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Prediction of textural changes in grass carp fillets as affected by vacuum freeze drying using hyperspectral imaging based on integrated group wavelengths

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ABSTRACT

This study aimed to simultaneously predict different textural features in grass carps fillets (*Ctenopharyngodon idella*) during vacuum freeze drying using hyperspectral imaging models developed based on integrated group wavelengths in the range of 400 nm–1000 nm. Warner-Bratzler shear force (WBSF) is commonly used as an objective indicator for tenderness evaluation in fish products. First, partial least squares regression (PLSR) was employed to develop a quantitative function between the textural variations and the spectra extracted from the acquired hyperspectral images in the full spectral range at mean and median. Then the important wavelengths most related to WBSF, hardness, gumminess and chewiness were separately selected by regression coefficients (RC) from PLSR. Moreover, the integrated wavelengths for all the textural characteristics were determined by RC by considering all the individual group wavelengths. Finally, PLSR was conducted using different simplified group wavelengths and the performance of all the simplified models at mean or median were compared. The results showed that the integrated group wavelengths at median spectra proved to be the best for simultaneous prediction of WBSF ($R_P^2 = 0.8774$), hardness ($R_P^2 = 0.8523$), gumminess ($R_P^2 = 0.7982$) and chewiness ($R_P^2 = 0.8453$). The current study should widen the applications of hyperspectral imaging in the food industry.

1. Introduction

As an important quality indicator affecting consumer preference, texture is frequently considered and evaluated in processed food products for controlling different processing operations involving heating (Barbut & Mittal, 1990), drying (Eshtiaghi, Stute, & Knorr, 1994; Pei, Shi *et al.*, 2014; Pei, Yang *et al.*, 2014), frying (Kita, Lisińska, & Gołubowska, 2007), freezing (Eshtiaghi et al., 1994; Li & Sun, 2002), packaging (Thybo, Martens, & Lyshede, 1998), canning (Abbatemarco & Ramaswamy, 1994; Anantheswaran, Sastry, Beelman, Okereke, & Konanayakam, 1986), and blanching (Kidmose & Martens, 1999). Fish is very nutritious, which is commonly consumed internationally. On the other hand, fish is a highly perishable food, and thus proper processing techniques such as drying (Cui, Sun, Chen, & Sun, 2008; Pu & Sun, 2016; Yang, Sun, & Cheng, 2017), cooling (McDonald, Sun, & Kenny, 2000; Sun, 1997; Sun & Brosnan, 1999; Sun & Hu, 2003; Sun & Wang, 2000; Wang & Sun, 2002a, 2002b; Wang & Sun, 2004; Zheng & Sun, 2004) and freezing (Cheng, Sun, & Pu, 2016; Cheng, Sun, Zhu, & Zhang, 2017; Kiani, Zhang, Delgado, & Sun, 2011; Ma *et al.*, 2015b; Pu, Sun, Ma, & Cheng, 2015; Xie, Sun, Xu, & Zhu, 2015; Xie, Sun, Zhu, & Pu, 2016) are needed for extending its shelf-life and keeping the desirable quality. Vacuum freeze drying, as an effective drying method by sublimation of a frozen product, is widely used for food preservation by producing dehydrated high-value food products with minimal quality reduction as compared

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Abbreviations

PLSR	Partial least squares regression
RC	Regression coefficient
HSI	Hyperspectral imaging
R_c^2	Coefficient of determination in calibration set
R_{cv}^2	Coefficient of determination in cross validation set
R_P^2	Coefficient of determination in prediction set
RMSEC	Root mean square error in calibration set
RMSECV	Root mean square error in cross validation set
RMSEP	Root mean square error in prediction set
ROI	Region of interest
TPA	Texture profile analysis
WBSF	Warner-Bratzler shear force

to the original foodstuffs (Ratti, 2001).

For assessing textural features of processed fish products, subjective sensory and objective instrumental analysis can both be used at present. Over the years, many instrumental approaches have been developed to provide alternatives to the conventional sensory evaluation by trained panels (Chen & Opara, 2013). The instrumental techniques available can be generally divided into two groups: destructive and non-destructive methods. The destructive methods include three-point bending test (Rojo & Vincent, 2009), single-edge notched bend (SENB) test (James et al., 2011), compression and puncture test such as TPA test (de Huidobro, Miguel, Blázquez, & Onega, 2005) and Magness-Taylor puncture test (M-T) (Ruiz-Altisent, Lleó, & Riquelme, 2006), WBSF test (Destefanis, Brugiapaglia, Barge, & Dal Molin, 2008), and some other destructive methods. As for non-destructive methods, mechanical (Herrero-Langreo, Fernández-Ahumada, Roger, Palagós, & Lleó, 2012), ultrasound (Mizrach, 2008), and optical techniques (Karoui, Mazerolles, & Dufour, 2003; Wu, Sun, & He, 2014) are popular in recent years.

Among the non-destructive methods available, optical techniques are rapid and potential for online monitoring (Cheng & Sun, 2015a; Kamruzzaman, Makino, Oshita, & Liu, 2015; Kavdir, Lu, Ariana, & Ngouajio, 2007; Lorente et al., 2012) and thus many relevant studies have been carried out. Sirisomboon, Tanaka, Kojima, and Williams (2012) conducted near infrared spectroscopy (1100–1800 nm) for measuring textural properties in tomatoes with the highest correlation coefficient (R^2) of 0.90. Yancey, Apple, Meullenet, and Sawyer (2010) developed PLSR models using absorbance spectra from 400 to 2498 nm to predict tenderness and WBSF values in beef with the highest correlation coefficients of 0.86 and 0.80, respectively. However, spectroscopic techniques can only provide point or very small area detection, which is suitable for homogeneous food products such as liquid foods (Qu et al., 2015b). As most foods are heterogeneous in nature, hyperspectral imaging, the combination of spectroscopy and imaging technique or computer vision (Du & Sun, 2005; Jackman, Sun, & Allen, 2009; Jackman, Sun, & Allen, 2011; Sun & Brosnan, 2003) to provide both spectral and spatial information, has recently been widely studied for diverse food quality and safety evaluation (Sun, 2010; Elmasry, Barbin, Sun, & Allen, 2012; Liu, Sun, & Zeng, 2014; Feng & Sun, 2013; Barbin, ElMasry, Sun, & Allen, 2013; Feng *et al.*, 2013; Wu & Sun, 2013; ElMasry, Sun, & Allen, 2013; Cheng & Sun, 2015b; Xiong *et al.*, 2015; Cheng, Sun, Pu, & Zhu, 2015; Pu, Kamruzzaman, & Sun, 2015; Cheng *et al.*, 2016).

HSI has been investigated for many texture-related studies in muscle foods. Kamruzzaman, ElMasry, Sun, and Allen (2013) developed a HSI system to predict instrumental and sensory tenderness of lamb meat with reasonable accuracy ($R_{cv} = 0.84$ for WBSF; $R_{cv} = 0.69$ for tenderness), and from the hyperspectral images, textural features were extracted by gray level co-occurrence matrix method as a supplementary in data processing and model development. Wu et al. (2014) employed HSI (400–1758 nm) to determine the spatial distribution of TPA parameters of salmon fillets including hardness, adhesiveness, chewiness, cohesiveness, and gumminess, and two spectral sets (400–1000 nm and 967–1634 nm) were compared in PLSR models development and improvement with the best R_{cv} of 0.717. For performance evaluation of the established models, the following indicators were calculated and used in the current paper: R_c^2, R_{cv}^2 and R_P^2, as well as RMSEC, RMSECV and RMSEP. Generally speaking, a model with the highest R^2 and the lowest RMSE is regarded as the best (Liu et al., 2014). However, in these previous studies, mean spectra were most frequently used for model establishment and different models were separately developed using diverse group wavelengths for different textural properties, which limited the practical applications of HSI in monitoring multiple textural attributes during processing. Therefore, the current paper aimed to predict multifarious textural features of grass carp fillets under different vacuum freeze drying periods simultaneously using PLSR models developed based on the integrated group wavelengths.

2. Materials and methods

2.1. Sample preparation

For sample preparation, a total of 14 fresh grass carps, each with an average weight of approximately 2 kg, were purchased from a local Wal-Mart supermarket (Guangzhou, China). The fresh grass carps were transported in 7 separate batches to the lab alive, and stunned by a sharp blow to the head with a wooden stick. The fish were then beheaded, gutted, skinned, and filleted. The fillets were washed with cold water and slightly wiped up by filter paper. Finally, a total of 112 fish fillets from different parts of the fish were obtained, each with a similar size of 4.0 cm × 6.0 cm × 1 cm (length × width × thickness). The 112 fillets were evenly divided into 7 groups for drying at different periods. For the vacuum freeze drying, the samples were first frozen at - 80 °C for 8 h to reach an average fillet core temperature of - 75 °C and then 7 drying experiments, each with 16 fillet samples, were performed in a vacuum freeze drier (Scientz-18N, Ningbo Xinzhi Biotech Co., Ltd.) for 3, 6, 12, 18, 24, 30 and 36 h, respectively. The drier operated at a condenser temperature of - 56 °C with a vacuum degree of 10 Pa for all the vacuum freeze drying experiments. Finally, textural properties with seven levels due to different drying periods were obtained in the samples, and each level contained 16 samples with comparable but slightly fluctuant values of textural properties. A wide range of textural property variations was needed in order to develop robust predictive models. The 16 samples after each drying experiment were kept in a desiccator temporarily for the subsequent spectral and chemical analyses.

2.2. Image acquisition and processing

A pushbroom HSI system as described by Qu et al. (2015a) was employed to acquire clear and non-deformable raw hyperspectral images. The obtained images were corrected according to the procedure given in Ma et al. (2015a) to remove the interference caused by uneven illumination, detector sensitivity as well as the differences between the camera and physical configuration of the HSI system. The background of the corrected images was then removed by applying a mask, which was a difference image