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Comparative assessment of feature-wavelength eligibility for measurement of water binding capacity and specific gravity of tuber using diverse spectral indices stemmed from hyperspectral images

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A number of investigations have been conducted to explore non-contacting measuring techniques for predicting chemical components of agricultural product, but there is no research on non-destructive inspection and quantification of water binding capacity (WBC) and specific gravity (SG) in tuber. The purpose of this study was to exploit a rapid analytical technique using reflectance spectra (RS), generalised logarithm spectra (GLS), absorbance spectra (AS), and power spectra (PS) derived from spectral image data to develop partial least squares regression (PLSR) and locally weighted principal component regression (LWPCR) models that predicted tuber WBC and SG. Based upon the RS, GLS, AS, and PS, corresponding feature wavelengths were then respectively selected by using genetic algorithm (GA), first-derivative and mean centering iteration algorithm (FMCIA), and reverse variable algorithm (RVA). Compared to FMCIA and GA, the method of RVA achieved the highest accuracy based on the RVA-PS-LWPCR model for predicting WBC and SG. Then, all combinations of feature wavelengths were refined with the method of regression coefficient (RC). The simplified GA-RC-PS-LWPCR model obtained highest accuracy to measure WBC, resulting in a coefficient of determination in prediction (R2P) of 0.966 and root mean square error of prediction (RMSEP) of 0.199. Besides, the FMCIA-RC-GLS-LWPCR model showed the best performance to determine SG, with R2P of 0.978 and RMSEP of 0.009. The optimal models were then applied to each pixel of the spectral image to generate distribution maps of WBC and SG of tested samples. Furthermore, the overall performances of wavelength selection methods in terms of FMCIA-RC and RVA-RC were equivalent and slightly better than GA-RC. The results demonstrated that effective wavelength selection method can improve the performance of multispectral imaging system for detection of WBC and SG.

1. Introduction

The tuber is an important food source. During storage, the quality of tuber decreases over time. Therefore besides using techniques such as cooling (Hu and Sun, 2000; Sun and Hu, 2003; Mc Donald and Sun, 2001; Wang and Sun, 2002a,b; Sun and Wang, 2000; Sun, 1997; Sun and Brosnan, 1999; Zheng and Sun, 2004; Wang and Sun, 2004), freezing (Kiani et al., 2011) and drying (Cui et al., 2008; Sun and Woods, 1994) commonly used in keeping agricultural and food products, development of effective ways to monitor the quality change over time is also necessary. The measurement of water binding capacity (WBC) and specific gravity (SG) is considered as an effective way to describe the changes of tuber quality over time. As a primary determining factor, WBC of tuber product is defined as the ability of tuber tissue to retain moisture even though external pressures (e.g. gravity, heating) are applied to it (Robertson et al., 2000). The tuber quality depends largely on the WBC which is of both economic and technological importance for consumers and food industry. Primarily, high WBC is vitally desirable because tuber is sold by weight and any moisture loss will cause a reduction of value of fresh products. Moreover, the WBC has a great influence on the organoleptic properties of tuber. For example, as the tuber moisture continues decreasing during storage, the moisture loss due to poor WBC can affect tuber hardness and then result in undesired appearances. This is because that the variation of WBC impacts the tuber texture, to a large extent, and the tuber flesh becomes soft with the reduction of WBC (Reeve, 1970). Tuber SG is another most widely

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accepted measure of food internal quality attribute, the influence of SG to tuber cooking quality has come to light early (Lulai and Orr, 1979). Since its close relationship with tuber total solids and starch content, it is commonly utilized by the tuber processing industry to evaluate acceptability (Laboski and Kelling, 2007). Moreover, tuber SG tends to increase as the tuber size increases, and also is high for tubers with a large number of starch and dry matter, and higher during dehydration (Iritani and Weller, 1985; Simmonds, 1977). However, fresh tubers with low SG require more time for processing and are apt to have darker fry color (Lyman and Mackey, 1961). Although higher tuber SG is desirable, the high SG of fresh tuber may bruise more easily (Baritelle and Hyde, 2003). In addition, the genotype, soil and climatic factors have a decisive effect on SG determination of different tuber varieties (Thornton, 1974). Therefore, it is very necessary to determine the WBC and SG of tuber products throughout the whole process and supervisory system to make the products have higher quality, and to recognize how the different processing mechanisms affect the quality of the final product.

The measurement of WBC is normally carried out using laborious techniques, such as gravimetric method, moisture sorption isotherm values and centrifugation method (Fleury and Lahaye, 1991; Chen et al., 1984). Besides, considerable researches have been conducted to investigate tuber SG using salt solution method and the method of weighing in air and water (Sinha et al., 1992; Clark et al., 1940). Nevertheless, these conventional techniques for WBC and SG determination are inefficient and unsuitable for real-time application. In order to inspect the quality characteristics of tuber products at different levels of WBC and SG, consumers expressed their interest in rapid identification techniques. Furthermore, on-line detections of WBC and SG are more favourable in the food industry for large-scale tuber production. Thus, rather than using time-consuming and invasive instruments, optical technique is one of the most acceptable methods to rapidly predict food quality and ideally would allow each unit of tuber to be analysed (Saccon et al., 2016; Neethirajan and Jayas, 2011; Menesatti et al., 2009; Woodcock et al., 2008; Karoui and Blecker, 2011; Lu et al., 2011; Brosnan and Sun, 2002; Su and Sun, 2016b; Yang et al., 2015). For the various non-destructive optical methods, near-infrared spectroscopy has shown its capacity to determine SG of potato tuber and is a potential approach for real-time implementation (Chen et al., 2005). However, both WBC and SG vary along heterogeneous tuber products, which means it is a tough assignment to acquire the entire distribution of WBC and SG at different positions using only spectroscopy technique because its small sample area generates very limited spatial information (Zhang et al., 2014; Antonucci et al., 2011). The difficulty in detecting WBC and SG under industrial environment required effective measure approaches, among which spectroscopic technique in terms of hyperspectral imaging was particularly promising (Su et al., 2015; Xie et al., 2016; Zhang et al., 2016; Cubero et al., 2016; Pan et al., 2016; Su and Sun, 2016c).

Hyperspectral imaging is technique that combines spectroscopy and computer vision (Wu and Sun, 2013b; Jackman et al., 2009; Du and Sun, 2005) into one system, and thus hyperspectral imaging technique can collect images of an object for each pixel in hundreds of continuous spectral bands with the ability of visualizing the spatial distribution of its quality attributes (Zhu et al., 2014; Pu et al., 2015; Sun, 2016; Cheng and Sun, 2015; Kamruzzaman et al., 2012a; Mahesh et al., 2015). In the past few years, hyperspectral imaging technique has been widely studied for food quality and safety analysis and assessment (Barbin et al., 2012, 2013; Kamruzzaman et al., 2012b, 2013; Elmasry et al., 2012; Feng and Sun, 2012; Wu and Sun, 2013a; Liu et al., 2014; Feng and Sun, 2013; Feng et al., 2013; ElMasry et al., 2013). However for potato tuber, only a few studies are available, which investigated hyperspectral imaging coupled with chemometric techniques to detect potato tuber quality for on-line applications in the food industry. Do Trong et al. (2011) demonstrated the potential of hyperspectral imaging for the contactless detection of optimal cooking time for potatoes with relative error of less than 10%. Based on hyperspectral imaging, the external and internal potato tuber disorders such as the common scab and hollow heart were successively recognized using support vector machines (SVM) and image processing approaches (Dacal-Nieto et al., 2011a,b). According to their results, the correct classification accuracies of 97.10% and 89.10% were achieved for detecting the tuber common scab and hollow heart, respectively. Besides, the potential for non-invasive detection of blackspot in potatoes was investigated by López-Maestresalas et al. (2016). The results obtained in their study suggested that it was possible to map the areas affected by blackspot in potato samples with a pixel classification accuracy above 93% by combining hyperspectral imaging and partial least squares discriminant analysis (PLSDA). Moreover, Rady et al. (2015) implemented this technique based on partial least squares regression (PLSR), feed forward neural networks (FFNN) and radial basis functions neural networks (RBFNN) for prediction of the glucose and sucrose percentages in two potato cultivars. Several feature wavelengths selected using principal component analysis (PCA) and genetic algorithm (GA) achieved similar results as the full wavelength models, which gave promise to rapid measurement of tuber quality using multispectral imaging system (Pu et al., 2015). Possessing the most important spectral information of food products, multispectral imaging makes non-invasive and visual inspection more efficient, accurate and economical (Kamruzzaman et al., 2015; Tsakanikas et al., 2016; Lorente et al., 2012; Qin et al., 2013; Dissing et al., 2013; ElMasry and Wold, 2008). Additionally, other common wavelength selection methods such as successive projection algorithm (SPA) and competitive adaptive reweighted sampling (CARS) have been extensively used for selecting feature wavelengths to design multispectral imaging systems over the last several years (Cheng et al., 2016; Yu et al., 2014; Liu et al., 2014; Lorente et al., 2013; Wei et al., 2014).

To the best of our knowledge, no research has been carried out to determine WBC and SG of potato and sweet potato tubers based on hyperspectral imaging technique. The objective of this study was to measure and visualize the heterogeneous distributions of WBC and SG in six tuber categories based on hyperspectral imaging in the spectral range of 897–1753 nm. The detailed steps were to: (a) identify region of interests (ROI) of tuber samples on hyperspectral images, (b) extract their reflectance spectra data and transform the reflectance information into other effective spectral indices, (c) design new methods for feature wavelength selection to evaluate tuber WBC and SG, (d) develop image processing technique for the visualization of heterogeneous distributions of tuber WBC and SG.

2. Material and methods

2.1. Grabbing hyperspectral image and internal quality parameters of tuber

Fresh tuber samples of golden wonder potato (origin: Ireland), rooster potato (origin: Ireland), Melody organic potato (origin: UK), Cultra white potato (origin: Ireland), Covington sweet potato (origin: USA) and Evangeline sweet potato (origin: Egypt) were collected from different categories and regions in order to obtain a representative model. All these samples were transported to laboratories of Food Refrigeration & Computerized Food Technology (FRCFT), University College Dublin (UCD), Ireland, and stored in a refrigerator at 4 °C to prevent moisture loss and browning as the