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Potential of hyperspectral imaging combined with chemometric analysis for assessing and visualising tenderness distribution in raw farmed salmon fillets

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ABSTRACT

Tenderness is a critical quality characteristic of salmon fillets and Warner–Bratzler shear force (WBSF) is a widely used objective indicator for tenderness evaluation of salmon fillets. This research studied rapid and non-destructive prediction of tenderness in fresh farmed salmon fillets using visible and near-infrared (Vis–NIR) hyperspectral imaging. Hyperspectral images of tested fillets with different tenderness levels were acquired and their spectral features were extracted in 400–1720 nm. Two calibration algorithms, namely partial least squares regression (PLSR) and least-square support vector machine (LS-SVM) analysis, were used to correlate the extracted spectra of salmon samples with the reference tenderness values estimated by WBSF method. Optimal wavelength selection was carried out based on full range spectra with two methods, regression coefficients (RC) from PLSR analysis and successful projections algorithm (SPA). The best set of optimum wavelengths was determined as the one containing four wavelengths (555, 605, 705 and 930 nm) selected by SPA. These four optimum wavelengths were then used to build an optimised SPA-LS-SVM prediction model, reaching the best result with a correlation coefficient (r_P) of 0.905 and root mean square error estimated by prediction (RMSEP) of 1.089. At last, an image processing algorithm was developed to transfer the SPA-LS-SVM model to each pixel in salmon fillets for visualising their WBSF distribution. The overall results of this study reveal the capability of hyperspectral imaging as a fast and non-invasive technique to quantitatively predict tenderness of salmon fillets with a good performance.

1. Introduction

Quality is a main concern of the modern agri-food industry, and the industry is always looking for innovative processing technologies such as novel cooling (Sun and Brosnan, 1999; Sun and Zheng, 2006; Sun and Hu, 2003; Wang and Sun, 2001), freezing (Delgado et al., 2009; Zheng and Sun, 2006; Sun and Li, 2003; Li and Sun, 2002), drying (Sun and Woods, 1993, 1994a,b,c; Cui et al., 2004) and edible coating (Xu et al., 2001) methods and new evaluation techniques such as non-destructive measurement to enhance and control product qualities. For fish products, it is widely accepted that tenderness is one of the most important quality characteristics, relating to the texture, juiciness, flavour as well as mouthfeel, and, to a great degree, accounting for eating quality of fish and other meat products. Tenderness is also closely correlated with some important physical and chemical characteristics such as moisture/water-holding capacity, protein (e.g. myofiber and collagen) and fat. Lower water-holding capacity always gives higher expressible moisture content and higher shear strength (implying lower tenderness) of fish muscle (Jønsson et al., 2001; Williams et al., 2012). Protein denaturation often leads to shrunken muscle fibers, and subsequently harder and more compact tissue texture. In specific, the structure disruption of myofibrillar protein (i.e. myofibrillar fragmentation) can cause increased tenderness and therefore the unacceptability of the fish flesh (Jasra et al., 2001). Besides, tenderness has also been found to be influenced by collagen and fat content. Higher content of collagen in flesh produces lower tenderness (Ayala et al., 2005), while an increased fat content contributes to the increased tenderness of raw fish flesh like salmon (Sveinsdottir et al., 2002). In current fish market, tenderness is regarded as one of the most popular parameters taken into account in assessing whether the products are of superior quality, like salmon fillets (Quevedo and Aguilera, 2010; Sallam, 2007). High quality fish products always make consumers feel pleased, content and satisfied. Salmon fillets with higher tenderness are likely to be accepted, otherwise consumers' satisfaction and

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confidence will reduce and the products will be rejected. In practice, consumers would be willing to pay a higher price in the market for salmon fillets as long as they are guaranteed with good quality. To a certain extent, a decision to purchase or repurchase salmon fillets depends on whether the flesh is of acceptable tenderness. On the other hand, ensuring satisfactory tenderness of salmon fillets is of benefit throughout the whole value chain. It is worth noting that tenderness inconsistency has become one of the main causes for consumer complaint and for failure to repurchase. To avoid quality degradation especially tenderness reduction and to develop strategies to satisfy customers' preferences, more advanced and efficient technologies should be developed and applied for tenderness assessment of salmon products.

Normally, tenderness of fish fillets is evaluated by means of subjective assessment, providing information concerning product acceptability or preference for one kind of fish product over another. This evaluation procedure is always performed with a consumer panel using a "finger" test, exhibiting the ability to return to original position by touching and visually assessing the fish flesh (Quevedo and Aguilera, 2010). However, this method is subjective and poorly consistent. Objective instrumental methods are also designed to assess the force in shearing, penetrating, biting, mincing, compressing and stretching the fish flesh (Ashton et al., 2010; Coppes-Petricorena, 2010). One of the most common ways considered for tenderness assessment is to determine Warner–Bratzler shear force (WBSF) (Jønsson et al., 2001; Li et al., 2010). WBSF value used as an objective parameter for tenderness evaluation has been reported in fish products (Kong et al., 2007; Veland and Torrissen, 1999). Generally, the WBSF value is measured by a texture testing machine (e.g., Instron universal testing machine and TA-TX2 texture analyser) equipped with a Warner–Bratzler device (Ashton et al., 2010; Mørkøre et al., 2009). However, although the WBSF method is objective and reliable, it is destructive and time-consuming, and therefore not suitable for large-scale online applications.

Spectroscopic techniques mainly including visible and near-infrared (Vis–NIR) and mid-infrared spectroscopy have been investigated and proven to be effective and useful tools for the quality analysis and control of fish and other meat products (Cozzolino and Murray, 2012; Prieto et al., 2009). Instead of the destructive WBSF method, Vis–NIR has been widely applied as a rapid and non-destructive technique for tenderness assessment in fish and other meat products, such as salmon (Isaksson et al., 2002), pork (Arvanitoyannis and Stratakos, 2012), beef (Yoshimura et al., 2013) and poultry (Alexandrakis et al., 2012). Nevertheless, in spite of its ability to evaluate tenderness of samples, Vis–NIR spectroscopy cannot achieve the acquisition of spatial distribution information. The inspection of tenderness variation in spatial dimension can enhance the understanding of the quality change within samples. Moreover, spatial information of tenderness would also be helpful to indirectly reflect the variation of some other quality attributes such as water-holding capacity, protein and fat. In view of the application limits of spectroscopy, it is required to measure spectral and spatial information simultaneously, so that the tenderness evaluation of salmon fillets could be exploited in a more comprehensive way.

Recently, hyperspectral imaging or imaging spectroscopy has emerged by assembling spectroscopy and computer vision (Du and Sun, 2005; Jackman et al., 2008; Valous et al., 2009; Sun, 2004; Wang and Sun, 2002; Sun and Brosnan, 2003) a new system, providing both spectral and spatial information of tested food samples (He et al., 2013b; Wu and Sun, 2013a,b). Many studies and applications of using hyperspectral imaging have been reported for the prediction of quality attributes in diverse food products, including fruit and vegetables (Lorente et al., 2012), pork (Dissing et al., 2012), beef (Wu et al., 2012c), maize kernel (Williams et al., 2012), and egg (Liu and Ngadi, 2012). Especially, hyperspectral imaging technique has been applied to assess the physical and chemical attributes of fish such as texture assessment (Wu and Sun, 2013d), fat determination (Segtnan et al., 2009), moisture and water-holding capacity evaluation (He et al., 2013a; Wu and Sun, 2013c), colour measurement (Wu et al., 2012b), parasite (nematode) detection (Sivertsen et al., 2011) and spoilage inspection (Wu and Sun, 2013e) as well as fresh/frozen classification (Zhu et al., 2012). However, to the best of our knowledge, few reports have been found in literatures on the use of hyperspectral imaging to evaluate tenderness in fish products, especially in salmon fillets. Therefore, the objective of this study was to explore the potential of using visible and near-infrared (Vis–NIR) hyperspectral imaging technique to predict and visualise tenderness of fresh farmed Atlantic salmon fillets. The specific aims were to

- acquire hyperspectral images of salmon fillets using two hyperspectral imaging systems working in 400–1000 nm and 900–1700 nm, respectively;
- extract spectra of examined salmon samples with different tenderness levels and use the extracted spectra to develop quantitative relationships with reference WBSF values of samples using two calibration methods of partial least squares regression (PLSR) and least-square support vector machine (LS-SVM), respectively;
- compare the prediction abilities of models established using two wavelength ranges of 400–1000 nm and 900–1700 nm to design a better hyperspectral imaging system;
- select the optimal wavelengths to further optimise calibration models by means of two methods, regression coefficients (RC) of PLSR and successful projections algorithm (SPA);
- build optimised calibration models based on the selected optimal wavelengths using PLSR, LS-SVM and multiple linear regression (MLR), respectively; and
- develop an image processing algorithm to visualise distribution maps of tenderness variation in spatial dimension within salmon fillets.

2. Materials and methods

2.1. Preparation of raw salmon fillets

Twenty-eight Atlantic farmed salmon (*Salmo salar*) fillets (length, 16 ± 1.5 cm; width, 30 ± 0.5 cm) originated from Ireland ($n = 14$) and Norway ($n = 14$) were supplied by local supermarkets in Dublin, Ireland. The proximate composition of raw salmon fillets was (48–60) g/100 g moisture, (20–20.4) g/100 g protein, and (14.1–15.7) g/100 g fat. The salmon fillets were delivered in 72 h after slaughtering. The fillets were labelled, packed and then transported in ice boxes to the laboratory of Food Refrigeration & Computerized Food Technology (FRCFT), University College Dublin (UCD), Ireland, and stored at 4 °C until the next day when hyperspectral image acquisition and WBSF measurements were performed. Salmon fillets were first scanned by two laboratory hyperspectral imaging systems and then their reference WBSF values were measured using the instrumental method mentioned below.

2.2. Hyperspectral imaging system

Hyperspectral images of salmon fillets were acquired by using two laboratory pushbroom linescanning hyperspectral reflectance imaging systems, called System I and System II. Specim V10E spectrograph (Spectral Imaging Ltd., Oulu, Finland) was used in System I to acquire hyperspectral images covering the spectral range of