Hyperspectral imaging as an effective tool for quality analysis and control of fish and other seafoods: Current research and potential applications

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Introduction

It is generally acknowledged that seafoods such as fish, shrimp, and crab comprise a significant part of nutritional and healthy diets due to their nature of direct sources of high-quality and digestible animal proteins, vitamins, and minerals and supplies of particular poly-unsaturated fatty acids mainly related to the long-chain ω-3 eicosapentaenoic acid and docosahexaenoic acid (Hernández-Martínez et al., 2013). Although consumer demands for these aquatic products have increased in recent years, relevant problems have also appeared, such as food adulteration and fraud, nutrition loss, freshness quality degradation, nematode contamination, and other interference and influence caused by processing factors such as freezing, thawing, salting, and smoking, fishing factors such as fishing grounds, catching and landing time, and species (Galvão, Margeirsson, Garate, Viðarsson, & Oetterer, 2010). Consequently, the issue of food safety and quality control and inspection has increasingly become prominent, which seriously impacts the confidence and acceptability of consumers. Therefore significant efforts have been made by the industries to enhance the quality and safety of all products including agricultural, aquatic, and food products using new technologies such as novel cooling (Sun, 1997; Sun and Brosnan, 1999; Sun and Zheng, 2006; Sun and Hu, 2003; Wang and Sun, 2001; HU and Sun, 2000), freezing (Delgado et al., 2009; Zheng and Sun, 2006), drying (Sun, 1999; Sun and Byrne, 1998; Sun and Woods, 1993, 1994a, 1994b, 1994c, 1997; Cui et al., 2004) and edible coating (Xu et al., 2001). Especially for fish, the most difficult...
technological problem linked with such seafood is its vulnerability and perishability that has a strong impact on the quality parameters involving water holding capacity, moisture content, fat and protein content and structure, colour, texture and freshness (Cheng, Dai, et al., 2013). As for fish freshness, it has always been acknowledged as one of the most important integrated quality attributes for assessing the quality of fish, either for direct consumption or as raw materials for the processing industry. This critical index of freshness to a large extent influences safety, nutritional quality, availability, and edibility, which mainly result from physical, chemical, biochemical and microbiological processes (Cheng, Sun, Zeng, & Liu, 2013).

With growing globalization of fishery product trades, manufacturers, consumers, and government regulators are much more imperative to look for rapid, reliable and practical analytical methods and techniques for safety inspection and evaluation of aquatic products. Even more important, throughout the chain of production process from farm to fork, preventing from foodborne illness occurrence and avoiding severe health hazards of consumers is to certify superior quality of raw materials, control the quality of seafood products and sustain sound development of modern seafood industry.

On one hand, there are many well established traditional analytical techniques and methods available. Sensory evaluation method as one of the most satisfactory approaches has been widely developed for quality assessment of fish freshness using quality grading schemes in the fishery industry and trade (Alasalvar et al., 2001). Various chemical methods for monitoring fish and seafood quality and safety are also available, which are mainly associated with measuring protein degradation (Rawdkuen et al., 2010), lipid oxidation (Goddard, McClements, & Decker, 2012) and compositional changes of amino acids and fatty acids. Furthermore, biochemical and microbiological methods are reliable and regularly used for quantitative determinations of K value to indicate adenosine triphosphate (ATP) decomposition and for total viable counts to reflect microbial spoilage and remaining shelf life (Koutsoumanis, Giannakourou, Taoukis, & Nychas, 2002). However, the above-mentioned traditional analytical techniques and methods are generally time-consuming, tedious, labious, destructive and requiring trained personnel or toxic pollution. Because of these disadvantages and deficiencies, these methods are normally not suitable for on-line detection and for large scale operations. Therefore, rapid, non-destructive and reliable techniques and methods for ascertaining fish and other seafood quality would be of great benefit for both the fishery industry and the consumers (Karoui & Blecker, 2011). In recent years, visible and near infrared spectroscopy technique as an effective and non-invasive tool has been broadly applied for quality evaluation of aquatic products (Cozzolino & Murray, 2012; Liu, Zeng, & Sun, 2013; Uddin & Okazaki, 2010; Zhu, Cheng, Wu, & He, 2011) with the target of monitoring the astaxanthin concentration of blue crab meat (Ottestad, Isaksson, & Wold, 2012), discrimination of sea bass quality cultured under diverse conditions (Costa et al., 2011), authentication of wild European sea bass (Ottavian et al., 2012), differentiation of fresh and frozen-thawed swordfish (Fasolato et al., 2012) and salmon (Fernández-Segovia et al., 2012), textural analysis (Kramer shear force) of farmed Atlantic salmon (Isaksson, Swensen, Taylor, Fjæra, & Skjervold, 2002), freshness assessment of thawed and chilled cod fillets packed in modified atmosphere (Bøknes, Jensen, Andersen, & Martens, 2002), cod and salmon stored in ice (Nilsen, Esaiassen, Heia, & Sigernes, 2002) and oysters (Madigan, Kiermeier, Carragher, de Barros Lopes, & Cozzolino, 2013), detection of trimethylamine content in fish and cephalopod samples (Armenta, Coelho, Roda, Garrigues, & de la Guardia, 2006; Klapyradit, Kerdpiboon, & Singh, 2011), determination of total fat, fatty acids and other nutritional parameters of Atlantic blue fin tuna, crevalle jack and Atlantic Spanish mackerel (Hernández-Martínez et al., 2013), analysis of chemical compositions of oysters (Brown, 2011), measurements of fat and pigment concentrations in live and slaughtered Atlantic salmon (Folkestad et al., 2008) and identification of adulteration in crab meat (Gayo & Hale, 2007).

Table 1 shows the applications of spectroscopic technique for quality evaluation of fish and other seafoods. All above published studies have confirmed that this technique has the capability of quality and safety evaluation of aquatic products and could serve as an on-line or at-line process controlling technique in a non-destructive and objective manner. On the other hand, computer vision as an automated, non-destructive and cost-effective technique is a simple and affordable alternative method to satisfy these expected requirements. A large number of researches have stressed its potential for the automatic inspection and classification of fruits and vegetables (Cubero, Aleixos, Moltó, Gómez-Sanchis, & Blasco, 2011), colour measurements of food for quality control (Du and Sun, 2005; Valous et al., 2009; Wu & Sun, 2012), and evaluation of meat quality (colour, marbling, maturity and textural tenderness) (Jackman et al., 2008; Jackman, Sun, & Allen, 2011). It has also been widely applied to evaluate and monitor quality of aquatic products for colour measurement of salmon fillets (Quevedo, Aguilera, & Pedreschi, 2010) and European sea bass (Costa, Menesatti, Rambaldi, Argenti, & Bianchini, 2013), quantification of gaping and morphology in smoked salmon slices (Merkin, Stien, Pittman, & Nortvedt, 2012), estimation of firmness in the salmon fillets (Quevedo & Aguilera, 2010), categorization of Atlantic salmon fillets (Misimi, Mathiasssen, & Erikson, 2007), assessment of pre- and post-ripeness variations in size and shape of Atlantic cod and Atlantic salmon fillets (Misimi, Erikson, Digre, Skavhaug, & Mathiasssen, 2008) and automated sorting for size, sex and skeletal anomalies of cultured sea bass (Costa, Antonucci, Boglione, et al., 2013), weight prediction of Alaskan salmon and pollock
The objective of this paper is to review the applications of hyperspectral imaging for the assessment of various chemical constituents without using hazardous chemical reagents. Due to its innovative nature of the technology, a number of review papers on the application of hyperspectral imaging have been published in the last two years, however they are primarily associated with quality evaluation of general food and agricultural products (Feng & Sun, 2012; Wu & Sun, 2013), fruit and vegetables (Gómez-Sanchis et al., 2014; Lorente et al., 2012) and meats (ElMasry, Barbin, Sun, & Allen, 2012).

However, no review is available to distinctively present the current research and potential application of hyperspectral imaging in assessing, measuring, predicting, and visualizing the quality of fish and other seafoods for quantitative and qualitative analysis. Consequently, the objective of this paper is to review the applications of hyperspectral imaging technique for quality inspection and evaluation of aquatic products.

### Hyperspectral imaging system

As an emerging technique, it is necessary to discuss the basic information of hyperspectral imaging technique.

#### Cube information of hyperspectral image

Hyperspectral imaging, also known as spectral imaging or chemical imaging, is an innovative technique that combines traditional optical spectroscopy and digital imaging or computer vision to obtain both spectral and spatial information from a tested object. In detail, a traditional optical spectrum instrument commonly presents a simplex spectrum $I(\lambda)$, whereas computer vision usually offers the two-dimensional distribution of the intensity at each pixel of the image $I(x, y)$. Therefore, a hyperspectral image is

<table>
<thead>
<tr>
<th>Species</th>
<th>Technique</th>
<th>Detection of</th>
<th>Method</th>
<th>$R^2$/$R^2_0$</th>
<th>RMSEC/RMSEP</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic salmon</td>
<td>Visible spectroscopy</td>
<td>Astaxanthin content</td>
<td>PLSR</td>
<td>0.92</td>
<td>0.5 mg kg$^{-1}$</td>
<td>Ottestad et al. (2012)</td>
</tr>
<tr>
<td>Atlantic salmon</td>
<td>Vis-NIR spectroscopy</td>
<td>Texture analysis</td>
<td>PLSR</td>
<td>0.85</td>
<td>0.72%</td>
<td>Isaksen et al. (2002)</td>
</tr>
<tr>
<td>Sea bass</td>
<td>NIR spectroscopy</td>
<td>Fat content</td>
<td>PLSR, PLS-DA</td>
<td>0.97</td>
<td>RPD = 5.69</td>
<td>Ottavian et al. (2012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moisture content</td>
<td>PLSR</td>
<td>0.98</td>
<td>RPD = 6.66</td>
<td></td>
</tr>
<tr>
<td>Swordfish</td>
<td>Vis-NIR spectroscopy</td>
<td>Freshness</td>
<td>PCR</td>
<td>0.83–0.84</td>
<td>0.2</td>
<td>Fasolato et al. (2012)</td>
</tr>
<tr>
<td>Cod fillet</td>
<td>NIR spectroscopy</td>
<td>Freshness</td>
<td>PLSR</td>
<td>0.90</td>
<td>3.4 d</td>
<td>Baknæs et al. (2002)</td>
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<tr>
<td>Cod</td>
<td>Visible spectroscopy</td>
<td>Freshness</td>
<td>PCA, PLSR</td>
<td>0.97</td>
<td>1.04 d</td>
<td>Nilsen et al. (2002)</td>
</tr>
<tr>
<td>Salmon</td>
<td>NIR spectroscopy</td>
<td>Total fat</td>
<td>PLSR</td>
<td>0.968</td>
<td>RPD = 4.76</td>
<td>Hernández-Martínez et al. (2013)</td>
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<tr>
<td></td>
<td></td>
<td>Fatty acids</td>
<td></td>
<td>0.893–0.996</td>
<td>RPD = 2.35 – 7.68</td>
<td></td>
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<tr>
<td>Atlantic salmon</td>
<td>Visible spectroscopy</td>
<td>Astaxanthin content</td>
<td>PLSR</td>
<td>0.85</td>
<td>0.9 mg kg$^{-1}$</td>
<td>Folkestad et al. (2008)</td>
</tr>
<tr>
<td>Oyster</td>
<td>NIR spectroscopy</td>
<td>Fat content</td>
<td>PLSR</td>
<td>0.94</td>
<td>1.0%</td>
<td>Brown (2011)</td>
</tr>
<tr>
<td></td>
<td>Vis-NIR spectroscopy</td>
<td>Moisture content</td>
<td>PLSR</td>
<td>0.92</td>
<td>0.53%</td>
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<tr>
<td></td>
<td></td>
<td>Protein content</td>
<td>PLSR</td>
<td>0.97</td>
<td>0.18%</td>
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<tr>
<td></td>
<td></td>
<td>Fat content</td>
<td>PLSR</td>
<td>0.97</td>
<td>0.11%</td>
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<td></td>
<td></td>
<td>Glycogen content</td>
<td>PLSR</td>
<td>0.94</td>
<td>0.24%</td>
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<tr>
<td>Oyster</td>
<td>NIR spectroscopy</td>
<td>Freshness</td>
<td>PLSR</td>
<td>0.8</td>
<td>RPD = 5.37</td>
<td>Madigan et al. (2013)</td>
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</tbody>
</table>

described as $I(x, y, \lambda)$ or $I(\lambda, x, y)$ that can be considered either as a detached spatial image $I(x, y)$ at each single wavelength ($\lambda$), or a spectrum $I(\lambda)$ at each individual pixel ($x, y$) (Sun, 2010). From this point, it can be understood that hyperspectral images are composed of hundreds of contiguous wavebands for each spatial location of a targeted object. Accordingly, each pixel in a hyperspectral image holds the spectrum of the corresponding position. The obtained spectrum possesses the functions of reflecting the hidden compositional information of that particular pixel. This characteristic is very beneficial to achieve the visualization of the distribution of biochemical and chemical components of an experimental sample on account those similar spectral characteristics indicate analogous chemical constituents.

**Hyperspectral imaging instruments**

Instruments of hyperspectral imaging system are fundamental and critical guarantee to obtain high-quality and authentic hyperspectral images for further analysis with reliable information. A typical hyperspectral imaging system commonly requires light sources, wavelength dispersion devices, area detectors and a computer system. Light source, as an essential part of optical detection system, generates the light for illumination of the testing sample. Halogen lamps are classical light sources used in a hyperspectral imaging system for lighting up the translation stage. The role of the wavelength dispersion device is to help distribute wideband light into different wavelengths. An imaging spectrograph has been developed as a popular dispersion device in the hyperspectral imaging system. For the area detectors, such as charge-coupled device and complementary metal-oxide-semiconductor cameras, they are two main types of solid state detectors with the capability of controlling and quantifying the intensity of the obtained light by means of transferring incident photons into electrons. With respect to the computer system, it is mainly used for acquisition and calibration of hyperspectral images. The control software usually regulates the exposure time, motor speed, combining mode, wavelength range and image acquisition and calibration. Fig. 1 shows a typical laboratory experimental setup of hyperspectral imaging system. In addition, the approaches for acquisition of hyperspectral images are referred to point scanning, line scanning, and area scanning with three diverse image sensing models of reflectance, transmittance and interac-
tance that are of difference in the positions of optical detector and the light source.

On the other hand, chemometrics as an effective support means has been serving for multivariate data processing and analysis in a hyperspectral imaging system with the aim of establishing the calibration and prediction models and other hidden information mining for practical applications of discrimination, classification, identification, quantification, measurement, detection and assessment of quality and safety of fish and other seafoods. Common linear regression methods such as multiple linear regression (MLR), principal component regression (PCR) and partial least squares regression (PLSR) and non-linear regression methods such as support vector machine (SVM) and artificial neural network (ANN) are two kinds of popular and classical multivariate analysis methods (Prats-Montalbán, De Juan, & Ferrer, 2011). In addition, classification approaches mainly including linear discriminant analysis (LDA), partial least squares discriminant analysis (PLS-DA), soft independent modelling by class analogy (SIMCA), principal component analysis (PCA), support vector machine (SVM), artificial neural network (ANN) and their integrated applications have also been widely developed in hyperspectral imaging when objects have to be classified (Forina, Oliveri, Lanteri, & Casale, 2008). Meanwhile, the analysis procedure of hyperspectral images data based on above hyperspectral imaging system, regardless of the intention of qualitative description or

![Fig. 1. Schematic diagram of main components of Vis-NIR hyperspectral imaging system.](image-url)
quantitative regression, is subjected to the processes of calibration, cross-validation and prediction based upon the above-mentioned chemometrics. As for their performances of the established models, it is necessary to look for effective methods to evaluate the predictive effectiveness, reliability and accuracy for practical applications. Commonly, the evaluation indicator systems are mainly related to the coefficients of determination ($R^2$) and root mean square errors in calibration ($R^2_C$, RMSEC), cross-validation ($R^2_{CV}$, RMSECV) and prediction ($R^2_P$, RMSEP), respectively, and residual predictive deviation (RPD).

Generally speaking, an admirable and comparable model should have higher values of $R^2_C$, $R^2_{CV}$, $R^2_P$ and RPD, and lower values of RMSEC, RMSECV and RMSEP as well as a small difference between them. In details, $R^2$ indicates the proportion of the variance in reference data that can be explained by the variance in the predicted data. The values of $R^2$ are usually expected to be fine in the range of 0.82–0.90 and admirable with values of more than 0.91. The values of RMSEC, RMSECV and RMSEP are measurements of the root mean square errors in the analysis and assessment of the fitting degree of regression during

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**Fig. 2.** Main procedure of application of hyperspectral imaging for seafood quality evaluation. SNV: standard normal variate, MSC: multiplicative scatter correction, RC: regression coefficient, GA: genetic algorithm, SPA: successive projection algorithm.
calibration, cross-validation and prediction with lower values implying better predictive capacity. The values of RPD are considered satisfactory, good or excellent in the region of 3.1–4.9, 5–6.4 or 6.5–8, respectively (Hernández-Martínez et al., 2013). Fig. 2 shows the general procedure of application of hyperspectral imaging for fish and other seafood quality analysis and evaluation.

Applications
In recent years, investigative and exploratory studies have been developed by using this potential and emerging hyperspectral imaging technique for non-destructive and rapid analysis and evaluation of fish and other seafood quality.

Quality analysis and evaluation of fish
Nowadays, fish quality has become an important issue in the fishery industry due to the close linkage of dietary benefits and requirements in terms of human health. Hyperspectral imaging technique has been conducted to detect nematode contamination, determine physical properties, predict chemical compositions, discriminate and measure freshness and inspect microbial spoilage.

Detection of nematode contamination
Nematode infection is a common problem occurring in fishing nations, and it is also a severe issue of food safety. These incidents about nematodes such as parasites in fish muscle to a great extent result in an instant negative response from consumers towards the product, and further generate disbelief in fish as a healthy and nutritious product as well as the noteworthy reduction of fish international trade and consumption (Heia et al., 2007). Therefore, it is important for the fish processing industry to avoid the occurrence of parasites in fish products and detect them on-line. Currently, commercial means of detecting parasites commonly depends on manual and candling inspection with a white light table. However, the efficiency of recognition by traditional method is relatively low (Heia et al., 2007; Sivertsen, Heia, Stormo, Elvevoll, & Nilsen, 2011). Hyperspectral imaging has been developed to detect parasite contamination. In an early study, Wold, Westad, and Heia (2001) investigated the multispectral imaging technique in the visible and near infrared spectral region in alliance with soft independent modelling by class analogy (SIMCA) approach for automatic detection of parasites in cod fillets. It was observed that the spectral features of parasites obtained from the images were different from those of fish muscles free of parasites and this technique was capable of detecting parasites at the depths of 6 mm into the fish flesh, which created fairly good classification evidence and benefited to on-line assessment. It was in concurrence with the study reported by Heia et al. (2007) using the imaging spectroscopy to discriminate good fish muscle from those with parasites for the same cod species. The only difference was that in this study, partial least squares discriminant analysis (PLS-DA) and image filtering techniques were used to analyse the spectral information. Encouragingly, the measuring depth has also been extended to 8 mm below the fillet surface that was 2 or 3 mm deeper than the depth observed by manual inspection of fish fillets (Petursson, 1991). It has also proved that this technique has the potential to identify parasites located both on the outside and inside of the fillets for on-line industrial purposes. In another work, transillumination hyperspectral imaging was conducted to automatically detect nematodes in cod fillets. It was shown that for all the nematodes, the detection rate was 58%, and for dark and pale nematodes, the detection rate was 71% and 46%, respectively, which was comparable to manual inspection under industrial situations (Sivertsen et al., 2011). However, there was a relatively high false alarm rate. In order to improve the correct classification rate, Sivertsen, Heia, Hindberg, and Godtliebsen (2012) made some efforts to solve this problem and the Gaussian maximum likelihood classifier was applied to optimize and reach an ideal recognition effect. Results indicated that the increased detection rate was 70.8% and 60.3% for the dark and pale nematodes, respectively. To some extent, these studies indicate that the hyperspectral imaging has the potential to replace the manual inspection. However, the depth of detection of parasites and the correct detection rate both need to be improved in future.

Measurement of physical properties
Physical properties are important indices for evaluation of fish quality. Colour is one of the significant physical properties indicating fish freshness quality. The colour of fish and fish product is generally the first quality parameter perceived and assessed by consumers for their acceptance or rejection due to the fact that the recognition of certain abnormalities or defects can be easily observed by the changing colour features (Menesatti, Costa, & Aguzzi, 2010; Wu & Sun, 2012). The measurement of colour can be traditionally carried out by visual detection or by using colour measuring instrument such as a colorimeter. However, these measurement methods have been proved to be subjective, laborious and changeable (Erikson & Misimi, 2008). In order to develop a more objective and non-destructive colour analysis technique, the investigation of long-wave near infrared (LW-NIR) hyperspectral imaging in the spectral region of 964–1631 nm was carried out for colour measurement of salmon fillets. The best prediction models were obtained with $R_p$ of 0.876, 0.744, and 0.803 for $L^*$, $a^*$, and $b^*$, respectively (Wu, Shi, et al., 2012; Wu, Sun, & He, 2012). It also indicated that this LW-NIR hyperspectral imaging system could be further designed for simultaneous detection of both colour (visible) and chemical components (invisible) of fish muscle, instead of using a computer vision system for measuring colour and a hyperspectral imaging system to measuring chemical components.

Water holding capacity is another principal parameter for evaluation of fish muscle quality. Rapid determination
of water holding capacity is of great attention for both the industry and the consumers, which can be used to improve the processes of automatic production for further control and classification of the products (Brøndum et al., 2000; Kristensen & Purslow, 2001). However, the present methods for measuring water holding capacity are time-consuming and destructive. Wu and Sun (2013b) developed a non-destructive method for determination of water holding capacity by using two hyperspectral imaging systems conducted in the spectral range of 400–1000 nm and 897–1753 nm. Partial least squares regression (PLSR) and least squares support vector machines (LS-SVM) were applied to establish the calibration models and competitive adaptive reweighted sampling (CARS) algorithm was used to choose the optimal wavelengths for reducing redundancy and collinearity of the hyperspectral images. By comparison, the CARS-PLSR predictive model was acknowledged as the better method to predict water holding capacity of salmon fillet muscle.

Texture also as an important parameter can determine the overall quality perception of fish flesh. There is no doubt that soft flesh is prone to resulting in degenerative acceptability of consumers and quality losses in the fish processing industry (Cheng, Sun, Han, & Zeng, 2014). Fish texture is a complicated term that involves several interrelated physical parameters such as hardness, adhesiveness, chewiness, springiness, cohesiveness, and gumminess. Texture of fish is commonly tested in the industry by the finger method. A finger is pressed on the skin and firmness is evaluated as a combination of the hardness when pressed on fish with mark or hole left in the fish after pressing. This is not desirable to the consumers. This method depends to a large extent upon subjective evaluation of the person who performs the measurements (Özogul et al., 2000). Therefore, it is crucial to achieve objective and non-invasive measurement methods for evaluation of fish texture given that conventional instrumental analysis is difficult to describe and simulate the overall process of texture (Mørkøre & Einen, 2003). Visible and near infrared hyperspectral imaging in the wavelength range of 400–1758 nm as an objective and non-invasive tool was used for determination of texture profile analysis (TPA) in salmon fillet. The results showed that spectral features were more advantageous to predict TPA parameters of fish fillets than image texture features, and the performance of spectral set I (400–1000 nm) was better than that of spectral II (967–1634 nm) (Wu & Sun, 2014). Similarly, He, Wu, and Sun (2014) and Cheng, Qu, Sun, and Zeng (2014) assessed and visualized tenderness distribution of raw farmed salmon fillets and firmness of grass carp fillets as affected by frozen storage. The results also revealed that hyperspectral imaging technique has a great potential to predict the textural features distribution of fish fillets non-destructively and accurately for the food industry. Although this innovative technique has been successfully applied to determine the physical properties of fish quality, these studies still focus on the spectral information obtained from the hyperspectral images. Due to the abundant hidden information of physical image information such as colour and texture, further study should consider information fusion technology (integration of spectra and image information) for improving the reliability and accuracy of hyperspectral imaging system.

**Determination of chemical compositions**

It is well known that fresh fish is an extremely perishable aquatic product and its original chemical properties can be easily modified due to the chemical reactions of fat, protein and other organic compounds and the external and inherent factors such as fish species, age, sex, growth environment, feeding ingredients, seasonal capture and different handling methods (Özogul et al., 2000). These variations of chemical compositions can cause a severe deterioration of sensory quality and loss of nutritional and commercial values. Conventional procedures for monitoring and determination of the contents and structural changes of chemical compositions such as fat and protein are laborious, expensive, and polluted. For that reason, it is attractive and necessary to develop rapid, economic, reliable and environmentally-friendly analytical techniques for assessment of fish quality. Hyperspectral imaging technique coupled with chemometrics has highlighted its ability to determine a variety of chemical properties of fish products simultaneously without using chemicals or time-consuming sample preparation. ElMasry and Wold (2008) used on-line imaging spectroscopy technique to quantitatively determine the content distributions of fat and moisture in six species of fish fillets. PLSR was applied to analyse the spectral data and the predictive models for moisture and fat content showed the $R_p$ of 0.94 and 0.91 with RMSECV of 2.73% and 2.99%, respectively. Another work reported by He, Wu, and Sun (2013) developed the visible and near infrared (Vis-NIR) hyperspectral imaging for non-destructive and rapid analysis of moisture content in farmed Atlantic salmon fillets. Likewise, PLSR was also successfully used to build quantitative relationship between spectral data and the reference measured moisture content values. In addition, three spectral ranges of 400–1000 nm, 900–1700 nm and 400–1700 nm were compared and it was considered that the best spectral region was 900–1700 nm with the $R_p^2$ of 0.902 and RMSEP of 1.450%, respectively. Based upon the eight optimal wavelengths (420, 445, 545, 585, 635, 870, 925 and 955 nm) selected by using regression coefficients of PLSR models, the best simplified new prediction model was obtained with the $R_p^2$ of 0.893 and RMSEP of 1.517%, respectively. It has also been proved that using several sensitive and important wavelengths showed similar prediction functions compared with the whole spectral ranges, which revealed that hyperspectral imaging technique has a great potential to non-destructively and precisely predict the moisture content and distribution of salmon fillets. Another two studies reported by Ljungqvist
et al. (2012) and Cheng, Sun, Zeng, and Pu (2013), who also confirmed that it was possible to predict the level of synthetic astaxanthin coating and total volatile basic nitrogen (TVB-N) value using the hyperspectral imaging technique.

**Discrimination of fresh and stale samples**

The intention of frozen storage of fish is to retain its good quality and extend the shelf life by limiting microbial and enzymatic activities that cause deterioration. Additionally, frozen fish has an advantage of high commercial value and growing demand by the reason of its viable price and extended shelf life (Boonsumrej, Chaiwanichsiri, Tantratian, Suzuki, & Takai, 2007). On the other hand, frozen storage temperature and changeability can easily influence the final quality with the possible changes of colour, texture, lipid oxidation, protein denaturation and ice recrystallization that can lead to rancidity, dehydration, drip loss and increase in volatile basic nitrogen as well as final microbial spoilage and autoysis (Boonsumrej et al., 2007; Sriket, Benjakul, Visessanguan, & Kijroongrojana, 2007). From another point of view, it is significant to differentiate fresh fish from those previously frozen in order to prevent from unfair competition by false labelling and provide the authenticity for consumers. Control of labelling or documentation of quality with respect to freshness and frozen-thawed is possible. Costa, Antonucci, Menesatti, et al. (2013) proposed a non-destructive colorimetric imaging method to detect the whole external body of sea breams for assessment of the freshness preserved under four refrigeration modalities. The results showed that this method was effective to discriminate fresh and non-fresh sea breams based upon the important colorimetric differences and an innovative passive refrigeration system was also proposed for the best fish freshness conservation. In addition, Vis-NIR hyperspectral imaging in the spectral region of 380–1030 nm was investigated to discriminate the fresh and frozen-thawed halibut fillets. LS-SVM classification model was conducted based on the textural feature variables extracted by grey-level co-occurrence matrix analysis. A classification rate of 97.22% was obtained for confirming this technique having potential for reliable discrimination of fresh and frozen-thawed fish fillets (Zhu, Zhang, He, Liu, & Sun, 2013). Similar results were also obtained at farmed Atlantic salmon fillets for prediction of freshness and classification of frozen-thawed samples by using Vis-NIR imaging spectrometer in the region of 400–2500 nm. It has been stressed that there was an accuracy of 58 h for prediction of freshness as storage days in ice for individual fillets, and it was possible to isolate fresh salmon fillets from frozen-thawed samples, which were analogous to earlier results achieved by sensory evaluation with trained panelists (Kimiya, Sivertsen, & Heia, 2013). Also, Menesatti et al. (2010) used Vis-NIR hyperspectral imaging technique to identify the freshness of two fish species with PLS-DA method and the results indicated that a high percentage of correct classification between fresh and non-fresh was obtained at values of 88% for chub mackerel and 82.5% for sea bass. In another work, categorization of fresh Atlantic salmon fillets stored under diverse atmospheres (air, 60% CO₂/40% N₂ and 90% vacuum) using hyperspectral imaging was investigated by Sone, Olsen, Sivertsen, Eilertsen, and Heia (2012), who used principal component analysis (PCA) and K nearest-neighbour classifier. Successful classification of over 88% was obtained that was mainly associated with spectral features at the wavelengths of 606 and 636 nm (Sone, Olsen, Sivertsen et al., 2012). These spectral changes of Atlantic salmon muscle during above storage conditions are mainly due to the oxidation state of heme (Sone, Olsen, & Heia, 2012). Similarly, in order to look for a non-destructive method to detect shelf life of packed processed fish, Ivorra et al. (2013) applied visible and near infrared hyperspectral imaging to distinguish fresh and expired vacuum-packed smoked salmon based on PLS-DA method for classification purposes. A classification rate of 82.7% was achieved with great accuracy and reliability of 0.926 and 0.797 for R_C and R_CVa, respectively. On the basis of the data obtained from the above studies, in order to boost and accelerate the industrial application of hyperspectral imaging technique with the higher correct classification rate near to 100%, it is necessary to promote the hardware of hyperspectral imaging system and develop the suitable classification algorithms.

**Inspection of microbial spoilage**

The potential of visible and near infrared hyperspectral imaging in the region of 400–1700 nm was developed to rapidly and non-invasively determine total viable count (TVC) of salmon muscle during spoilage process. PLSR and LS-SVM were applied to establish the prediction models and CARS algorithm was intended to recognize the sensitive and optimal wavelengths that largely reflected the changes of microbial spoilage. As a consequence, eight important wavelengths (495, 535, 550, 585, 625, 660, 785, and 915 nm) were preferred, and the CARS-PLSR model built in the spectral range of 400–1000 nm was deemed to be the most suitable for TVC prediction of salmon fillet muscle with R² of 0.985 and residual predictive deviation (RPD) of 5.127 (Wu & Sun, 2013c).

Quality analysis and evaluation of other seafoods

As a potential imaging technique, hyperspectral imaging has also confirmed its great ability for the quality analysis and evaluation of other seafoods such as prawn/shrimp and crab. These studies are mainly related to measurement and visualization of moisture content and distribution, detection of adulteration and prediction of the amount of edible meat of crab.

**Determination of moisture content**

Shrimp or prawn as one of the most accepted seafood products is rich in proteins, calcium, vitamins and various
extractable nutrition compounds and it is available as raw materials for making delicious dishes along with development and improvement of the aquaculture industry (Mohebbi, Akbarzadeh-T, Shahidi, Moussavi, & Ghoddusi, 2009). However, this kind of aquatic product is also susceptible to spoilage. Thus, methods for keeping freshness quality and prolonging shelf life are necessary. Dehydration is one of the methods (Niamnuy, Devahastin, & Soponronnarit, 2007). Assessment of dehydration level for food quality control is frequently performed by trained visual inspectors. Currently shrimp quality evaluation is a subjective sum of visual, smell and texture characteristics, and the manual determination of count and uniformity ratio of a sample batch. An automated process is desirable for a more rapidly and objectively repeatable evaluation, without the characteristics of subjectivity, tediousness, and laboriousness as well as unsoundness. Hyperspectral imaging is an alternative technique to rapidly predict moisture content of dehydrated prawns in the wavelength range of 380–1100 nm (Wu, Shi, et al., 2012; Wu, Sun, et al., 2012). In this study, PLSR and LS-SVM were used to build the calibration models and SPA was applied to choose the important and optimal wavelengths (428, 445, 544, 569, 629, 672, 697, 760, 827, 917, 958, and 999 nm) for prediction and visualization of prawn moisture contents and distribution.

Detection of adulteration

Food adulteration is an important aspect of food safety as well as a serious fraudulent practice due to the fact that illegal traders and enterprises commonly and craftily utilize cheaper, inferior and unqualified ingredients and raw materials to act as substitutions of high-cost ingredients and high-quality products. This behaviour of economic adulteration defrauds consumers and disturbs the normal operation of markets with the irrational prices. Presently, ordinary detection methods for food adulteration are both time and effort consuming, and require a great quantity of chemicals. For this reason, there is a demand for non-invasive detection to solve the problem of illegal adulteration in food industry such as seafood (Gayo & Hale, 2007). Potential application of hyperspectral imaging in tandem with multivariate analysis for rapid and non-invasive detection of gelatin adulteration in prawn muscle was investigated in the spectral region of 897–1753 nm (Wu, Shi, He, Yu, & Bao, 2013). It has been illustrated that this emerging technique is reliable and accurate for screening the gelatin adulteration with $R^2$ of 0.965 based upon the LS-SVM calibration model.

Prediction of the amount of edible meat

Crab as another popular seafood is an admirable source of minerals (calcium, iron, zinc, potassium and phosphorus) and essential amino acids for serving a mouth-watering taste and distinctive pleasant aroma (Chen, Zhang, & Shrestha, 2007). Therefore, prediction of the amount of edible crab meat content in a rapid and non-destructive way is obviously important in the fishery industry. Near infrared hyperspectral imaging spectroscopy was first used to determine the edible meat content in individual live crab on a conveyor belt at a high speed as reported by Wold, Kermit, and Woll (2010). Results showed that this technique was capable of realizing on-line classification of crabs according to the edible meat content with a correlation coefficient of 0.96. Meanwhile, the possibility of pixel-wise predictions of crab meat content could accomplish instructive and meaningful images for further revealing the distribution and amount of each crab with the help of pseudo-colour.

Strengths and weaknesses of hyperspectral imaging technique

Based upon the above studies, it has been confirmed that hyperspectral imaging technique is potentially applicable for analysis and evaluation of quality of fish and other seafoods. Compared with traditional techniques and methods, this innovative technique shows its great strengths in quality analysis and assessment. Hyperspectral imaging is a chemical-free measurement and evaluation method that cannot bring environmental pollution. Meanwhile, it has been proved that this technique is time-saving, labour-replacing and highly efficient due to the minimal sample pre-treatments. For practical application, on account of integrating computer vision and spectroscopy for simultaneous acquisition of spatial and spectral information, this non-destructive and non-invasive technique is potential to realize quantitative measurement and qualitative analysis as well as rapid real-time and on-line detection (Wu & Sun, 2013a). Furthermore, the great advantage of hyperspectral imaging is the capability of collecting a full spectrum of every pixel within the scene and visualizing the quality and quantity distribution for the purpose of understanding and interpreting of heterogeneity of food products for further sorting and labelling (Hernández-Hierro, Nogales-Bueno, Rodriguez-Pulido, & Heredia, 2013). Fig. 3 illustrates two examples of visualization for TVC and moisture content distribution in salmon muscle. However, there are also some weaknesses about the hyperspectral imaging technique that need to be resolved in future research and industrial application. Hyperspectral images contain much unnecessary information than a single colour image and therefore it certainly will carry substantial challenges and require more time and superior skills to mine the hidden data by multivariable analysis and to obtain valuable information from the hyperspectral images. The hardware speed of the hyperspectral imaging system needs to be progressed and enhanced to satisfy the fast acquisition and analysis of the enormous hyperspectral data. On the basis of these disadvantages, this hyperspectral imaging technique is not advisable and suggested for direct achievement in on-line purpose. In addition, it is more difficult to explore developed or novel algorithms for eliminating data
redundancy and accelerating on-line inspection speed (Calin, Parasca, Savastru, & Manea, 2013). Besides, there is still a demand for method optimization to limit the sources of error and to enhance the robustness and reliability of the calibrations and predictions such as the accuracy of reference values of food attributes and the selection of ROIs.

Conclusions and future trends

Applications of hyperspectral imaging technique are playing a significant role in analysis and evaluation of quality of fish and other seafoods in research and potential industry service. This review presents the basic information of hyperspectral imaging system including the cube

Fig. 3. Visualization and compositional distribution of hyperspectral images. (a) TVC distribution maps of salmon fillets with different TVC values. (b) Moisture distribution maps of salmon fillets with different moisture values.
information of hyperspectral images, the typical instruments of hyperspectral imaging. Additionally, this review condenses and updates representative selections of current research and potentially industrial applications for the purpose of foreseeing the general trends in how this innovative hyperspectral imaging technique is used to inspect and evaluate quality of fish and other seafoods in future. As a result of integrating both spatial and spectral information in one system, hyperspectral imaging technique can provide 3-D cube information for simultaneous measurements of external and internal properties of aquatic products with the details of detection of nematode contamination, determination of physical properties such as colour, water holding capacity and texture such as firmness and tenderness, prediction and visualization of chemical compositions and distributions mainly related to fat, moisture and protein as well as the relevant value of TVB-N, discrimination of fresh and handled samples and inspection of microbial spoilage and economic adulteration. These studies have confirmed that hyperspectral imaging strengthens its potential for quantitative and qualitative analysis and evaluation of aquatic product quality in a non-destructive, objective, rapid and effective style although there was not enough literature available. On the other hand, some disadvantages in the application of hyperspectral imaging are also presented and discussed in the aspect of computation speed, regression and image processing algorithms, and limitations of computer hardware. Therefore, it is of difficulty for this technique for future industrial application. Correspondingly, there is more room to motivate the development of this emerging technique to be a multispectral imaging system acquiring the spectral images only using several wavelengths depending on the improving and high-performance imaging systems and the fast-growing computing power of computers in the future. In the end, the creation of systems that can be actually transferred to the industry and work at industrial level, or also the creation of systems allowing the inspection of other quality or diseases issues not included in the text.

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