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Potential of hyperspectral imaging for visual authentication of sliced organic potatoes from potato and sweet potato tubers and rapid grading of the tubers according to moisture proportion

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ABSTRACT

The reliability and veracity of hyperspectral imaging integrated with multivariate analyses were investigated for authentication of sliced organic potato (OP) from non-organic tubers and rapid grading of tubers on the basis of different moisture levels. Hyperspectral images of all the tuber samples were obtained and their spectral data were extracted and pre-processed. Then, partial least squares discriminant analysis (PLSDA) model was established for recognition of the tested samples. Loading plots of the second derivative (SD) and principal component analysis (PCA) were used for selecting characteristic wavelengths. The OP samples were identified correctly (100% accuracy) from non-organic tubers by MC-PLSDA model using only characteristic wavelengths, with predicted sensitivities of 1.000, specificities of ⩾0.944, classification error of ⩽0.028, coefficient of determination (R_P^2) of no more than 0.979 and the root mean square error of prediction (RMSEP) of ⩽0.532 for each adulterate type. Another simplified PLSDA model was applied for grading tuber moisture levels, resulting in a correct classification of ⩾91.6%. The visualization results shown on classification maps achieved a rapid and convenient interpretation of tuber varieties and moisture levels. These results indicated that hyperspectral imaging has a great potential for discrimination of OP and identification of tuber moisture levels.

1. Introduction

During the past years, the fast expansion of innovative farming approaches has been stimulated by the demands of consumers for healthier and higher quality foods along with the emphasizing of environmentally sustainable agricultural systems from the government policies. By complying with organic standards of governmental food safety authorities (e.g., European Commission), organic foods are produced relying on crop rotation, green manure, compost and biological pest control instead of using synthetic pesticides and chemical fertilizers, and normally processed with no use of ionizing radiation, industrial solvents, or synthetic food additives. These organic foods are considered to be possibly more environmentally friendly, more nutritious and safer than non-organic food (Hjelmar, 2011). Consumers quote the health benefit of organic food products as a dominating purchasing motivation regardless of a general lack of conclusive data to back this up, which has driven the market demand leading to rapid increase in organic foods production despite their higher prices (Marian et al., 2014). Meanwhile, besides using processing techniques such as cooling (Sun and Wang, 2000; Desmond et al., 2000; Zheng and Sun, 2004; Wang and Sun, 2004), freezing (Kiani et al., 2011) and drying (Delgado and Sun, 2002; Cui et al., 2008) to enhance food quality, the industry has paid more attention to the quality valuation and authenticity of food products, in particular the authenticity of organic foods. Carillo et al. (2009) assessed the process optimization and physicochemical characterization of organic and conventional potato products by comparing their proteins, amino acids carbohydrates, color, water activity and rheological properties based on physical and chemical methods. Barbosa et al. (2015) classified Brazilian organic and non-organic sugarcane by analyzing 32 elements in sample using machine-learning algorithms. A result of 95.4% accuracy was achieved using Naive Bayes algorithm with eight minerals (Rb, U, Al, Sr, Dy, Nb, Ta, Mo) chosen. Then, organic rice discrimination was verified by soft independent modeling of class analogy (SIMCA) and K-nearest neighbors (KNN) based on 20 chemical elements determined via inductively coupled plasma mass spectrometry (Borges et al., 2015). However, these

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destructive and inefficient analyzing methods are not suitable for on-line detection. Non-invasive and fast authentication of organic food products has long been a challenging problem worldwide, as witnessed by the EU-funded Network of Excellence MoniQA, the EU CORE Organic II project AuthenticFood (Muilwijk et al., 2015).

The needs for organically grown potatoes has increased worldwide in recent years, and organic potato (OP) (*Solanum tuberosum* L.) cultivation for industrial processing into French fries or potato crisps will be an inexorable trend (Dresow et al., 2013). In fact, consumers have made potato one of their top organic purchases although the nutritional characteristics of these OP tubers are equivalent to traditional potatoes (Carillo et al., 2012). Furthermore, the sweet potato (*Ipomoea batatas* L.) is also an popular healthy and nutritious staple food that can provide starch, vitamins and minerals for populations in many parts of the world, but the mechanical automation processing technology of sweet potato is not advanced enough, which hindered the development of tuber industry (Aina et al., 2012; Bovell-Benjamin, 2007). It is known that both potato and sweet potato belong to tuber crops, and have similar genes, nutrients and internal appearance. In this study, the sliced potato and sweet potato tubers were mixed together with OP. Because of the genes and genome structures in OP and common potato are much more resemble, the possibility of OP authenticated from potato would be lower than sliced sweet potato if the performance of the developed model is good. Additionally, since potato and sweet potato are mainly made up of water (average content of 75%), the moisture loss is always existence during their storage. In order to improve food stability and reduce microbiological activity, dehydration of these tubers is frequently carried out during industry processing (Karizaki et al., 2013; Fan et al., 2014; Srivastava et al., 2015). Nevertheless, the measurement of tuber moisture is usually manual manipulation and poor efficiency. It is more difficult to visualize tuber moisture levels. For the purpose of monitoring the dehydration process, we need to know the ranges of moisture content of tubers in many cases. On the other hand, it is important to authenticate the sliced product rather than the whole tuber. During the entire process of tuber, real-time inspection of its quality is the first principle for a food company, especially for the sliced tubers that are more to easier to be mixed. Moreover, it is also a big challenge for the government sector to inspect the authentication of the sliced or processed tuber products. In addition, food adulteration matters are continuing occurrence despite repeated prohibition. The consumers are concerned more about their health than before and devote their mind to the authentication of the processed organic food as well. While the traditional machine vision or computer vision (Wu and Sun, 2013b; Jackman et al., 2009a,b; Wang and Sun, 2002; Cubero et al., 2011) as an fast and efficient imaging technique can only be developed to evaluate potato qualities in terms of surface defects (Sun, 2011) and sorting of irregular potatoes based on size and color (Hasankhani and Navid, 2012). Furthermore, some more reliable, rapid and non-destructive spectroscopy techniques including visible/infrared spectroscopy (Abdel-Nour et al., 2011; Sun, 2009; Ouyang et al., 2013), Raman spectroscopy (J. Liu et al., 2013; Lee and Herrman, 2015) and nuclear magnetic resonance spectroscopy (Wu et al., 2014; Zhang et al., 2013), have gained a wider recognition on tuber quality aspects in terms of internal defects (Zhou et al., 2015), authentication of starch powder (B. Liu et al., 2013), and component analysis (Helgerud et al., 2015; Zhao et al., 2015). Unfortunately, all these techniques alone cannot provide detailed spatial and spectral information of tested samples simultaneously. Consequently, it is of critical importance to develop an accurate, rapid, non-destructive and economic technique for both identification of OP from common potato and sweet potato tubers and classification of tubers according to different moisture levels.

Hyperspectral imaging which combines with both imaging and spectroscopic techniques in one system has obtained much interest (Wu et al., 2012; Barbin et al., 2012; ElMasry et al., 2012a,b; Wu and Sun, 2013c; Kamruzzaman et al., 2012; Feng and Sun, 2012; Liu et al., 2014; Barbin et al., 2013; Feng and Sun, 2013; Feng et al., 2013; Su et al., 2015). Hyperspectral images are constituted of hundreds of contiguous spectral bands in each spatial point of the imaged object, which means each pixel of a spectral image contains a spectral fingerprint (Sun, 2010). Thus hyperspectral imaging technique can be deeply employed to evaluate food quality by analyzing the detailed spectral characteristics (Wei et al., 2014; Lorente et al., 2012; Cheng and Sun, 2015). Hyperspectral imaging has already been successfully implemented for quality determination of staple foods such as chemical component (Rady et al., 2015), mycotoxin contamination (Kandpal et al., 2015), and optimal cooking time of boiled potato tubers (Do Trong, 2011). As an alternative, a reliable multispectral imaging system with several feature wavebands has the capability to meet the needs of fast and real-time applications (Dissing et al., 2013; Liu et al., 2014). The elimination of the redundant wavelengths is helpful not only to save computational time and storage space, but also to enhance the model performance (Karimi et al., 2012; Kamruzzaman et al., 2015). To our knowledge, no research has yet been published for real-time and rapid authentication of sliced OP and visual classification of tubers based on moisture levels using hyperspectral imaging technique. Therefore, the main aim of this work was to investigate the potential of near infrared (NIR) hyperspectral imaging (900–1700 nm) for on-line authentication of OP and grading of tubers in terms of potato and sweet potato during dehydration.

2. Materials and methods

2.1. Tuber samples and hyperspectral image acquisition

Tuber cultivars in this research were grown at four different geographical locations: USA, UK, Ireland and Egypt. These tuber crops including OP (variety: Melody, origin: UK), rooster potato (RP) (origin: Ireland), white potato (WP) (variety: Cultra, origin: Ireland), golden wonder potato (GWP) (origin: Ireland), sweet potato 1 (SP1) (variety: Covington, origin: USA) and sweet potato 2 (SP2) (variety: Evangeline, origin: Egypt) were grown in two kinds of systems (one organic and five conventional) under controlled conditions in a long-term field trial and were sampled in 2015. These OP samples were produced in organic system which relied on no use of genetically modified (GM) materials and was managed in full compliance with the guidelines for organic farming (European Community Council Regulation EEC 2091/91 and EC 834/2007) whereas the conventional system applying non-organic standards depended on the routine use of pesticides and synthetic fertilizers. All the fresh samples were transported to laboratories of Food Refrigeration & Computerized Food Technology (FRCFT), University College Dublin (UCD), Ireland. To prevent moisture loss and tuber browning after slicing, all the samples were stored in a refrigerator at 4 °C before experiment. This is due to that low temperature can slow down the enzyme activity of agriculture food and the optimal temperature was found at 4 °C (Altunkaya and Gökmen, 2008). These tubers were washed and peeled before slicing with an electric slicing machine. One sample cut from each tuber was used for analysis. Sliced tuber samples were dehydrated in an oven under the temperature of 80 ± 2 °C for six time periods of 0, 30, 60, 90, 150, and 210 min (the samples of ¾ used for calibration set and ¼ used for prediction set by random selection), resulting in number of 72 samples (12 × 6) in total for each tuber variety, with 54 training samples for calibration and 18 samples for prediction. Eventually, 432 samples (72 × 6) were