 1998; De Smedt, 2000). Hardness, expressed in KN/m, was determined by the slope between 1/3 and 2/3 of the maximum force of the force–deformation curve measured during compression (Moshou et al., 2003).

For measuring the juiciness, a filter paper (Whatman Grade No. 5 (1005-090)) was placed beneath the sample holding block to recover the juice extracted during the compression test. The juiciness level was determined by measuring the juice-soaked area (in cm^2) on the filter paper using a monochromatic imager (Hitachi, Tokyo, Japan) (Barreiro et al., 1998).

The instrumental measurements of hardness (‘*S*’) and juiciness (‘*J*’) were used for determining the mealiness of the test apples. A fruit was considered ‘hard’ when the *S* value was equal to or greater than 40 KN/m, or ‘not hard’ when *S* was less than 40 KN/m. Likewise, a fruit would be considered ‘juicy’ when the *J* value was equal to or greater than 5.0 cm^2, or ‘not juicy’ when *J* was less than 5.0 cm^2. An apple sample was considered mealy when it was graded ‘not hard’ and ‘not juicy’ simultaneously. The threshold values for *S* and *J* were selected according to Barreiro et al. (1998) and in view of the specific testing configurations used in the experiment.

2.4. Data analysis

Different methods may be used to characterize the scattering profiles (Fig. 2); they include the fundamental method of calculating the absorption and scattering coefficients (Qin and Lu, 2008), empirical models like the modified Lorentzian functions (Peng and Lu, 2008), and a simple method of calculating mean reflectance (Lu, 2007). In this study, the method of calculating mean reflectance for each scattering profile for a distance of 10 mm was used (Lu, 2007) because it is much simpler and faster. In addition, mean reflectance also provides good characterization of the scattering profiles because they can be well described by Gaussian or Lorentzian type functions. Mean reflectance, $\bar{R}_S$, for the apple samples was calculated for each wavelength. It was then corrected by the mean reflectance $\bar{R}_T$ obtained from the white Teflon disk using the following equation:

$$\bar{R} = \frac{\bar{R}_S}{\bar{R}_T} \quad \text{for} \quad 0 \le x \le 10\,\text{mm} \tag{1}$$

Prior to the mean calculations, each scattering profile was corrected for nonuniform instrument response and fruit size by following the procedures described in Qin and Lu (2008).

Partial least squares (PLS) regression was applied to predict the hardness and juiciness using the relative mean reflectance spectra. The samples were arranged in descending order for the hardness (or juiciness). The first sample was selected for validation, and the second and third samples were selected for calibration. The procedure was repeated for the rest of the samples, resulting in 67% apples for the calibration set and 33% apples for the validation set. The PLS models for hardness and juiciness were built for the calibration samples using leave-one-out cross validation. The number of factors chosen for the PLS models was determined based on the root mean square error of cross validation (RMSECV). Thereafter, the prediction models were evaluated by the validation samples, in terms of the correlation coefficient and standard error between predicted and the measured variables (i.e., hardness and juiciness).

Furthermore, partial least squares discriminant analysis (PLS-DA) was performed on the relative mean reflectance spectra for mealiness classification based on the categorical instrumental

Table 1
Classification of apple mealiness according to the destructive instrumental measurements of hardness and juiciness.

	Two classes		Four classes	
	Juicy ($\geq$5 cm^2)	Not juicy (<5 cm^2)	Juicy ($\geq$5 cm^2)	Not juicy (<5 cm^2)
Hard ($\geq$40 KN/m)	Nonmealy	Nonmealy	Fresh	Dry
Not hard (<40 KN/m)	Nonmealy	Mealy	Soft	Mealy

mealiness scale. PLS-DA is an inverse-least-squares approach to linear discrimination analysis (LDA), and it produces essentially the same results with the LDA but with the noise reduction and variable selection advantages of PLS (Barker and Rayens, 2003). The selection process for calibration and validation samples for classification was the same as the one described earlier for the quantitative prediction model development. Similarly, the classification errors for cross validation (leave-one-out) were used to determine the most suitable number of factors for the PLS-DA models. In this procedure, the calculated threshold was estimated using Bayes' theorem and the available data to minimize total errors.

The PLS and PLS-DA were run in Matlab (R2007b) with PLS Toolbox 5.0 (Eigenvector Research, Inc., Wenatchee, WA, USA).

Several sample groupings for the apples of two origins were used in performing the mealiness classification. Classification models were first established for each group of samples (i.e., commercial packinghouse or CP and MSU), and then for the pooled data of the two groups. In addition, classification models were also developed using the samples from the first two tests (i.e., 0 and 2 weeks) of the first group and the last two tests (i.e., 4 and 5 weeks) of the second group. This sample grouping was used for mealiness classification because the two groups of samples had gone through different storage treatments in terms of both time and storage condition (i.e., temperature and humidity) and more severe mealiness would have been developed in those apples under longer time of high humidity treatment. The selected samples included 200 samples from CP and 90 samples from MSU.

Three schemes were used in performing apple classifications according to the method shown in Table 1 (or Fig. 3). In the first scheme, the samples were classified into two classes, i.e., 'nonmealy' and 'mealy'. A sample was assigned to the 'mealy' class when it was rated both not 'hard' and not 'juicy' at the same time; otherwise, the sample would be rated as 'nonmealy'. In the four-class classification scheme, the samples were classified into 'fresh' ('hard' and 'juicy'), 'mealy' ('not hard' and 'not juicy'), 'soft' ('not hard' and 'juicy'), or 'dry' ('hard' and 'not juicy'). Three-class classification was also performed; those samples that had been rated either 'soft' or 'dry' were considered as 'semi-mealy' because only a few samples fell into these two classes in the four-class classification. The ratings of 'hard' and 'juicy' were based on destructive instrumental measurements, as described in Section 2.3.

3. 3 Results and discussion

3.1. Destructive instrumental measurements

The fruits kept in cold storage (4 °C) had the mean value of 65.90 N/mm for hardness and 5.98 cm^2 for juiciness; their standard deviation (SD) was 9.66 KN/m for hardness and 1.36 cm^2 for juiciness. For the fruits stored at 20 °C and 95% relative humidity, they had the mean value of 36.2 KN/m for hardness and 4.21 cm^2 for juiciness; the standard deviation (SD) was 8.26 KN/m for hardness and 1.10 cm^2 for juiciness.

Fig. 3 shows the mealiness classification of the apple samples for the two storage treatments, based on the instrumental measurements for hardness and juiciness. For the cold storage group (or group 1), 98% of the apples were greater than 40 KN/m in hardness and 75% apples had a juiciness value of greater than 5 cm^2. For the apples stored at room temperature (group 2), 70% of the samples had firmness values below 40 KN/m and 80% of the samples had a juiciness reading lower than 5 cm^2. These results indicate that only less than 2% apples stored in cold storage had developed mealiness, while more than 60% apples stored at room temperature had developed mealiness.

3.2. Characterization of spectral scattering profiles

Fig. 4 shows relative mean reflectance spectra for 10 'nonmealy' apples and 10 'mealy' apples. Values of the relative reflectance spectra for 'nonmealy' apples were greater than those for 'mealy' apples.

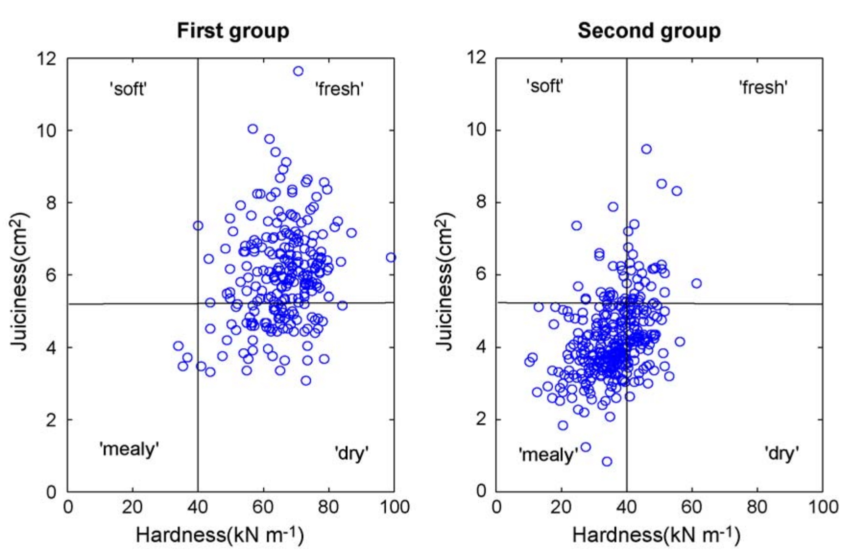

Fig. 3. Classification of apple samples based on the destructive confined compression tests. Apples for the first group were kept in cold storage at 4 °C and those in the second group were kept at room temperature (20 °C) with 95% relative humidity.

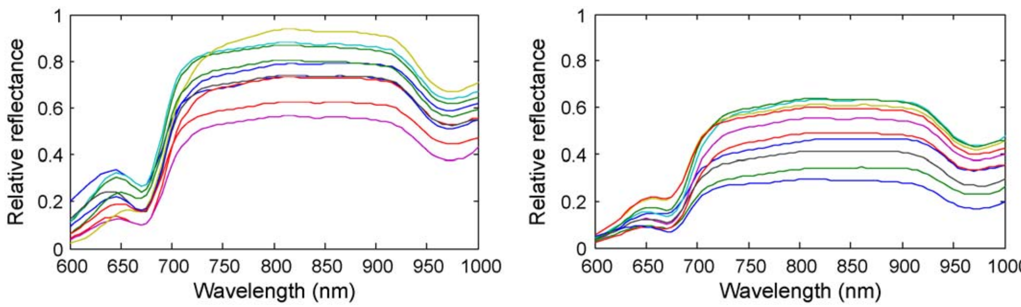

Fig. 4. Relative mean reflectance for 10 'nonmealy' apples (left) and 10 'mealy' apples (right).

Table 2
Partial least squares (PLS) prediction of fruit hardness and juiciness for the validation set of 'Red Delicious' apples.

Output	Sample origin[a]	Factors	Calibration		Validation	
			r	SEC[b]	r	SEP[b]
Hardness	CP	16	0.778	10.59	0.741	11.53
	MSU	5	0.794	9.56	0.761	10.67
	Pooled	14	0.773	10.86	0.689	12.61
Juiciness	CP	10	0.696	1.06	0.512	1.34
	MSU	2	0.581	1.21	0.539	1.29
	Pooled	7	0.588	1.20	0.524	1.31

[a] CP = commercial packinghouse, MSU = Michigan State University's experimental orchard in Holt, MI.
[b] SEC = standard error for calibration, SEP = standard error for validation.

Large variations in the spectra in the visible range of 600–730 nm were observed. A distinctive downward peak was observed around 675 nm due to chlorophyll absorption. Over the spectral region of 730–920 nm, reflectance was relatively flat. Around 970 nm, another downward peak was observed due to water absorption. While the mean relative reflectance spectra are somewhat similar in pattern to conventional visible/near-infrared reflectance spectra, their specific features and underlining interpretation are quite different because of the different lighting/detecting configurations used for acquiring the optical signal. The mean relative reflectance spectra calculated from the spectral scattering images (Fig. 2) carry spatial scattering information, whereas the same cannot be said of visible/near-infrared reflectance spectra.

3.3. Prediction models for apple hardness and juiciness

Table 2 summarizes the calibration and validation results for hardness and juiciness prediction for the three groups of samples, i.e., commercial packinghouse (CP,) MSU, and their pooled data. The models had better prediction results for hardness, with the r values for validation being equal to 0.741 and 0.761 for the CP and MSU groups, respectively. The hardness prediction model had a lower r value (=0.689) for the pooled data. The predictions for juiciness were much poorer ($r < 0.6$ and SEP > 1.2 cm^2) compared to the hardness prediction results. This may be due to the fact that juiciness is not directly related to water content; instead it relates to how easily juice is liberated during compression. These results indicate the difficulty of accurate prediction of apple hardness and juiciness. However, the results obtained from this study compare favorably with those ($r < 0.4$) reported by Valero et al. (2005) when time-resolved technique was used, which could have been attributed to the differences in measurement method and sample preparation used in the two studies. The models for MSU fruit contained fewer factors (5 and 2 for 'Hardness' and 'Juiciness' prediction, respectively) compared to the modes for CP fruit (16 and 10 factors, respectively). This could be because MSU fruit were more homogeneous after the storage treatment while the commercial fruit were more variable. The large differences in the number of factors for

Table 3
Two-class classification results for the validation sets of 'Red Delicious' apples from two origins for all test dates.[a]

Sample origin[b]	Instrumental classification	Model classification		Classification accuracy, %
		Mealy	Nonmealy	
CP	Mealy	33	7	82.5
	Nonmealy	24	68	73.9
	Overall	57	75	76.5
MSU	Mealy	22	6	78.6
	Nonmealy	9	22	71.0
	Overall	31	28	74.6
Pooled	Mealy	56	11	83.6
	Nonmealy	36	87	70.7
	Overall	92	98	75.3

[a] Rows: classified by compression measurements. Columns: predicted by hyperspectral scattering technique.
[b] CP = commercial packinghouse; MSU = Michigan State University's experimental orchard in Holt, MI.

Table 4
Two-class classification results for the selected validation sets of 'Red Delicious' apples of two origins from the first two test dates (weeks 0 and 2) of cold storage (4 °C) and the last two test dates (weeks 4 and 5) of storage at 20 °C and 95% relative humidity.[a]

Sample origin[b]	Instrumental classification	Model classification		Classification accuracy, %
		Mealy	Nonmealy	
CP	Mealy	25	1	96.2
	Nonmealy	8	32	80.0
	Overall	33	33	86.4
MSU	Mealy	16	0	100.0
	Nonmealy	4	10	71.4
	Overall	20	10	86.7
Pooled	Mealy	39	3	92.9
	Nonmealy	11	43	79.6
	Overall	50	46	85.4

[a] Rows: classified by compression measurement. Columns: predicted by hyperspectral scattering technique.
[b] CP = commercial packinghouse; MSU = Michigan State University's experimental orchard in Holt, MI.

each set of fruit also demonstrated that the models were not robust and accurate enough to predict fruit hardness and juiciness.

3.4. Discriminant models for two-class mealiness classification

Table 3 shows the two-class ('mealy' and 'nonmealy') classification results for each group of validation samples (i.e., CP and MSU) and their combined data for all test dates. The model achieved 75.3% classification accuracy for the calibration set of CP samples, while 76.5% of the validation samples were correctly classified. A higher misclassification rate (26.1%) for the 'nonmealy' class was obtained compared with 17.5% misclassification rate for the 'mealy' class. The overall classification results for the MSU samples were similar to those for the CP samples; the percentage of correctly classified samples was 84.4% for calibration and 74.6% for validation. Again more nonmealy samples were incorrectly classified as 'mealy' (29.0%) versus 21.4% misclassification rate for mealy samples. When the samples from the two groups were pooled, the classification accuracy was 83.6% for mealy apples and 70.7% for nonmealy apples. In summary, for all three sample groups, better classification was achieved for the 'mealy' class than for the 'nonmealy' class and the overall classification results for the pooled data fell between the results for each individual group.

Table 4 further shows two-class classification results for the three groups of validation samples that came from the first two test dates (weeks 0 and 2) of cold storage and the last two dates (weeks 4 and 5) of high temperature/humidity storage. Compared with the validation results in Table 3, significant improvements in the overall classification accuracies were achieved for these selected groups of samples; an increase of 9.9 percentage points in classification accuracy was achieved for the CP samples, 12.1 percentage points for the MSU samples and 10.1 percentage points for the pooled samples. Significantly higher classification accuracies were achieved for the 'mealy' class, ranging between 92.9% and 100% for the three groups. Better classification results for the selected groups of samples indicate that the technique can be effective in discriminating more severe mealy apples.

3.5. Discriminant models for three-class and four-class mealiness classification

Table 5 shows the results for classifying apples into three classes (i.e., 'mealy', 'semi-mealy' and 'fresh'). As expected, the three-class classification accuracies declined compared with the two-class classification results. For the calibration sets of samples, the overall classification accuracy for the three-class model was only 63.7% for the CP samples versus 75.3% for the two-class model. Likewise, the overall three-class classification accuracies were only 64.1% for the MSU samples and 64.0% for the pooled samples. For the validation samples, the models only achieved 60.2%, 63.2% and 61.3% for the CP and MSU groups and the pooled data, respectively. As shown in Table 5, better classification accuracies were achieved for the 'mealy' and 'fresh' classes, while the 'semi-mealy' class (i.e., the class of either 'dry' or 'soft') was worst predicted in all cases, with the classification accuracies ranging between 24.0% and 35.7% for the three groups of samples. The overall classification accuracies for the three sample groups were similar; the model for the pooled group fell between the two other models.

Table 5
Three-class classification of the validation sets of 'Red Delicious' apples from two origins for all test dates.[a]

Sample origin[b]	Instrumental classification	Model classification			Classification accuracy, %
		Mealy	Semi-mealy	Fresh	
CP	Mealy	27	11	2	67.5
	Semi-mealy	15	12	9	33.3
	Fresh	11	5	41	71.9
	Overall	53	28	52	60.2
MSU	Mealy	20	5	2	74.1
	Semi-mealy	5	5	4	35.7
	Fresh	2	3	11	68.8
	Overall	27	13	17	63.2
Pooled	Mealy	44	12	11	65.7
	Semi-mealy	20	12	18	24.0
	Fresh	6	7	61	82.4
	Overall	70	31	90	61.3

[a] Rows: classified by compression measurement. Columns: predicted by hyperspectral scattering technique.
[b] CP = commercial packinghouse; MSU = Michigan State University's experimental orchard in Holt, MI.

Table 6
Three-class classification of the selected validation sets of 'Red Delicious' apples from two origins for the first two test dates (weeks 0 and 2) of cold storage at 4 °C and the last two dates (weeks 4 and 5) of storage at 20 °C and 95% relative humidity.[a]

Sample origin[b]	Instrumental classification	Model classification			Classification accuracy, %
		Mealy	Semi-mealy	Fresh	
CP	Mealy	20	6	0	76.9
	Semi-mealy	5	5	3	38.5
	Fresh	2	3	22	81.5
	Overall	27	14	25	71.2
MSU	Mealy	10	3	3	62.5
	Semi-mealy	2	3	0	60.0
	Fresh	2	0	8	80.0
	Overall	14	6	11	67.7
Pooled	Mealy	34	8	0	81.0
	Semi-mealy	7	6	5	33.3
	Fresh	2	6	29	78.4
	Overall	43	20	34	71.1

[a] Rows: classified by compression measurement. Columns: predicted by parameter spectra of hyperspectral scattering technique.
[b] CP = commercial packinghouse; MSU = Michigan State University's experimental orchard in Holt, MI.

Table 6 further shows the results for the three-class classification of validation apples from the first two dates (0 and 2 weeks) of cold storage at 4 °C and the last two dates (4 and 5 weeks) of storage at 20 °C and 95% relative humidity. The classification accuracy increased by 11.0 percentage points for the CP samples, 4.5 percentage points for the MSU samples and 9.8 percentage points for the pooled samples. These results are considerably better than those presented in Table 5 when all apple samples were used.

When the PLS-DA models were used to estimate the four textural classes (i.e., 'mealy', 'soft', 'dry' and 'fresh'), the overall classification accuracies for the CP, MSU and pooled validation groups decreased to 57.1%, 61.0% and 61.0%, respectively (Table 7). Poor classification accuracies (<38%) were obtained for the 'soft' and 'dry' classes. It should be mentioned that because of fewer samples for these two classes, especially for the 'soft' class, the classification results may have not adequately reflected the actual performance of the models.

3.6. Discussion

This research showed that hyperspectral scattering technique was not accurate enough to predict the hardness and juiciness of apples, two textural attributes for quantifying apple mealiness. Overall, better prediction was achieved for hardness ($r \sim 0.7$) than for juiciness ($r \sim 0.5$). Although still not satisfactory, the results from the research are better than those ($r < 0.4$) reported in Valero et al. (2005).

The PLS-DA models for estimating the instrumental mealiness states of 'nonmealy' and 'mealy' apples showed relatively good discrimination accuracies (≥75%). But the PLS-DA models did not perform as well in three-class classification (i.e., 'fresh', 'semi-mealy' and 'mealy'). As expected, the classification results further decreased when the apples were classified into four classes (i.e., 'fresh', 'mealy', 'soft', and 'dry'). The models performed much better (>92% accuracy) in classification of 'mealy' apples that had undergone longer time of mealiness treatment (i.e., 20 °C and 95% relative humidity). Since the level of mealiness, as measured by the hardness and juiciness, increases with the time of mealiness treatment, this suggests that hyperspectral scattering technique can discriminate more severe mealy apples, even though it is not effective for detecting less mealy apples. Several factors may have contributed to lower classification results. First, the apples used in this study came from the same harvest date and, therefore, had relatively small variability among them, as shown by the distribution of their hardness and juiciness values (Fig. 3). Mealiness classification results are expected to improve when apples of different

Table 7
Four-class classification of the validation set of 'Red Delicious' apples from two origins for all test dates.[a]

Sample origin[b]	Instrumental classification	Model classification				Classification accuracy, %
		Mealy	Soft	Dry	Fresh	
CP	Mealy	23	2	12	3	57.5
	Soft	1	0	1	2	0.0
	Dry	12	2	12	6	37.5
	Fresh	8	3	5	41	71.9
	Overall	44	7	30	52	57.1
MSU	Mealy	21	4	1	2	75.0
	Soft	3	2	1	0	33.3
	Dry	1	1	3	3	37.5
	Fresh	1	3	3	10	58.8
	Overall	26	10	8	15	61.0
Pooled	Mealy	40	11	13	3	59.7
	Soft	4	1	4	1	10.0
	Dry	13	5	8	14	20.0
	Fresh	7	2	13	52	70.3
	Overall	64	19	38	70	61.0

[a] Rows: classified by compression measurement. Columns: predicted by hyperspectral scattering technique.
[b] CP = commercial packinghouse; MSU = Michigan State University's experimental orchard in Holt, MI.

maturity/ripeness levels, hence greater ranges of mealiness, are included for study. Second, this study used confined compression to measure the hardness and juiciness of apples for determining fruit mealiness. While this destructive instrumental method has been used by other researchers (Barreiro et al., 1998; De Smedt, 2000), more study is needed on the effectiveness of using hardness and juiciness to quantify mealiness levels and discriminate mealy apples from nonmealy ones. For instance, the range of juiciness measurements between and/or among mealy and nonmealy apples was relatively small and there was considerable overlapping between the two storage treatments (Fig. 3). This may also partly explain why juiciness prediction results were worse than those for hardness (Table 2). A larger range of hardness or juiciness measurements is necessary or desirable in developing either quantitative prediction models or discriminative models for effective mealiness classification. Finally, the acquisition of hyperspectral scattering images was susceptible to the effect of fruit size/shape as well as factors such as light beam size and its positioning. Hence further improvement of the system would enhance its ability for detecting apple mealiness.

4. Conclusions

The quantitative models for predicting hardness and juiciness resulted in lower correlation with destructive instrumental measurements, indicating the difficulty of using hyperspectral scattering technique to accurately predict fruit mealiness levels. However, the partial least squares discriminant analysis models achieved relatively good two-class ('mealy' versus 'nonmealy') classification results, with an overall classification accuracy of 75% or higher. Hyperspectral scattering technique did not give good classification results when apples were classified into three classes, (i.e., 'fresh', 'mealy' and 'semi-mealy') or four classes ('fresh', 'mealy', 'soft', and 'dry'). Better classification accuracies (>92%) for mealy apples undergoing longer time of mealiness treatment demonstrated that hyperspectral scattering technique can effectively detect more severe mealy apples from normal, nonmealy apples. The technique, however, still cannot accurately determine mealiness levels in terms of hardness and juiciness or to discriminate less severe mealy apples.

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