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Research Paper

Spatial assessment of soluble solid contents on apple slices using hyperspectral imaging

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A partial least squares regression (PLSR) model to map internal soluble solids content (SSC) of apples using visible/near-infrared (VNIR) hyperspectral imaging was developed. The reflectance spectra of sliced apples were extracted from hyperspectral absorbance images obtained in the 400–1000 nm range. Prediction models for SSC mapping were developed for three different measurement/sampling designs that varied in the number and size of the regions of interest (ROIs) used for apple SSC measurement and spectral averaging. Case 1 used 29 small ROIs per apple, Case II used 9 moderate-size ROIs per apple, and Case III used 5 large ROIs per apple. The optimal pre-treatment of the spectra extracted from the hyperspectral images was investigated to enhance the performance of the prediction models. The coefficients of determination and root mean square errors of the best-performing models were, respectively, 0.802 and ±0.674 °Brix for Case I, 0.871 and ±0.524 °Brix for Case II, and 0.876 and ±0.514 °Brix for Case III. The accuracy of the PLSR models was enhanced by using the spectra and SSC measured/averaged from the fewer but larger areas of the apples rather than from more numerous but smaller areas. PLS images of SSC showed the predicted internal distribution of SSC within the apples. The overall results demonstrate that hyperspectral absorbance imaging techniques may be useful for mapping internal soluble solids content of apples.

1. Introduction

High-quality agricultural products are required to enhance the competitiveness of agricultural products. The quality of apples is determined by factors such as weight, soluble solids content (SSC), colour, and internal browning. SSC is an important apple quality element because of its commercial value; consumers prefer apples with a high and uniform SSC. However, the SSC

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Nomenclature

CH	carbon–hydrogen
EMCCD	electron-multiplying charge-coupled-device
F	number of factors
FOV	field of view
HSI	hyperspectral imaging
I_i	ith image of *n* absorbance spectral images
NIR	near-infrared
OH	oxygen–hydrogen
PLSR	partial least squares regression
QTH	quartz-tungsten halogen
R_i	regression coefficient derived from the PLSR model
R_C^2	coefficient of determination of the calibration set
R_V^2	coefficient of determination of the validation set
RMSEC	root mean square error of calibration
RMSEP	root mean square error of prediction
ROI	regions of interest
S.G.	Savitzky–Golay
SSC	soluble solids content
VNIR	visible/near-infrared

distribution in apples varies depending on the cultivars and cultivation environment (Barritt, Rom, Guelich, Drake, & Dilley, 1987). The composition of apples is also subject to within-tree variations such as the position within trees, lighting effects, and shading (Barritt et al., 1987; Jackson, Palmer, Perring, & Sharples, 1977; Robinson, Seeley, & Barritt, 1983; Tustin, Hirst, & Warrington, 1988). Apples receive a variety of sunlight exposures during growth such as exposure of all regions, only one side, and small regions. Thus, SSC mapping technology capable of determining the difference in sugar contents inside apples is required. This mapping technique can provide the basic data, such as the number, depth, and positions of measuring SSC, required to identify high-quality apples and develop a portable SSC-measuring device.

Hyperspectral imaging (HSI) can be used as a method for mapping the distribution of SSC. HSI can distinguish the positions containing different characteristics, combined with spectroscopy which can measure the components, can provide a useful assessment technique (Kim, Chen, & Mehl, 2001). Studies of imaging techniques have been examined for the objective measurement of colour and other quality attributes of agricultural products and foods, such as the detection of defects in apples, tissue damage in vegetables, and chilling injuries in bananas (Hashim et al., 2012; Leemans, Magein, & Destain, 1999; Luo & Tao, 2003). Visible and near-infrared (VNIR) spectroscopy technology has been frequently used as a rapid and non-destructive tool to measure the internal quality and attributes of agricultural and food products primarily for moisture, protein, soluble solids, organic acids, fat content, and capsaicinoid contents (Delwiche, Mekwatanakarn, & Wang, 2008; Joshi, Mo, Lee, Lee, & Cho, 2015; Lee, Kang, & Choi, 2004; Lim, Mo, Kim, Kim, & Lee, 2015; Norris & Williams, 1984; Peiris, Dull, Leffler, & Kays, 1998). In particular, a number of studies have been performed to measure the SSC of apples (Lee, Hruschka, Abbott, Noh, & Park, 1998; Mendoza, Lu, Ariana, & Cen, 2012). VNIR spectroscopy can estimate chemical components based on the scattering and selective absorption of VNIR radiation depending on the overtone and combination of bands of specific functional groups. Research into the applications of hyperspectral imaging and the combination of both techniques in the field of food and agriculture has increased recently, particularly for the quality evaluation of seeds and defect detection in apples and tomatoes, as well as the assessment of bacterial biofilms (Jeong, Kim, Lee, Lee, & Cho, 2013; Jun, Kim, Lee, Millner, & Chao, 2009; Kim et al., 2008; Lee, Kang, Delwiche, Kim, & Noh, 2008; Lee et al., 2014; Lohumi, Mo, Kang, Hong, & Cho, 2013).

Near-infrared (NIR) spectroscopy can measure the average SSC of apples but has difficulty in determining the differences in SSC occurring spatially within apples. NIR spectroscopy techniques can also determine the concentrations of specific compounds in a sample by analysing the spectrum obtained by the transmission or reflection from a sample with irradiated light on a small portion (e.g., 10-mm diameter spot) or >50% of the surface of the object. Thus, the spectrum represents an ensemble of transmitted and re-emitted light that has interacted with the medium without the fine detail of spatial variation. Conversely, imaging techniques can obtain spatial information but seldom provides spectral detail.

HSI is capable of simultaneously obtaining both spectral and spatial information for each pixel in the sample image. This technique can also be used to determine subtle physical and chemical characteristics of an object and to visualise the chemical image map of the spatial distributions of the chemical components. Thus, HSI is a promising technique for the prediction of average SSC in apples as well as the spatial SSC distribution across all pixels in an apple image. Unlike conventional NIR spectroscopy methods of predicting SSC using the average SSC of each apple or portion of apples, the HSI method of SSC mapping can be performed using SSC and hyperspectral images measured on sliced apples.

The objective of this study was to develop a prediction model for the mapping of SSC distribution of inner apples using VNIR hyperspectral imaging and to reduce prediction errors such as those resulting from internal spatial variation in SSC to provide basic data for the development of portable SSC measurement devices. The measurements of SSC and VNIR hyperspectral images were examined using sliced apples to map the SSC. In addition, the optimal pre-treatment of the spectra from hyperspectral images was investigated to enhance the performance of the prediction model.

2. Material and methods

2.1. Materials

'Fuji' apples were purchased from a commercial orchard in Pennsylvania, USA and used for the experiments. The apples were transported to the Environmental Microbial and Food Safety Laboratory in Beltsville, MD, USA and stored in a cold room (4 °C) until the imaging experiments were conducted. A