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Prediction of color and moisture content for vegetable soybean during drying using hyperspectral imaging technology

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ABSTRACT

Dried soybean is among the most popular snack foods consumed in numerous countries, and its quality has received considerable attention from processors and consumers. Color and moisture content are two critical parameters used to evaluate dried soybean quality. This study thus aimed to develop regression models for predicting the color and moisture content of soybeans simultaneously during the drying process using a hyperspectral imaging technique. Hyperspectral reflectance images were acquired from fresh and dried soybeans over the spectral region between 400 and 1000 nm for 270 samples. After the automatic segmentation of soybean images at each wavelength based on an active contour model, mean reflectance and image entropy parameters were extracted and tested separately and in combination for predicting the color and moisture content of the processed soybeans. Predicting models were built using the partial least squares regression method. Better prediction results for both color and moisture content were achieved using the mean reflectance data (with correlation coefficients or $R_P = 0.862$ and root-mean-square errors of prediction or RMSEP = 1.04 for color, as well as $R_P = 0.971$ and RMSEP = 4.7% for moisture content) than when using entropy data ($R_P = 0.839$ and RMSEP = 1.14 for color, as well as $R_P = 0.901$ and RMSEP = 9.2% for moisture content). However, the integration of mean reflectance and entropy data did not show significant improvements in predicting the color or moisture content. Overall, a simple hyperspectral imaging technique involving rapid image preprocessing and single spectral features showed significant potential in measuring the color and moisture content of soybeans simultaneously during the drying process.

1. Introduction

Vegetable soybean [*Glycine Max (L.) Merrill*], also known by the Japanese term "edamame", is a soybean harvested at approximately 80% maturity (Hu et al., 2006b). Soybean is popularly consumed after blanching in China, Korea, Japan, and other countries for its rich protein, fat, calcium, vitamin, and diet fiber content. Soybean also has potential for cancer prevention and suppression owing to its high genistein content (Hu et al., 2006b, 2007; Hou et al., 2011).

Color and moisture content are two of the most important parameters in evaluating the drying quality of dried soybeans (Hu et al., 2006a). Color measurements of vegetable soybeans are performed using conventional colorimeters and spectrophotometers after drying. However, these traditional instrumental techniques are time-consuming because of the repeated measurements required to obtain a representative color profile and to reduce the measurement error (Hu et al., 2006b, 2007). Moreover, these instruments are designed for color measurements on flat surfaces rather than on curved surfaces, which are found in soybeans. The uncertainty of these instrumental measurements might introduce further error in analysis (Aguilera, 2003).

The gravimetric oven method and Karl Fisher titration are commonly used laboratory methods for moisture content measurements of agricultural foods and their products. These methods are destructive measurements, such that the same samples cannot be used for further analysis. Moreover, current methods for measuring color and moisture content cannot measure the two parameters simultaneously. Moreover, existing methods are only suitable for testing a small number of vegetable soybeans.

Rapid nondestructive technologies for measuring the drying qualities of agricultural products and food products have been studied extensively. Among these approaches, machine vision and near-infrared spectroscopy are the two main methods (Fernández et al., 2005; Mendoza et al., 2006; Faustino et al., 2007; Lucas et al., 2008; Wu et al., 2010; Romano et al., 2012). However, the conventional machine vision method can only acquire average image information within the visible range (i.e., external characteristics of the sample from grayscale or color images). Near-infrared spectroscopy, although used in a wide range of wavelengths, can only acquire spectral information and cannot obtain the spatial

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information of the samples. Thus, these methods have limitations in that they cannot provide spectral and spatial information simultaneously, which may result in the loss of useful information.

As a relatively novel non-destructive technology, hyperspectral imaging integrates the advantages of machine vision and visible-infrared spectroscopy, while overcoming the drawbacks of both techniques when used alone. Hyperspectral imaging can provide more detailed or complete information, including internal structure characteristics, morphological information, and chemical composition (Huang et al., 2013). This technology has been applied to the nondestructive measurement of agricultural products for evaluating internal quality (Liu et al., 2006; Ariana and Lu, 2008; Huang et al., 2010; Li et al., 2012) and pesticide residues (Del Fiore et al., 2010; Shahin and Symons, 2011; Peng et al., 2011). Thus, this technology may also be used as an alternative for predicting the color and moisture content of vegetable soybeans during drying.

The overall objective of this study is to use a hyperspectral reflectance imaging technique in the wavelength range of 400–1000 nm for predicting the color and moisture content of vegetable soybeans simultaneously during drying. The specific objectives are as follows:

- To extract image traits from preprocessed hyperspectral reflectance images of dried soybeans using mean and entropy methods; and
- To evaluate the capability of partial least squares regression (PLSR) models for predicting the color and moisture content of vegetable soybeans during drying.

2. Materials and methods

2.1. Raw materials

Two hundred and seventy fresh soybeans [*Glycine Max (L.) Merrill*] harvested from the Garden of Haitong Food Company in Cixi, Zhejiang Province, during the 2012 harvest season were used in this study. The soybeans were washed, peeled and blanched using the microwave heating method and then stored at 4 °C and 95% relative humidity in a refrigerator before the experiments. The soybeans were used within 3 days.

2.2. Microwave-assisted pulse-spouted bed vacuum-drying

Vegetable soybeans were dried using a high-precision laboratory dryer developed at the State Key Laboratory of Food Science and Technology, Jiangnan University, China. This microwave-assisted pulse-spouted bed vacuum-drying (PSMVD) experimental system essentially consisted of seven units: (a) a cylindrical multimode microwave cavity, (b) two circular vacuum drying chambers, (c) a pulse-spouted system as a nitrogen gas source, (d) a refrigeration system with a set of air-cooling refrigeration compressor units, (e) a vacuum system, (f) two energy supply systems, and (g) a water load system to prevent magnetron from overheating using a cooling/heating circulating water unit. A detailed description of the dryer system is given by Wang et al. (2013).

In this study, the experimental parameters were set as follows: (1) the pressure was set at 9 ± 1 kPa; (2) the power was set to 516 W; and (3) the samples were spouted in the preselected time interval of 1 s and held for 3 s by allowing nitrogen gas to flow periodically into the drying chamber. Fresh soybeans with a mass of 200 g were used for each trial. To achieve broad sample distribution of color and moisture content, eight groups at different drying times (from 10 min to 80 min, in steps of 10 min) were tested. The experiments were replicated thrice for each drying condition. Fresh and dried samples were measured using the hyperspectral imaging system and then tested using reference methods for color and moisture content.

2.3. Hyperspectral reflectance image acquisition

An in-house developed line-scan hyperspectral reflectance imaging system was used to acquire hyperspectral reflectance images of soybeans. The hyperspectral reflectance image system mainly consisted of a hyperspectral imaging unit, a light source, and a sample handling platform. The hyperspectral imaging unit comprised a back-illuminated 1392 × 1024 pixel charge-coupled device (CCD) camera (Pixelfly QE IC∗285AL, Cooke, USA), an imaging spectrograph (1003A-10140 Hyperspc™ VNIR C-Series, Headwall Photonics Inc., Fitchburg, USA) with a 25 μm slit covering an effective range of 400–1000 nm and connected to a zoom lens (10004A-21226 Lens, F/1.4 FL23 mm, Standard Barrel, C-Mount., USA), and a computer for controlling the camera and acquiring the images. The light source system consisted of a 150 W DC light source (halogen lamp, EKE, 3250K, Techniquip, USA) and a single optic fiber coupled to a 9 inch parallel light lamp. The sample handling unit consisted of a horizontal motorized stage. Ten soybeans were placed onto a 20 cm × 20 cm black background board in two rows and perpendicular to the scanning line of the hyperspectral imaging unit (see Fig. 1).

For each group of samples, 625 scans covering a 50 mm distance were acquired at an exposure time of 250 ms for each hyperspectral reflectance image. The hyperspectral imaging system had 0.15 mm/pixel spatial resolution and 0.644 nm/pixel spectral resolution covering the spectral region of 400–1000 nm using a 1392 pixel camera. After 10 spectral binning operations, the resultant hyperspectral reflectance images had 6.44 nm/pixel spectral resolution and 94 wavelengths. Thus, a spatial block of a 1392 × 625 × 94 image was created, which was represented by a 2-D image with x-axis and y-axis coordinate information. Another axis was represented by spectral information. The darkness and reflectance images of white Teflon were also acquired for every six groups of samples and used as reference to obtain relative reflectance images.

2.4. Reference measurements

A CR-400 Chroma Meter (Konica Minolta Sensing, Inc., Japan) was used for soybean surface color measurements. Color difference (ΔE) was used to describe the color change in the fresh and dried samples and was calculated as follows:

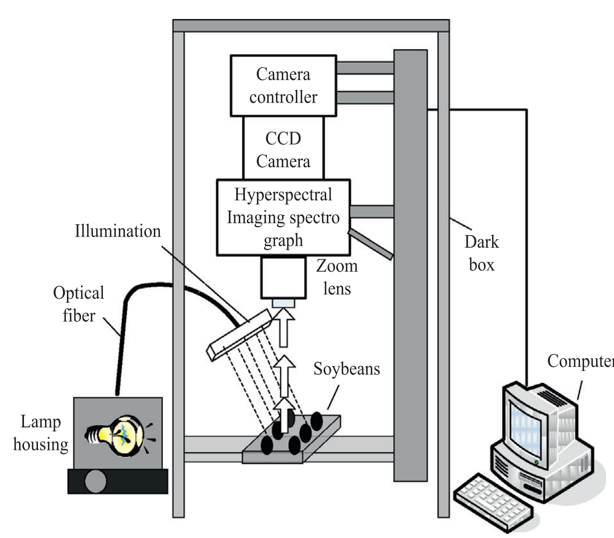

Fig. 1. Schematic of the hyperspectral reflectance imaging system.