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Assessment of internal quality of blueberries using hyperspectral transmittance and reflectance images with whole spectra or selected wavelengths

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ABSTRACT

Hyperspectral imaging has been used in previous studies for assessing firmness and soluble solids content of fresh fruit. To assess the applicability of this technique for automatic sorting and grading of blueberries, we investigated different sensing modes (i.e., reflectance and transmittance), evaluated the effect of fruit orientation on fruit quality prediction, and developed robust prediction models with fewer wavelengths. In this study, a hyperspectral imaging system was used to acquire reflectance and transmittance images from 420 blueberries in three fruit orientations (i.e., stem end, calyx end and equator) for the spectral region of 400–1000 nm. Mean spectra were extracted from the hyperspectral images of each blueberry. Calibration models for soluble solids content (SSC) and firmness index (FI) were developed using partial least squares regression for the reflectance and transmittance spectra as well as their combination. Further, interval partial least squares (iPLS) regression with 10 different intervals of nine wavelengths was used to reduce the spectral dimensionality. Overall, reflectance gave better results (the best correlation for prediction (R_p) of 0.90 for SSC and 0.78 for FI) than transmittance (R_p of 0.76 for SSC and 0.64 for FI). For reflectance, SSC and FI predictions for the stem end orientation were better than for the other two orientations, while fruit orientation had little or insignificant effect on transmittance predictions. Combination of reflectance and transmittance spectra did not yield improved prediction results for both SSC and FI. On average, the prediction errors for iPLS increased by only 5%, compared to PLS for the whole spectra. The research demonstrated that it is feasible to use hyperspectral imaging technique for prediction of internal quality of blueberries with a few selected wavelengths with results similar to that with whole spectral information.

Industrial relevance: Because of the distance traveled from the South to the North hemisphere, it is especially important to perform internal and external quality determination for individual fresh blueberries to ensure their quality upon arrival at the destination. Soluble solids content and firmness are important fruit quality parameters. Hyperspectral imaging has emerged as a new technique for quality and safety inspection of food and agricultural products and could be useful for blueberry quality assessment. However, there are several limitations to be afforded before: technique implementation velocity since this method uses multiple images from contiguous wavelengths (increasing computational costs), fruit light interaction, and fruit orientation effect between others. Specifically, the submitted manuscript presents results in order to demonstrate the hyperspectral imaging technique feasibility with a few selected wavelengths to achieve acceptable results for the prediction of internal quality of blueberries, thus, this would make it possible to implement the technique in the near future for online commercial sorting and grading of blueberries.

1. Introduction

In recent years, countries in the southern hemisphere have increased blueberry export to the northern hemisphere. Because of the distance traveled, it is especially important to perform internal and external quality determination for individual fresh blueberries to ensure their quality upon arrival at the destination. Soluble solids content (SSC) is an important fruit quality parameter (Rodriguez-Saona, Fry, McLaughlin, & Calvey, 2001); it is usually determined from the juice extracted from the fruit flesh using the refractometric method (Noh & Lu, 2007). Softening of blueberries is a major quality concern because it promotes mold development and enzymatic browning, resulting in inferior products that are not suitable for marketing. Hence individual blueberries should be inspected for firmness to avoid spoilage and possible rejection by the consumer.

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Considerable research has been reported on automatic detection and segregation of defective or inferior blueberries. Earlier research from the late 1970s until the mid-1980s was mainly focused on segregating soft berries using mechanical techniques such as vibration (Bower & Rohrbach, 1976), roll bounce (Wolfe, Singh, & Puthur, 1980), and impact (Lee & Rohrbach, 1983; Rohrbach, Franke, & Willits, 1982). In recent years, more research has been focused on non-destructive optical techniques, such as image analysis, to segregate defective berries (Leiva-Valenzuela & Aguilera, 2013). Reflectance near-infrared (NIR) spectroscopy was used to evaluate the blueberry's nutraceutical content (Sinelli, Spinardi, Di Egidio, Mignani, & Casiraghi, 2008), monitor dehydration (Sinelli, Casiraghi, Barzaghi, Brambilla, & Giovanelli, 2011) and build quality grading models (Yang, Lee, & Williamson, 2012). Optical techniques have wide acceptance in agriculture because they are efficient and fast in acquiring a large quantity of information and have the potential for simultaneous assessment of multiple quality attributes such as SSC and titritable acidity in mandarins (Antonucci et al., 2011) in the case of spectroscopy and for simulating human vision in the case of image analysis.

More recently, hyperspectral imaging has emerged as a new technique for quality and safety inspection of food and agricultural products (ElMasry & Sun, 2010). A typical hyperspectral image consists of hundreds or even thousands of narrow-band or spectral images, with each pixel in the image being associated with a spectrum which may cover both visible and NIR wavelengths. Many studies have been reported on using hyperspectral imaging for prediction of SSC and firmness, two important quality attributes for large fruits like apple (Lu, 2004; Mendoza, Lu, Ariana, Cen, & Bailey, 2011; Mendoza, Lu, & Cen, 2012; Peng & Lu, 2007, 2008; Romano, Nagle, Argyropoulos, & Muller, 2011; Vanoli et al., 2011; Wang, Huang, & Zhu, 2012). Several studies also demonstrated the feasibility of the technique for assessing SSC and firmness in small fruits like strawberry (Nagata, Tallada, Kobayashi, & Toyoda, 2005) and blueberry (Leiva-Valenzuela, Lu, & Aguilera, 2013). Hyperspectral imaging and NIR spectroscopy may be implemented in different sensing modes (i.e., reflectance, interactance and transmittance). While reflectance is the most used (García-Ramos, Valero, Homer, Ortiz-Cañavate, & Ruiz-Altisent, 2005), transmittance was also used to detect internal defect such as bruises in apple (McGlone, Martinsen, Clark, & Jordan, 2005), pear (Han, Tu, Lu, Liu, & Wen, 2006) and pickling cucumber (Ariana & Lu, 2010; Ariana, Lu, & Guyer, 2006), predict SSC in cantaloupe (Dull, Birth, Smittle, & Leffler, 1989) and honeydew melon (Dull, Leffler, Birth, & Smittle, 1992), and the SSC and firmness of apple (Fan, Zha, Du, & Gao, 2009). Transmittance measurements are, however, influenced by such factors as fruit geometry and size. The fruit's internal structures such as calyx, pit or pedicel can change the light transfer pattern by blocking, absorbing or deviating the light passing through the fruit. Moreover, spectral profiles could also be affected by irregularities in the geometry of the samples. In implementing the transmittance mode, it is important that sufficient light penetrates the entire fruit without causing heat damage (Clark, McGlone, & Jordan, 2003; Fraser, Jordan, Künnemeyer, & McGlone, 2003; Nicolaï et al., 2007). Blueberries are small and round with a relatively homogeneous internal structure (i.e., with no hard pit or core). Hence it should be technically feasible to use hyperspectral transmittance imaging for assessing internal quality of blueberries. However for the blueberry industry, neither spectroscopy nor hyperspectral imaging is now being used for quality grading or sorting. In interactance measurement, the path length of the light transmitted into the sample can be better controlled, the sensing mode can, thus, obtain more representative measurements of the sample. However, interactance mode is more complicated in implementation, compared to reflectance and transmittance, (Gou et al., 2013), and it is not suitable for small fruits like blueberry.

Image processing is a critical step in the application of hyperspectral imaging technology. Hyperspectral images are usually processed using such techniques as filtering, correction and segmentation to extract specific features such as mean intensity in the region of interest. These features are then used to build linear or non-linear prediction or discriminant models. Partial least squares (PLS) regression is one of the most popular methods that have been used to build models with orthogonal latent variables that are oriented along directions of maximal covariance between the spectral matrix and the response vector (Nicolaï et al., 2007). In PLS modeling, it is assumed that the process can be described by just a few latent variables (LV's), which are not directly observed but are rather inferred (Wold, Sjostrom, & Eriksson, 2001). These variables are hidden in the spectra of the samples. Although non-linear techniques have been increasingly used recently, PLS allows simpler interpretation and comparison of results, avoiding the overtraining problem that is commonly encountered with complex non-linear models. However, the need for processing a large number of spectral images has been the main obstacle in the application of hyperspectral imaging for high-speed online sorting and grading of agricultural products. Consequently, considerable studies have been focused on the development of spectral data reduction algorithms. Interval partial least squares (iPLS) is one of the commonly used algorithms in selecting the most efficient wavelength regions for developing an optimized local PLS model built with fewer variables (Nørgaard et al., 2005; Ulissi et al., 2011). Basically, with the iPLS method, the entire spectra are first split into smaller equidistant regions and PLS regression models are then developed for each of the sub-intervals, using the same number of LV's for the selected region with lower error. An optimized region can be found by subtracting or adding new variables (Nørgaard et al., 2000; Zou, Zhao, & Li, 2007) Hence, iPLS could yield similar prediction results without using complete spectra information. It has the advantages of facilitating further implementation using less expensive sensors (such as multispectral) and knowing specific wavelength regions, from which the most useful information is obtained.

This article reports on the use of hyperspectral imaging technique for predicting internal quality attributes of blueberries using either whole spectra or selected wavelengths in the visible and short-wave NIR region of 400–1000 nm. Hyperspectral reflectance and transmittance images were acquired for blueberries in three different orientations (i.e., stem end, equator and calyx end facing toward the imaging device). Calibration models using PLS, coupled with iPLS for selection of wavelengths, were developed to predict SSC and firmness, and the effect of fruit orientation on the performance of the prediction models was evaluated.

2. Materials and methods

Experiments were carried out in the postharvest engineering laboratory of the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) at Michigan State University (MSU) in East Lansing, Michigan, USA between March and May of 2012.

2.1. Samples

Commercial “Rabbit edge” blueberries (*Vaccinium corymbosum. Var Tifblue*) produced in Chile, were purchased from a local grocery store in East Lansing, (MI, USA). Berries were visually inspected for appearance and surface defects. Only fruits free of visual defects such as scar cuts and shrivel were selected for the experiment and stored at 4 °C for three to 14 days before the experiments were performed. Blueberries were removed from cold storage 3 h before the experiment to allow them to reach room temperature (~22 °C). The diameter of each blueberry fruit was measured around the fruit equator using a digital caliper in two perpendicular directions so as to discard over or under sized fruits.

2.2. Hyperspectral image acquisition

Hyperspectral images were acquired for 420 blueberry fruits using a prototype hyperspectral imaging system developed in the USDA/ARS