Journal of Food Engineering 224 (2018) 53–61

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Noncontact evaluation of soluble solids content in apples by near-infrared hyperspectral imaging

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ARTICLE INFO

Article history:
Available online 30 December 2017

Keywords:
SSC mapping
Partial least squares regression analysis
Monte Carlo simulation
Light propagation

ABSTRACT

Near-infrared (NIR) hyperspectral imaging was used to evaluate soluble solids content (SSC) in 'Fuji' apples [*Malus sylvestris* (L.) Mill. var. *domestica* (Borkh. Mansf.)]. Eighty 'Fuji' apples were analyzed by collecting four small block samples from each one (approximately 2.0 cm × 2.0 cm × 1.5 cm). Partial least squares (PLS) regression analysis was performed to determine the relation between SSC reference data and NIR spectral data measured from each sample. The cross-validation coefficient of determination (r^2) between predicted and measured SSC values is 0.89 with a root mean squared error of cross-validation (RMSECV) of 0.55%. Then, we successfully mapped SSC at a high spatial resolution (375 μm per pixel). In addition, the absorption and reduced scattering coefficients of the measured samples were determined based on a diffusion theory model. The absorption coefficients are positively correlated to the SSC values (chemical information), whereas water cored tissue content (physical information) causes a characteristic change in light scattering coefficients. The fitting results were validated by Monte Carlo simulation, and the light penetration depth in 'Fuji' apples was estimated to be around 0.33 cm at 1198 nm and 0.17 cm at 1450 nm, respectively.

1. Introduction

The apple is an important agricultural commodity in the global market. It is highly appreciated by consumers due to its crunchy texture and high nutritional value. Soluble solids content (SSC) is one of the most important internal properties of apples and is a key index for harvest time (Peng and Lu, 2008). Today, people are increasingly concerned about the quality of their food and make their purchases of foods based not only on the external aesthetic appearance but also based on the internal quality. Thus, the producer must go beyond the traditional visual inspection methods. Instead, more efficient and less time-consuming digital sensors are increasingly required to assure consumers of high internal food quality.

Near-infrared (NIR) spectroscopy (780–2500 nm) is a well-suited method to characterize organic compounds, mainly in combination with multivariate mathematical techniques. When NIR light illuminates and transmits through an object, the energy of the incident electromagnetic waves changes because of the stretching and bending vibrations of chemical bonds such as O-H, N-H, and C-H (Huang et al., 2014). Fast, noncontact, quality and quantity evaluation of the object can be achieved by analyzing the light reflectance and transmittance values. The increasing importance of NIR spectroscopy in postharvest technology is apparent from recent publications (Nicolaï et al., 2007; McGlone et al., 2002; Veraverbeke et al., 2005), as well as from the fact that many manufacturers of on-line grading lines have now implemented NIR systems to measure various quality attributes. SSC is an organic molecule that contains bonds C-H, O-H, C-O, and C-C, NIR spectroscopy has been successfully applied for the nondestructive measurement of SSC (Zou et al., 2007; Giovanelli et al., 2014; Xiaobo et al., 2007). However, conventional NIR spectrometry acquires the spectral data from a single point on the measured sample. Depending on the uniformity of the quality attribute within the fruit, it is necessary to repeat the spectral acquisition at several positions on the same sample. This process takes a long time even for low spatial resolution. Measuring SSC at a high spatial resolution and fast speed is expected to be useful not only for evaluation of apple taste, but also for physiological analysis (Tsuta et al., 2002).

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https://doi.org/10.1016/j.jfoodeng.2017.12.028
0260-8774/

NIR hyperspectral imaging (HSI) provides an NIR spectral image at each wavelength, enabling quality evaluation across the entire surface. NIR-HSI is suitable for the use in food industry because it is safer than X-ray imaging, more affordable than MRI and superior in image quality compared to thermal imaging (Jiang et al., 2016; Qin et al., 2009).

Many studies have used Vis-NIR (400–1000 nm) HSI for the evaluation of fruits because the hardware equipment cost is less than that for longer wavelength range NIR (1000–2500 nm). However, the absorption features of tissue constituents such as water (1150, 1450, and 1900 nm), lipids (1040, 1200, 1400, and 1700 nm), and collagen (near 1200 and 1500 nm) at the longer wavelength range are much more conspicuous than the features observed in the Vis-NIR range. Thus, the longer wavelengths NIR range has the potential to provide enhanced sensitivity compared to the Vis-NIR range (Wilson et al., 2015).

A significant issue for HSI method now is its time-consuming nature owing to the huge data analysis involved. for instance, in case of establishing a calibration model by using all the measured wavelength images. Such a full spectrum prediction model is likely to contain much unnecessary information, which can hinder the stability of the developed model. In addition, it is difficult to determine which wavelengths are responsible for the developed model from multivariate analysis. Thus, determination of the key wavelengths for the purpose of evaluation is very important, because it can enhance the stability and accuracy of the prediction model and increase the efficiency of data analysis. Previous studies have shown that better prediction accuracy could be obtained using the selected wavelengths rather than the full spectrum (He et al., 2014; Carlini et al., 2000). Competitive adaptive reweighted sampling (CARS) is a wavelength selection algorithm proposed by Li et al. (2009) and has been successfully validated in NIRS analysis (Fan et al., 2016). In this study, CARS was tested for selection of the key wavelength images, and we expected an improvement of the final SSC mapping results.

In most previous HSI studies, the surface of the fruit sample was considered to be flat or spherical. However, HSI is best suited to flat sample measurement, where its penetration depth is between 0.2 and 0.3 cm for the 'Jonagold' apple in the 900–1900 nm range (Lammertyn et al., 2000). In addition, the behavior of transmitted light in an agricultural product is directly affected by the chemical and physical properties of its tissues. Knowledge of the optical characteristics of the tissues is very important to develop an effective measurement system for practical use by the apple industry (Tsuchikawa et al., 2002). The objective of this study was aimed to obtain a method for mapping the SSC of cut apples with a flat surface and for better understanding the light propagation features inside 'Fuji' apple tissues. The specific objectives of this study were: (1) to acquire sensitive NIR hyperspectral reflectance images of 'Fuji' apples and reduce nonperiodic stripes caused by the different sensitivity among camera pixels using the 2D-discrete Fourier transform (DFT) method. (2) to identify key wavelengths by the competitive adaptive reweighted sampling (CARS) method. (3) to establish a calibration model for SSC based on the averaged NIR spectra of each sample and SSC reference values (Brix meter) using partial least squares (PLS) regression analysis, and mapping SSC distribution at a high spatial resolution. (4) to calculate the absorption and reduced scattering coefficients of 'Fuji' apples based on a diffusion theory model. (5) to simulate light propagation inside the apple samples by the Monte Carlo simulation method, validate the calculated absorption and reduced scattering coefficients and estimate the light penetration depths through the simulated results.

2. Materials and methods

2.1. Sample preparation

Fig. 1 briefly summarizes the sample preparation and data measurement steps. In this study, eighty 'Fuji' apples were collected from at a local supermarket in Nagano Prefecture, Japan. Some of them included water cored tissues, which is caused by the accumulation of sorbitol (primary transport carbohydrate in the apple) in the intercellular spaces of apple tissues (Marlow and Loescher, 1985). The sorbitol is somehow inhibited from being absorbed by the cells in the apple cortex (Gao et al., 2005), leading to a decrease in reducing sugars (fructose and glucose). Normally, the watercore tissues is located near the vascular strands and is radial in nature. Such apples are preferred in some countries such as Japan, but these fruits are susceptible to oxidation and are unsuitable for long-term storage (Zupan et al., 2016). The different SSCs between water cored and normal apple tissues will increase the variance among samples and the enhance the prediction and mapping of SSC results. Because cutting the samples and changing the light source required much time, all the measurements could not be finished in one day. Thus, 80 samples were randomly separated into 16 groups (5 samples/group), and two groups were measured every day. Before each measurement, samples were kept under controlled conditions (20 °C and 50 RH) for 12 h to reduce measurement variations due to temperature changes. Subsequently, each apple was cut in half, and one-half part was used for making a calibration model between NIR spectral data and SSC reference values, while the other half was tested for SSC mapping. Four block samples (around 2.0 cm × 2.0 cm × 1.5 cm) were cut from each apple half that was used for SSC calibration.

2.2. NIR hyperspectral imaging and SSC measurements

NIR hyperspectral images were obtained using a push-broom line scanning system (Compovision, Sumitomo Electric Industries, Ltd., Tokyo, Japan). The camera is equipped with a spectroscope and a 2D photosensitive element [256 pixels (wavelength) × 320 pixels (position)] that can receive NIR light from 913 nm to 2519 nm, at a spectral interval of 6.2 nm. In this study, the distance between the target and the camera was manually adjusted to achieve a horizontal field of view at 50 mm for apple blocks and 150 mm for half apple scanning (with a spatial interval of 156 μm and 375 μm per pixel, respectively). The light source used to obtain NIR spectral images was a tube-shaped one, illuminated by two halogen lamps from the two sides. The irradiation angle was adjusted to 45°. Each sample was positioned on the slider and scanned line-by-line. The frame rate was set to 200 frames s^{-1}. To improve the signal-to-noise ratio, 16 scans were measured for each sample; then, the averages of the 16 full images for each wavelength were used for further analysis. As a reference, a white plate was imaged under the same condition, and dark images were obtained by turning off the light source and completely covering the lens with its cap. After the collection of NIR spectral images by the HSI camera, flat light (the tube light) was changed to spot light (the light from one halogen lamp was focused at a spot with a 1 mm in diameter) to capture the spatially resolved spectral images using the same HSI camera. The irradiation angle of the spot light was adjusted to 15° from the vertical direction. Finally, the SSC of each block was immediately measured by a Brix meter (Model IPR-201, Spittz, Atago Co., Tokyo, Japan). Duplicate measurements were carried out, and SSC results were reported in directly given as Brix degrees (°Brix), which correspond to the amount of soluble sugars in a solution (%).