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Potential of multispectral imaging for real-time determination of colour change and moisture distribution in carrot slices during hot air dehydration

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ABSTRACT

Colour and moisture content are important indices in quality monitoring of dehydrating carrot slices during dehydration process. This study investigated the potential of using multispectral imaging for real-time and non-destructive determination of colour change and moisture distribution during the hot air dehydration of carrot slices. Multispectral reflectance images, ranging from 405 to 970 nm, were acquired and then calibrated based on three chemometrics models of partial least squares (PLS), least squares-support vector machines (LS-SVM), and back propagation neural network (BPNN), respectively. Compared with PLS and LS-SVM, BPNN considerably improved the prediction performance with coefficient of determination in prediction (R_P^2) = 0.991, root-mean-square error of prediction (RMSEP) = 1.482% and residual predictive deviation (RPD) = 11.378 for moisture content. It was concluded that multispectral imaging has an excellent potential for rapid, non-destructive and simultaneous determination of colour change and moisture distribution of carrot slices during dehydration.

1. Introduction

Carrot (*Daucus carota* L.) is considered one of the healthiest vegetables due to its pleasant flavour, nutritive value and great health benefits related to its antioxidant, anticancer, antianaemic, healing and sedative properties (Doymaz, 2004; Gamboa-Santos, Montilla, Soria, & Villamiel, 2012). In recent years, the consumption of carrot and its related products has increased steadily (Hiranvarachat, Devahastin, & Chiewchan, 2011). However, as with the rest of vegetables, carrot is highly seasonal and abundantly available at particular times of the year. Furthermore, carrot is a high-moisture food with moisture content of 90/100 g and wilts rapidly after harvest if it is not stored under appropriate environmental conditions, which results in poor appearance that is not acceptable to consumers (Toğrul, 2006). For extending the availability of this root, several preservation processes have been assayed. Among them, dehydration is one of the most important since it not only significantly extends vegetable shelf life and retains the nutritional quality but also diversifies the offer of foods for consumers (Prakash, Jha, & Data, 2004). Furthermore, it brings about substantial reduction in weight and volume, minimising packaging, storage and transportation costs and enables storability of the product under ambient temperatures (Baysal, Icier, Ersus, & Yıldız, 2003). Currently, dehydrated carrots are used as an ingredient in many prepared foods such as instant soups and are an excellent ingredient for developing oil-free, healthy snack foods (Lin, Durance, & Scaman, 1998). Owing to changing lifestyles, there is now a great demand for a wide variety of high quality dehydrated carrots with emphasis on freshness and convenience.

Dehydrated carrots are commonly prepared by sun drying, hot air drying, freeze drying, or vacuum microwave drying (Lin et al., 1998), and its quality, e.g., colour and moisture content, has received considerable attention from processors and consumers. The applied dehydrating conditions and pre-treatments highly influence the resulting physical, chemical, microbial, functional and organoleptic properties of the carrot products. Therefore, the improvement of carrot products quality and the rationalisation of production in many branches of industry require a permanent quality control of intermediate and finished products and continuous monitoring of technological processes. The assessment of

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moisture content is very important in the production of dehydrated carrots. The removal of moisture prevents the growth and reproduction of microorganisms which cause decay, and minimises many of the moisture-mediated deteriorative reactions. However, too low moisture content can badly influence food taste, and even destroy nutrition contents such as carotenoids and vitamin. In addition, the moisture content controlling has great influence on dehydrated carrots transportation and storage. Common methods for moisture analysis include oven-drying (AOAC, 1990), freeze-drying or lyophilisation (Seligman & Farber, 1971) and electronic moisture analyser (Sinija & Mishra, 2011). However, these methods are time-consuming, tedious and destructive, and not suitable for the situation where a large number of samples are required to be measured. A rapid, reliable, robust and non-destructive analytical method is needed for the prediction of moisture content in carrots during dehydration.

In addition to moisture content, the colour of the dehydrated carrots is another important quality factor, which is affected by the operation conditions. Food colour usually is the first quality parameter evaluated by consumers and is critical in the acceptance of the products. In addition, colour measurement is an objective parameter for the evaluation of quality changes during food processing, storage, and distribution. At present, colour measurements of carrots are performed using conventional colorimeter and spectral photometer after drying (Baysal et al., 2003; Rawson, Tiwari, Tuohy, O'Donnell, & Brunton, 2011; Wu, Ma, et al., 2014; Wu, Pan, et al., 2014). However, these traditional instrumental techniques are time-consuming because of the repeated measurements required to obtain a representative colour profile and to reduce the measurement error. Moreover, these instruments are designed for colour measurements on flat surfaces rather than on out-of-flatness surfaces, which are found in dehydrating carrot slices. The uncertainty of these instrumental measurements might introduce further error in analysis (Huang, Wang, Zhang, & Zhu, 2014). Furthermore, current methods for measuring moisture content and colour cannot measure the two parameters simultaneously.

Multispectral imaging is an increasingly used optical technology that integrates image with spectroscopic technique to obtain both spatial and spectral information from an object simultaneously. It has the advantages of being non-destructive, rapid, and requires no sample pre-treatment, which makes this technology directly useful for real-time applications in the field (e.g., fruit packinghouses and food processing plants) (Gowen, O'Donnell, Cullen, Downey, & Frias, 2007; Qin, Chao, Kim, Lu, & Burks, 2013). More importantly, this technique has the great potential to measure the multiple components at the same time for quality assurance. Recently, this technology has been applied as a powerful process analytical tool for non-destructive and on-line process monitoring and quality control in the food industry (Andresen, Dissing, & Løje, 2013; Kim et al., 2008; Lu & Peng, 2007; Park et al., 2007). Therefore, multispectral imaging is a promising method for industrial use since it has potential to be used as an on-line instrument for non-contact measurements of carrots on a conveyer belt during production.

To our knowledge, there is no research reported about the application of multispectral imaging technique for determining colour change and moisture distribution in carrot slices during hot air dehydration. Therefore, the overall objective of the present study was to evaluate the feasibility of using multispectral imaging technique in the spectral region of 405–970 nm for the colour change detection and moisture content prediction of carrot slices during dehydration process. The specific objectives were to: (1) determine the colour change and moisture content in carrot slices during dehydration process; (2) compare the performances of linear partial least square (PLS) and nonlinear least square-support vector machine (LS-SVM) and back propagation neural network (BPNN) analyses for the prediction accuracy of moisture content; (3) develop image processing algorithms for the visualisation of moisture content of carrot slices in all pixels within an image to form distribution maps of moisture content of carrot slices.

2. Materials and methods

2.1. Sample preparation

Two batches of fresh carrots (*D. carota* L.) were obtained from the local fruit and vegetable distribution centre of Hefei (China). Carrots with no visible damage were selected for the experiment. Carrots were properly washed in tap water to remove external impurities and cut into slices of 40 ± 2 mm diameter and 4 mm thickness. Fifty carrot slices from each batch (n = 100 slices in total) were used for analysis. The multispectral images of the carrot slices were first captured using the multispectral imaging system. Then, the sliced carrot slabs were weighed and blanched immediately in boiling water for 1 min to inactivate the enzymes responsible for quality deterioration of processed carrots (Gamboa-Santos et al., 2013). An air temperature of 60 °C was selected to simulate industrial practice and preserve the bioactivity of heat-sensitive carrot constituents. In order to obtain different levels of moisture content, carrot slices were dehydrated in a hot wind oven for seven time periods of 0, 30, 60, 120, 180, 240 and 300 min, resulting in a total of 700 samples (100 repeats for each dehydration period). For each dehydration period, each carrot sample was first scanned by the multispectral imaging system and then its reference value of moisture content was determined.

2.2. Multispectral image acquisition and analysis

The data acquisition was done using the VideometerLab equipment (Videometer A/S, Hørsholm, Denmark) which acquired the multispectral images at 19 different wavelengths ranging from 405 to 970 nm and the detailed information of the measured wavelength were 405, 435, 450, 470, 505, 525, 570, 590, 630, 645, 660, 700, 780, 850, 870, 890, 910, 940 and 970 nm. The acquisition system recorded the surface reflections with a standard monochrome charge coupled device chip, nested in a Point Grey Scorpion camera (Point Grey Research GmbH, Ludwigsburg, Germany). The carrot slice was placed inside the integrating sphere or Ulbricht sphere with a matte white coating to ensure a uniform reflection of the cast light, and thereby a uniform light in the entire sphere. At the rim of the sphere, light emitting diodes (LEDs) with narrow-band spectral radiation distribution were positioned in the pattern of side by side distributing the LEDs of each wavelength evenly across the whole perimeter to avoid shadows and specular reflections. The setup of the instrument is further described in Liu et al. (2014). The system was first calibrated radiometrically and geometrically using well-defined standard target, followed by a light setup based on the type of object to be recorded (Dissing et al., 2013). Image segmentation was performed using the VideometerLab software version 2.12.23. To remove the image background, all items except the carrot slice were removed by a Canonical Discriminant Analysis (CDA) (Cruz-Castillo et al., 1994) and segmented using a simple threshold. The mean spectra were calculated as mean values of all the pixels in carrot slice samples.

2.3. Reference measurements

The moisture content, expressed in per cent wet basis (%), was measured by the gravimetric method using the oven-drying method (AOAC, 1990). Colour values (L^*, a^* and b^* values) of carrot