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Feasibility of using hyperspectral imaging to predict moisture content of porcine meat during salting process

Dan Liu [a], Da-Wen Sun [a,b,*], Jiahuan Qu [a], Xin-An Zeng [a], Hongbin Pu [a], Ji Ma [a]

[a] College of Light Industry and Food Sciences, South China University of Technology, Guangzhou 510641, PR China

[b] Food Refrigeration and Computerised Food Technology, Agriculture and Food Science Centre, University College Dublin, National University of Ireland, Belfield, Dublin 4, Ireland

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ABSTRACT

The feasibility of using hyperspectral imaging technique (1000–2500 nm) for predicting moisture content (MC) during the salting process of porcine meat was assessed. Different spectral profiles including reflectance spectra (RS), absorbance spectra (AS) and Kubelka–Munk spectra (KMS) were examined to investigate the influence of spectroscopic transformations on predicting moisture content of salted pork slice. The best full-wavelength partial least squares regression (PLSR) models were acquired based on reflectance spectra (R_c^2 = 0.969, RMSEC = 0.921%; R_c^2 = 0.941, RMSEP = 1.23%). On the basis of the optimal wavelengths identified using the regression coefficient, two calibration models of PLSR and multiple linear regression (MLR) were compared. The optimal RS-MLR model was considered to be the best for determining the moisture content of salted pork, with a R_c^2 of 0.917 and RMSEP of 1.48%. Visualisation of moisture distribution in each pixel of the hyperspectral image using the prediction model display moisture evolution and migration in pork slices.

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1. Introduction

Salting treatment is a common operation in the production of high quality meat products, which renders meat products of much higher long-term stability, by delaying or preventing microbial growth. The quality of salted meat is related to both their composition and the manufacturing process. In order to produce meat products with high quality, it is important to maintain strict controls during the salting process. Therefore, an in-depth study of rapid detection method for quality evaluation of salted meat products is a necessity for process improvement and quality control technology development. Deficient controls during the salting process could result in nutrition loss and texture problems. Moisture content (MC) is an important chemical parameter affecting processing and storage of agri-food products (Cui, Xu, & Sun, 2004; Delgado & Sun, 2003; Sun, 1999; Sun & Byrne, 1998; Sun & Woods, 1993, 1994a, 1994b, 1994c, 1997). For salted meat products, MC is closely related to the sensory, textural and microbiological quality attributes. Several studies have showed that there is a high relationship between texture parameters with moisture contents in dry-cured meat (Ruiz-Ramirez, Arnau, Serra, & Gou, 2005; Serra, Ruiz-Ramirez, Arnau, & Gou, 2005). Moreover, moisture is also a key factor for inhibiting the growth of foodborne pathogens and spoilage bacteria (Mathlouthi, 2001), influencing the shelf life of salted meat products. Therefore, it is necessary and useful to rapidly and accurately monitor moisture contents in order to control the salting process and the quality of salted products.

Common methods for moisture analysis include oven-drying (AOAC., 1997) and microwave drying methods, and infrared moisture analyser (Sleagun & Popa, 2009). However, these analytical methods are time-consuming and difficult to perform on-line in a production setting. Furthermore, these methods are not suitable for monitoring the moisture contents continuously or non-destructively. Near infrared (NIR) spectroscopy has been widely used for the estimation of quality attributes in meat and meat products due to its fast measurement, simple sample preparation and non-invasiveness (Prieto, Roehe, Lavin, Batten, & Andres, 2009; Weeranantanaphan, Downey, Allen, & Sun, 2011). NIR spectrum provides complex structural information of samples related to the vibration behaviour of molecular bonds such as C—H, O—H and N—H (Ghosh & Jayas, 2009), caused by their interaction with electromagnetic radiation absorbed at wavelengths between 700 and 2500 nm. The capability of using NIR spectroscopy for moisture analysis is mainly due to the high absorbance of the NIR radiation by water (Osborne, 2006). Many studies have confirmed the ability of NIR spectroscopy to predict moisture content of raw meat (Barlocco, Vadell, Ballesteros, Galietta, & Cozzolino, 2006; Kestens, Charoud-Got, Bau, Bernreuther, & Emteborg, 2008), as well as pork products such as fermented sausages (Collell, Gou, Picouet, Arnau, & Comaposada, 2010; Gaitan-Jurado, Ortiz-Somovilla,

* Corresponding author at: College of Light Industry and Food Sciences, South China University of Technology, Guangzhou 510641, PR China. Tel.: +353 1 7167342; fax: +353 1 7167493.

E-mail address: dawen.sun@ucd.ie (D.-W. Sun).

URLs: http://www.ucd.ie/refrig, http://www.ucd.ie/sun (D.-W. Sun).

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Espana-Espana, Perez-Aparicio, & De Pedro-Sanz, 2008). However, although traditional NIR spectroscopy can determine the major composition of meat products rapidly and non-invasively, it cannot detect compositional gradients within the sample. In reality, there are many cases where spatial evolution of quality parameters is also required. In the meat industry, during the meat salting process, it is important to guarantee a controlled concentration and homogeneous distribution of moisture in final salted meat products, therefore knowledge about spatial distribution of moisture content within the specimen is required. However, it is not easy to obtain moisture content at different spots within the specimen, by either conventional methods or spectroscopy.

Recently, a new technique referred to as hyperspectral imaging (HSI) has been developed (Sun, 2010). By integrating both spectroscopic and imaging techniques (Du & Sun, 2005; Zheng, Sun, & Zheng, 2006a, 2006b) in one system, hyperspectral imaging can generate a spatial map of spectral variation, displaying spatial distribution of inherent chemical and physical properties of the specimen (Lorente, Aleixos, & Gomez-Sanchis, 2012). Applications of this technique in the meat industry have recently been reviewed (Elmasry, Barbin, Sun, & Allen, 2012), revealing that HSI has the potential of predicting different attributes of meat quality quickly and accurately such as beef (ElMasry, Sun, & Allen, 2011; Wu et al., 2012), pork (Barbin, ElMasry, Sun, & Allen, 2013; Tao, Peng, Li, Chao, & Dhakal, 2012), lamb (Kamruzzama, ElMasry, Sun, & Allen, 2011, 2012), ham (Iqbal, Sun, & Allen, 2013), and fish (He, Wu, & Sun, 2012; Zhu, Zhang, He, Liu, & Sun, 2012). Particularly for moisture content evaluation, Barbin et al. (2013) applied a pushbroom hyperspectral imaging system to determine the moisture of intact and minced pork. Wu et al. (2012) applied the hyperspectral imaging technique to determine the moisture content of beef slices at different periods of the dehydration process. Recently, HSI has also been used to determine the moisture content in salmon fillet (He et al., 2012). Besides, several other authors have also explored the feasibility of the HSI technique in moisture prediction of strawberries (ElMasry, Wang, ElSayed, & Ngadi, 2007), banana (Rajkumar, Wang, Elmasry, Raghavan, & Gariepy, 2012) and mushroom (Taghizadeh, Gowen, & O'Donnell, 2009). To the best of our knowledge, no research endeavourers have been reported yet for determining the moisture distribution in porcine meat during the salting process using hyperspectral imaging. Therefore, it is of our interest to implement the HSI technique to analyse the moisture evolution and migration in meat products during the salting process.

Therefore, the specific objectives of the current study were to (1) establish a satisfactory approach to extract spectral data from hyperspectral images of salted pork samples acquired in the NIR range (1000–2500 nm); (2) compare three spectral parameters, i.e., reflectance spectra (RS), absorbance spectra (AS) and Kubelka–Munk spectra (KMS), to improve the robustness of prediction models; (3) build robust PLSR calibration models between the obtained spectral information and the reference MC values; (4) identify the most significant wavelengths linked to MC predictions; (5) build new quantitative models with the selected important wavelengths based on different spectral parameters, and (6) apply the prediction models to hypercubes to obtain distribution maps depicting the variation of MC within salted meat samples.

2. Materials and methods

2.1. Sample preparation and measurement of moisture content

Pork meat samples (*longissimus dorsi*) were obtained from local markets at 0.5 days post-mortem. For salting treatment, 30% NaCl (w/w) was employed and samples were treated at room temperature (25 °C). Ninety meat slices (7 mm in thickness) were cut. In order to obtain representative samples at different salting periods, a salting treatment was conducted on these slices for different time periods (0, 5, 15, 30, 60, and 180 min). After treatment, the surface moisture was wiped by paper towels before image acquisition. By implementing the above method, a contrast was highlighted between pork meat samples with different moisture contents to achieve better predictions. Reference moisture content of meat was determined using the AOAC oven drying method, and the moisture content was calculated based on the mass loss after drying. Each sample was analysed in duplicate and the average values of moisture for each sample were used in subsequent analyses. There were wide variations in the moisture content for the examined pork slices. The overall measured moisture contents varied from 55.2% to 74.9% with a mean of 63.4% and a standard deviation of 5.22%.

2.2. Hyperspectral imaging system

A typical pushbroom hyperspectral imaging system (1000–2500 nm) was employed. It consisted of a line-scan spectrograph (Specim V25E, Spectral Imaging Ltd., Oulu, Finland) covering the spectral range of 1000–2500 nm, a high performance 320 × 256 CCD camera (XC403, Xenics Infrared Solutions, Leuven, Belgium), camera lens (OLES30, Xenics Infrared Solutions, Leuven, Belgium) for the spectral range of 1000–2500 nm, two halogen lamps forming the illumination unit (3900-ER, Illumination Technologies Inc., New York, USA), a conveyer belt operated by a stepper motor (IRCP0076-1COMB, Isuzu Optics Corp., Taiwan, China), data acquisition software (Spectral Image software, Isuzu Optics Corp., Taiwan, China) and a computer. The spectrograph had a fixed-size internal slit (30 μm) to define a field of view (FOV) for the spatial line (horizontal pixel direction) and collected spectral images in the reflectance mode in the wavelength range of 916–2534 nm with a spectral increment of about 6.32 nm between the contiguous bands, thus producing a total of 256 bands. The speed of the conveyer belt was adjusted to 22 mm s^{-1} to synchronise with the image acquisition by the Spectral Image software, which controlled the exposure time, motor speed, binning mode, wavelength range and image acquisition.

2.3. Image processing and extraction of spectral data

For each salting period, pork samples were placed on the conveyer belt and then moved to the field of view of camera and were scanned line by line. Finally, 90 hyperspectral images (15 pork samples × 6 periods) were obtained. The acquired images were stored in a raw format before being processed. Each acquired image called hypercube contains a stack of two-dimensional images at different wavelengths and can be described as I (x, y, λ). A visual inspection of the acquired hyperspectral images revealed a high level of noise at both ends of the spectral range, thus being not useful for the spectral data extraction. Therefore, the range spanning from 916 to 1000 nm and from 2452 to 2534 nm of the images were removed, leading to the images being resized to the spectral range of 1005–2445 nm with a total of 228 bands. To eliminate the differences in camera quantum and physical configuration of imaging systems, the original hyperspectral images (R_0) were corrected into the reflectance mode (R_c) based on white reference images W for a standard Teflon white tile (~100% reflectance) and black reference images B for dark current (~0% reflectance). The formula applied was as follows:

$$R_c = \frac{R_0 - B}{W - B} \times 100\% \quad (1)$$

After image acquisition and reflectance calibration, the region of interests (ROIs) can be easily identified based on segmentation with a simple thresholding, due to the distinctive spectral differences between meat sample and background spectrum. The

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