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HYPERSPSPECTRAL IMAGING (HSI): APPLICATIONS IN ANIMAL AND DAIRY SECTOR

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ABSTRACT

Hyperspectral imaging (HSI), also known as imaging spectroscopy or 3D spectroscopy, combines imaging and spectroscopy into a single system. With a high resolution measurement of spectral signatures, HSI is able to provide critical information of the target. Thus it is useful for various scientific and industrial applications, including food safety and disease diagnosis. Due to constantly increasing demands for safe animal products, there is pressure on the processing sector for applications of advanced, high throughput methods for non-destructive quality analysis of animal products. In this context, HSI finds its applications for grading, classification, quality & composition analysis of animal products including meat, egg, milk etc. Further, the technique is also a useful tool in poultry sector for assessment of wholesomeness and quality control of chicken carcasses, as well as, chicken meat products. In fish industry also, the technique has established its potential for determining freshness and quality attributes of sea-foods. Apart from quality control of animal products, HSI has also demonstrated its usefulness for disease diagnosis in animal models and for detection of mammary cancers in dogs. Thus, the future of HSI technology in animal industry is promising and associated with multivariate analysis, HSI technique will further dominate in animal products authentication and analysis in the future also.

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1 Introduction

Computer-aided diagnostic approaches are now approaching the stage where the routine use of such technologies is becoming a reality (Kruppinski, 2004; Rampun et al., 2016; Bekker et al., 2016). Hyperspectral imaging (HSI) is one such technology which has proved its usefulness for various scientific and industrial applications including remote sensing (Tanvir & Michael, 1990; Prasad et al., 2000; Ramakrishanan & Bharti, 2015), environmental monitoring (Moroni et al., 2013), geological search (Kruse et al., 2003; Ramakrishanan & Bharti, 2015), atmospheric composition analysis (Etzion et al., 2014), military target recognition (Richter, 2005), medical diagnostics (Akbari et al., 2011), and food safety inspection (Kamruzzaman et al., 2011). HSI combines conventional imaging, as well as, spectroscopy to obtain spatial information from target across a broad spectral range (Li et al., 2011).

Several narrow band images at different wavelengths are produced by the system, which can be utilized to identify and characterize the target analyte over a wide spectral range. HSI systems even allow studying the targets in ultraviolet (UV), near-infrared (NIR) or infrared (IR) regions, where the human eye is unable to function. In comparison to conventional cameras and other imaging technologies, hyperspectral imaging systems (HIS) provide spectral signatures for each image from a number of narrow, adjacent spectral channels at a very high resolution (a few nanometres), narrow waveband ($\leq 10\text{-}2\text{ }\lambda$) and wide spectral range (200-2500 nm) (Akbari et al., 2009). The measurement of high-resolution spectral signatures helps in revealing important information about the object, which is otherwise not possible with traditional cameras. The acquired multidimensional spectral signature not only reflects the external characteristics of the analyte, but also reveals their internal quality information. Although the technology was initially developed by NASA for remote sensing activities, decrease in price of these systems enables them to be used now for food quality analysis in laboratories (Gowen et al., 2007).

Since the global demand for livestock products is estimated to rise by more than 60 percent by 2050, the livestock sector is under substantial pressure to increase the amount of safe as well as, nutritious animal products in the future. Thus, to satisfy ever-increasing demands of the consumers, rapid non-destructive methods are required for safety and quality assessment of animal products. Recently, HSI has emerged as a potential non-destructive technique for food quality evaluation and has gained interest for meat & meat products analysis. Many studies are now focusing on HSI technology for safety and quality assessment of animal products. HSI has now opened up new avenues for non-destructive prediction of multiple attributes for quality and safety analysis of animal products such as meat (Kamruzzaman et al., 2011), fish (Sivertsen et al., 2011a), egg (Abdel-Nour & Ngadi, 2011) and milk (Qin & Lu, 2006).

Technological advances leading to development of advanced low cost systems have widened scope for its application over the past twenty years. Apart from food quality analysis, hyperspectral imaging is now being used in medicine for disease diagnosis. Very high resolution spectral information obtained by HSI enables detection of minor differences in the reflectance &/or fluorescence signatures of animal tissues and thus, hyperspectral image data represents a promising tool for non-destructive tissue analysis and disease diagnosis. The technique has also been studied in various animal models and dogs for cancer diagnosis. The technique has been used extensively in animal sector and all the potential applications of the technology in this context are covered extensively in this review.

2 Principles of Hyperspectral Imaging

The technique hyperspectral imaging (HSI) is also called as imaging spectroscopy as it combines properties of imaging and spectroscopy. It studies and measures spectra acquired through reflection of the electromagnetic radiation from the object under study. A typical hyperspectral imaging system (HIS) encompasses: (i) a source of light to illuminate the object, (ii) a lens for focusing and delineating field of view, (iii) a spectrograph for splitting the light into different spectral bands (iv) a camera for capturing final spatial-spectral images & (v) a software to monitor the image acquisition. Choice of the mode applied for image acquisition relies largely on the properties of the sample being analyzed. Basically there are three modes for acquisition: (1) Reflectance, (2) Transmittance and (3) Interactance, which mainly differs in configurations of lighting and detector systems. Differences between these 3 acquisition modes results in dissimilar effects of data acquisition from the same object. In Interactance mode, a blend of reflectance and transmittance modes, the source of light and detector are on the similar side of the object under study (Nicola et al., 2007). HSI in reflectance mode is able to detect external properties of the target like target shape, its color, size, etc., but is unable to determine internal quality parameters effectively. On the other hand, transmittance mode is useful in detecting internal characteristics as well (Ariana & Lu, 2008). The interactance mode is suitable for measuring turbid liquids, semi-solid and solid substances (Reich, 2005).

The technology involves image acquisition in the visible and IR or NIR regions. Then these images are combined to form a 3 dimensional hyperspectral cube, and finally the images are visualized as sections of the hypercube with its one spectral and two spatial dimensions. Every spectral pixel of the hypercube refers to a spectral signature, i.e., spectrum of the corresponding spatial region, and it records complete spectrum of the spatial point which is imaged. In other words, recorded spectrum specifies the sample's ability for scattering or absorbing the exciting light, thus characterizing the inherent properties of the sample. With combined properties of imaging and spectroscopy, the HSI technique results in unparalleled capabilities for sample detection, which is not

possible with either spectroscopy or imaging alone. Besides qualitative information, quantitative data can be retrieved from the data cube to predict the distribution of numerous constituents within the sample. The precision of HSI sensors is measured as spectral resolution. The spectral resolution is defined as the thickness of the narrowest spectral feature which can be resolved by the sensor. The bands in the HSI images are very narrow (ranging from 5nm–20nm) and range from UV to thermal IR regions (Muhammad et al., 2012) and thus hyperspectral images acquire a very high spectral resolution resulting in better identification and discrimination of the target.

3 HSI for quality and safety analysis of meat and meat products

Animal products are good sources of protein and vital micronutrients in diet (Ikutegbe & Sikoki, 2014). Due to increasing awareness among consumers, demands for superior quality meat & meat products is continuously rising. Thus modern meat industry requires quality control measures for supply of high quality meat and meat products. Conventionally, meat inspection is done by manual inspection which is labour-intensive, time-consuming and sometimes lacks accuracy. Hence, newer approaches and techniques for meat quality and safety analysis are need of the hour for meat industry. A number of techniques are now being explored for evaluating quality & safety of food products (Liu et al., 2003; Zheng et al., 2006a, Zheng et al., 2006b; Kumar & Mittal, 2010; Quevedo & Aguilera, 2010; Fathi et al., 2011). In the past decade, near-infrared (NIR) spectroscopy has been applied for analysis of food products as it provides analysis with lower costs, higher accuracy and minimal sample processing. Moreover, several quality parameters can be analyzed simultaneously (Wu et al., 2008; Stubbs et al., 2010; Klaypradit et al., 2011). However, it has limited scope as it is unable to determine distribution of chemical constituents within the sample. Therefore, HSI technique has been explored for simultaneous detection &/ or quantification and localization of chemical constituents of the sample. Due to combined features of imaging and spectroscopy, HSI has emerged as a promising technique for non-destructive food quality, as well as, safety analysis (Sun & Brosnan, 2003; Du & Sun, 2005; Jackman et al., 2008; Sun, 2008a; Sun, 2008b). Particularly in the meat industry, the technology has gained significant attraction. Quality aspects of meat and meat products which are currently studied using HSI includes

- Examination of tenderness (Naganathan et al., 2008a; Naganathan et al., 2008b; ElMasry et al., 2012a; Wu et al., 2012a), pH (ElMasry et al., 2012a), color (ElMasry et al., 2012a, Wu et al., 2012a), water content and water holding capacity (ElMasry et al., 2011b), chemical composition (Kobayashi et al., 2010; ElMasry et al., 2012b), and spoilage by microbes (Peng et al., 2011) in beef;
- Classification, grading (Qiao et al., 2007a; Barbin et al., 2012a), and prediction of sensory and quality

characteristics (Qiao et al., 2007b; Barbin et al., 2012b), chemical composition (Barlocco et al., 2006; Barbin et al., 2012c,) and microbial spoilage (Wang et al., 2011; Barbin et al., 2012c; Tao et al., 2012), in pork;

- Muscle discrimination (Kamruzzaman et al., 2011), determination of sensory and quality characteristics (Kamruzzaman et al., 2012a; Kamruzzaman et al., 2013a), and chemical composition (Kamruzzaman et al., 2012b);
- Authenticity analysis (Kamruzzaman et al., 2012c), & adulteration (Kamruzzaman et al., 2013b) in lamb; detection of faecal contaminants (Park et al., 2007), tumors (Nakariyakul & Casasent, 2008; Nakariyakul & Casasent, 2009), bacterial spoilage (Feng et al., 2013a; Feng et al., 2013b), and freshness of chicken (Grau et al., 2011);
- Prediction of contaminants (Segtnan et al., 2009a; Segtnan et al., 2009b), composition (ElMasry & Wold, 2008; Wu et al., 2012), and freshness (Sivertsen et al., 2011b; Sone et al., 2012) in fish.

3.1 Grading and classification of meat

Grading and classification of meat is an important requirement for meat industry. Grading of meat is generally done by manual inspection based on certain standards for grading &/or chemical methods. Manual inspection and chemical procedures are time-consuming, and destructive. Besides, there are chances of manual errors. Thus to overcome these, HSI have been successfully applied for classification of meat (ElMasry & Sun, 2010; Barbin et al., 2012a). For pork, Qiao et al. (2007a) first reported use of HSI technique for authentication wherein, pork samples were differentiated into 5 grades i.e., (1) reddish, firm, and non-exudative (RFN), (2) reddish, soft, and exudative (RSE), (3) pale, soft, and exudative (PSE) pork (4) pale, firm, and non-exudative (PFN) and (5) dark, firm, and dry (DFD); with a classification accuracy of 85.7%. Further, Barbin et al. (2012a) classified porcine meat into three grades (RFN, PSE and DFD), with an accuracy of 96%, using 900–1700 nm long-wave NIR spectral range. Results of these studies demonstrated usefulness of hyperspectral imaging in NIR region for classification and grading of pork. Further, the effectiveness of HSI for lamb quality inspection has also been demonstrated by Kamruzzaman et al. (2011). The technique was found to be efficient for the discrimination of three types of muscles of lamb; namely psoas major (PM), longissimus dorsi (LD), and semitendinosus (ST) muscle, which have entirely different anatomical localization. The researchers (Kamruzzaman et al., 2012c) were also able to differentiate the LD muscle of beef, pork, and lamb with an accuracy of 98.67% in minced pork, beef, and lamb. Furthermore, in cooked turkey ham slices also, classification as well as authentication could be successfully achieved using NIR hyperspectral imaging (ElMasry et al., 2011a). In the spectral range of 900–1700 nm, the technique was also found to be useful for differentiation of frozen-thawed pork from fresh pork (Barbin et al., 2013) and classification of Spanish cooked

ham (Talens et al., 2013) apart from pork fat from different subcutaneous layers (Foca et al., 2013).

3.2 Prediction of quality attributes

Another emerging application of HSI is the prediction of quality parameters and distribution map of chemical constituents in the food. This potent technology has been used successfully for determining various quality and compositional attributes of meat and meat products such as fat content, prediction of meat tenderness, sensory attributes, moisture content, water holding capacity (WHC), colour, pH, protein content etc.

3.2.1 Determination of fat content

As fat is an essential standard for quality assessment criteria, HSI has also been investigated for assessing the assessing proportions of fat in meat and meat products. Scientists have applied HSI technique in intertance mode in the short-wave NIR region (760 to 1040 nm) for developing on-line model for beef fat content evaluation (Wold et al., 2011) and pork trimmings (O'Farrell et al., 2010). Further, a push broom HSI in the reflectance mode (900–1700 nm) has also been developed for rapid non-destructive determination of fat in uncut as well as minced lamb (Kamruzzaman et al., 2012b), beef (ElMasry et al., 2013), pork (Barbin et al., 2012c) and cooked ham (Talens et al., 2013). In yet another study, HSI images within range of 1000–2300 nm were acquired for determining total fat content in beef cuts (Kobayashi et al., 2010). Recently, Huang et al. (2014) used GLCM and gabor filter based HIS technique in fresh loin cut for prediction of intramuscular fat content. Besides total fat content, HSI has also been proved useful for prediction percentage of saturated fatty acid, as well as, unsaturated fatty acid, and key fatty acids such as myristic, palmitic, stearic, myristoleic, palmitoleic, oleic and linoleic in beef cuts (Kobayashi et al., 2010). Undoubtedly, these studies indicate the usefulness of hyperspectral imaging for the non-destructive analysis of fat and fat attributes in meat and meat products.

3.2.2 Prediction of Sensory parameters such as meat tenderness

Apart from above mentioned quality parameters, meat quality is also evaluated based on human senses i.e., taste sight, smell, touch, and hearing. Thus, HSI has also been used for prediction of sensory qualities of meat products, such as tenderness, flavor, juiciness etc. (Barbin et al., 2012b; Kamruzzaman et al., 2013a). Tenderness is important criteria for consumer perception of meat and meat products quality assessment. The assessment of tenderness in meat using HSI technique has been explored recently (ElMasry & Sun, 2010). Meat toughness is generally represented by Warner-Bratzler shear force (WBSF), which is determined instrumentally. Although, using Warner-Bratzler for meat toughness determination yields best

correlation with sensory panel scores but, the technique is time consuming and requires trained manpower. Recently, Wu et al. (2010; 2012d) used HIS technique to determine Warner-Bratzler shear force (WBSF). The same group further used HSI within the spectral range of 400–1100 nm (Tao et al., 2012) for investigation of pork tenderness. Further partial least squares regression (PLSR) models were developed and important wavelengths in 900–1700nm spectral region were identified for the assessment of WBSF for beef (ElMasry et al., 2012a) and lamb (Kamruzzaman et al., 2013a), resulting in good prediction results.

3.2.3 Prediction of water content and water holding capacity (WHC)

Being vital component of food, water is an important attribute for quality assessment of food products (Delgado & Sun, 2002; Sun & Woods, 1993; Sun & Woods, 1994a; Sun & Woods, 1994b; Sun & Woods, 1994c; Sun & Woods, 1997). Apart from meat, in meat products also determination of water content is essential. Researchers have applied PLSR models for HSI in 900–1700 nm range for delineating water content in beef (ElMasry et al., 2013) and pork (Barbin et al., 2012c). Using similar methods, water content has also been estimated in lamb (Kamruzzaman et al., 2012b), cooked ham (Talens et al., 2013) and pre-sliced turkey hams (Iqbal et al., 2013). The results of these studies indicated effectiveness of HSI technique for prediction of water content. Kandpal et al. (2013) used HIS in 400–1,000 nm spectral range for determining water content in cooked chicken and developed PLSR model for extraction of correlation between the HSI spectra and water content. Besides water content, another attribute of concern for consumers purchasing meat, is water holding capacity (WHC). WHC (indicated as drip loss) is an important meat quality indicator because decrease in WHC correlates with reduced processing quality (Prevolnik et al., 2010). In the recent years scientists have also applied HSI techniques in pork, beef, and lamb for determining WHC (ElMasry et al., 2011b; Barbin et al., 2012b; Kamruzzaman et al., 2012a).

3.2.4 Colour, pH and protein content analysis

Market value of meat and meat products highly depends upon physical characteristics such as colour parameters (Wu & Sun, 2012) and pH. HSI is also useful for prediction of other criteria for quality assessment, like pH, color, and protein content and has demonstrated its efficacy for prediction of pH and colour in pork, beef, lamb and sliced turkey hams (Barbin et al., 2012b; ElMasry et al., 2012a; Kamruzzaman et al., 2012a; Iqbal et al., 2013). Further, the NIR hyperspectral imaging technique along with PLSR modelling showed respectable ability for determination of protein content in lamb (Kamruzzaman et al., 2012b), porcine meat (Barbin et al., 2012b), beef (ElMasry et al., 2013), and Spanish cooked ham (Talens et al., 2013) with high accuracy.

Figure 1 Determination of microbial spoilage distribution of muscle foods. (A) Distribution of *Enterobacteriaceae* in chicken fillets. (B) Distribution of TVC in salmon fillets. (C) Distribution of *E.coli* in grams carp fish fillets. [Source: reprinted with the permission from Jun-Hu Cheng, Da-Wen Sun. 2015. Recent applications of Spectroscopic and Hyperspectral Imaging Technique with Chemometric Analysis for Rapid Inspection of Microbial Spoilage in Muscle Foods. *Comprehensive Reviews in Food Science and Food Safety*, 14(4): 478-490. (@2015 Institute of Food Technologists® John Wiley and Sons)]

3.3 Microbial spoilage detection

There is rapid growth of spoilage bacteria on moist nutritious meat surface of meat, if not stored properly (Ellis & Goodacre, 2001). When total viable count (TVC) of bacteria increases over a certain threshold value, the meat & meat products becomes unacceptable for human consumption and thus TVC is an important indicator for evaluating safety of meat & meat products. Conventional methods for detection of bacterial spoilage in meat comprises of microbiological, chemical and physical techniques (Nychas et al., 2008), which are laborious, time-consuming, require specialized laboratory procedures and manpower. Moreover, most of the techniques are destructive (Ellis et al., 2004). Recently, in meat industry HSI has been applied in the area of microbial spoilage detection (Peng et al., 2011; Wang et al., 2011; Tao et al., 2012; Feng & Sun, 2013a, Feng & Sun, 2013b; Feng et al., 2013). Findings from these studies clearly indicate the utility of HSI in determining bacterial activity leading to change in meat quality. Quantitative information on bacterial contamination in beef and pork samples was also determined using HSI. Further the studies also showed usefulness of HSI in prediction of shelf

life of raw beef and pork. Peng et al. (2011) studied the microbial spoilage process (TVC determination) in beef using hyperspectral imaging system (HIS) (400–1,000 nm) in scattering mode. In pork meat also, HSI has been explored for TVC determination (Tao et al., 2010; Wang et al., 2010; Wang et al., 2011). HSI techniques have also been applied for quantitative detection of *Pseudomonas* (Feng & Sun, 2013a), and *Enterobacteriaceae* (Feng et al., 2012) in pork. The technique has also been utilized for determination of psychrotrophic plate count (PPC) and TVC in chilled porcine muscle (Barbin et al., 2012d).

3.4 Physical contaminants and defects detection

Consumers always want to be assured that the meat products in the market are safe, wholesome and free of contaminants & diseases. However, identification of various sorts of contaminants in meat & meat products is a challenging task and requires development of rapid reliable tests. Due to its potential advantages, HSI can be successfully employed to replace current manual inspection techniques. Although, equally effective for other meat species also, most research on

HSI for detection of physical contaminants and defects has been conducted on poultry carcasses (Nakariyakul & Casasent, 2008; Nakariyakul & Casasent, 2009). In the past decade, USDA Agricultural Research Service (ARS) has successfully developed HSI techniques for visualizing different contaminants and defects in chicken carcasses (Windham et al., 2005a; Windham et al., 2005b; Yoon et al., 2007) and these systems are in use for online inspection of poultry carcasses (Elmasry & Sun, 2010). Recently, Yoon et al. (2011) developed a prototype HIS based on line-scanning for online identification of ingesta and faecal material on chicken carcasses with detection accuracies from 89% and 98% depending on the algorithms used for detection (Yoon et al., 2011). Further, HSI systems have been designed for online inspection of carcasses and discrimination of systemically diseased chicken from wholesome ones at a high speed of approximately 140 birds per minute (Chao et al., 2010; Yang et al., 2010).

3.5 Detection of adulterants

Various meat products (patties, sausages, meatballs, etc) require minced meat materials, which are attractive targets for adulteration (Kamruzzaman et al., 2012c, Kamruzzaman et al., 2013b). Due to mincing structural characteristics of meat muscle are removed and thus it is often challenging to differentiate between different types of meat. Often, meat products are also adulterated with low-cost materials such as gelatin, offals or organ meats, flour etc. (Wu et al. 2013; Morsy & Sun, 2013). Such adulteration can cause serious health risks for example allergic reaction to an adulterant (Zhao et al., 2014). Several biochemical, immunological and molecular techniques have been utilized for detection of adulterants in minced meat. Although, these techniques are efficient in detection of adulterants, most of them are destructive, time consuming, and requires specialized laboratories. HSI has emerged recently as an effective tool for rapid, non-destructive detection of contaminants in food products (Kamruzzaman et al., 2014). Recently, Kamruzzaman et al. (2013b) developed a rapid technique based on HIS in 900–1700 nm range for detection of adulteration of pork, kidney, lung, heart, and in minced lamb. The study used PCA for identification of the most adulterated minced lamb. Gelation is another material, often used for adulteration for prawns and shrimps, which being transparent isn't easily identified by naked eyes. Wu et al. (2013) recently used HSI for successful detection of gelatin adulteration in prawns.

4 Applications of HSI in poultry sector

In poultry, most work related to HSI has been done for detection of faecal contaminants and ingesta (Park et al., 2007; Windham et al., 2003; Windham et al., 2005a, Windham et al., 2005b; Yoon et al., 2007; Nakariyakul & Casasent, 2008, Nakariyakul & Casasent, 2009). The differences between spectral properties of normal skin and the contaminants were exploited for detection of contaminants. Researchers have used these differences for developing an online imaging system for

real-time detection of contaminated chickens (Yoon et al., 2011; Chao et al., 2014). Researchers have also developed imaging systems for contamination detection in chicken carcasses in an off-line mode (Windham et al., 2003; Lawrence et al., 2004). On the basis of differences in the spectra of healthy and systemically diseased chicken, HIS was applied for identification of systemically diseased carcasses (Yang et al., 2006; Chao et al., 2007; Chao et al., 2008; Yang et al., 2010). HIS was also found to be useful for microbial spoilage detection (TVC) in chicken filets (Feng & Sun, 2012). Hyperspectral fluorescence imaging, yet another potential application of HSI was used for skin tumor detection on poultry carcasses with 76–98% overall detection accuracies (Kim et al., 2004; Kim et al., 2010; Nakariyakul & Casasent, 2007; Nakariyakul & Casasent, 2009).

Due to increasing throughput of egg industry, visual inspection of eggs by humans (candling), becomes a bottleneck in egg sorting chain. Thus, HIS based systems have been developed to provide solution for a number of egg problems, for example detection of blood spots in shell eggs (Schouenberg, 2003). Technique has also been used for detection of infertile, contaminated, and dead eggs (Chalker, 2003). During early incubation periods, detection of infertility using HSI would help hatcheries in removing infertile or problematic eggs, thus reducing costs and incubator space. Further, contamination due to exploding contaminated eggs will also be minimized. Another quality control aspect in production of designer eggs is estimation of PUFA, i.e., ω -3 polyunsaturated fatty acids. HSI systems have been successfully employed to classify eggs according to their PUFA content in a rapid and non-destructive manner (Abdel-Nour & Ngadi, 2011). Thus, HSI have a bright future in poultry industry for quality control of designer eggs and detection of defects in developing eggs.

4.1 HSI for quality and safety analysis of sea-foods

Sea-food products enrich human and pet foods with excellent protein, fat and other nutritional components. Due to low concentration of saturated fats and empty calories (good for weight control), with high protein content, fish and other seafood are a fantastic source of nutrition for dogs. Therefore evaluation of fish and other sea-foods quality is important for human and pet health. Sea-foods are highly perishable and therefore rapid techniques for non-destructive monitoring of quality as well as safety parameters are required. Due to its potential for food quality analysis, HSI has been exploited for safety and quality assessment of sea-foods such as trout, sea bass, salmon, halibut and cod. Recently, HSI has emerged as a method of choice to provide non-destructive evaluation of freshness of fish. In 2006, the technique was first applied for moisture and texture prediction (Casas et al., 2006), and then in 2010, it was used for determination of fat distribution in fishes (Elmasry & Sun, 2010). Since then, the technique has emerged as a potential alternative to traditional analytical methods for rapid non-destructive prediction of nematode contamination (Sivertsen et al., 2011a; Sivertsen et al., 2012; Coelho et al., 2013), determination of physical and chemical constituents

such as moisture (ElMasry & Wold 2008; Wu et al., 2012c; He et al., 2013), WHC (Wu & Sun, 2013b), colour distribution (Wu & Sun, 2012; Wu et al. 2013); texture (Wu et al., 2012a), ice fraction (Stevik et al., 2010), pH (He et al., 2012), fat content (ElMasry & Wold, 2008; Elmasry & Sun, 2010); freshness (Ivorra et al., 2013), detection of microbial spoilage (Wu & Sun, 2013a); storage time determination (Huang et al., 2011), and detection of adulterants (Dissing et al., 2011). Most studies preferred Salmon for prediction of quality aspects, while a number of different fish species were considered for moisture and fat determination by HSI technique. Recent research have also proven utility of the technique in detection of parasites such as nematodes and fish ridges (Elmasry & Sun, 2010; Sivertsen et al., 2011a; Sivertsen et al., 2012). Researchers have also established HIS based automated systems for nematode detection in full size cod filets operating at a belt speed of 25 mm/s (Sivertsen et al., 2011a) and 400 mm/s (Sivertsen et al., 2012) to meet the industrial requirements.

Another potential application of HSI in fish industry is freshness determination (Menesatti et al., 2010; Elmasry & Sun, 2010; Zhu et al., 2013). Researchers have extracted spectral and textural characteristics from hyperspectral images for successful differentiation of fresh, slow frozen-thawed and fast frozen-thawed fish filets (Zhu et al., 2013). Further, the technique is also useful for detection of expired smoked salmon (Ivorra et al., 2013). HSI was also used to differentiate between sea cage cultured and concrete tank cultured sea bass (Sone et al., 2012). Thus, recent research has demonstrated the utility of HSI for monitoring all steps during the production and supply of sea-foods.

4.2 Applications of HSI in dairy industry

Dairy products consist of complex assemblies of dissolved, suspended and emulsified substances, such as carbohydrates, fat, proteins, minerals and vitamins. Traditional methods for analysis of dairy food require destruction of samples and, are time consuming, as well as, laborious. The HIS technique has amazing potential in dairy industry as a non-destructive analysis tool for wide range of applications. However, to date there are few published applications of HSI related to dairy industry. As fat concentration of milk varies spatially, HSI technique holds promise for measuring size distribution of milk fat globules during homogenization. Applications of HIS in this context could help in characterizing effects of homogenization parameters on particle size distribution. This could lead to accurate prediction of the end-point for the homogenization parameters. Qin & Lu (2006) have used the technique for prediction of milk fat content by application of imaging in reflectance line-scanning mode. Further, the technique has scope for developing quality control systems for the cheese-making process. During cheese making process, changes in the light-scattering properties of milk are observed due to modifications in the size and distribution of fat globules. These changes can be successfully used for non-destructive monitoring of cheese-making process. HSI based technique has

been used by Woodcock et al. (2008) for determining cheese quality, as well as, authenticity.

So far, in milk industry HSI has been used mainly to detect adulterants such as melamine. Adulteration of melamine (2,4,6-triamino-1,3,5-triazine) in food is an important safety issue. In 2007, adulteration of pet food with melamine was the reason behind death of many pets (Tyan et al., 2009). Fu et al., (2014) successfully used HSI technique for melamine detection in milk powders. Qin et al. (2013) used Raman hyper-spectral imaging to detect multiple adulterants in milk powder.

4.3 HSI in animal disease diagnosis and surgery

Apart from food quality analysis, HSI applications have extended in the area of disease diagnosis. Since animal tissues have certain optical features corresponding to their chemical characteristics, HSI is useful for determining physiologic and pathologic alterations at tissue level. Thus the technique can determine healthy or diseased status of the tissue effectively. Since the technique is based on camera, and is a non-destructive technique, without any requirement of close contact, it is useful in a wide range of medical applications for example in disease diagnosis or for monitoring surgical treatments. Moreover, it is useful in providing quantitative information related to oxygen saturation in the tissues of cases suffering from vascular disease (Kellicut et al., 2004). Further, it is also useful during intestinal surgery for prediction of ischemic regions of the intestine during surgery (Akbari et al., 2010) and for diagnosis of hemorrhagic shock (Cancio et al., 2006). In diabetic patients, HSI has been found to be useful for prediction and follow-up of foot ulcers for healing (Khaodhiar et al., 2007). An important application of HIS in medicine is discrimination of cancerous tissue from healthy tissue (Martin et al., 2006). Thus, apart from determining quality and safety attributes of livestock products, the technique can also be used for non-destructive diagnosis of diseases such as cancers (Siddiqi et al., 2008; Akbari et al., 2011; Liu et al., 2012).

In veterinary medicine, HSI has not been exploited to full extent, however, it has been used for quantitative assessment of canine mammary tumours (Manea et al., 2015), including, (i) identification of the tissue types in the tumour affected area, (ii) generation of a map for representing different tissue types, and, (iii) analysis of this map & assessment of the apparent area of each identifiable tissue type. The utility of the technique for cancer and other disease diagnosis has also been demonstrated on various animal models (Fei et al., 2012). Further, it has also been exploited for detection of tumours (Kim et al., 2004; Kong et al., 2004; Nakariyakul & Casasent, 2007) and systemic diseases (Yang et al., 2006; Yang et al., 2010) in chicken carcasses. Moreover, as HSI can differentiate between healthy and diseased tissues, the technique can be used as a monitoring tool during surgery for improving the chances of removal of all cancerous tissue by enhancing visualization of cancerous tissue during surgery (Panasyuk et al., 2007). Therefore, the technique provides reliable, real-time

evaluation of intra-operative margins during surgery. This application would be of great value for cancer surgery in animals and should be further explored for veterinary applications.

5 Conclusion, challenges and future prospective

Applications of HSI delineated through this review undoubtedly prove the usefulness of HSI in livestock and poultry sector. As the technique is rapid, non-destructive, reagent-less and applicable for analysis of broad range of quality attributes, currently designed low-cost systems has now moved the technology from laboratories to meat, poultry and fish screening, as well as, processing lines. However, compared to standard cameras, systems for HSI are still expensive and for further extending the utility of technique in animal industry, new models with comparatively lower cost are required. Further, the potential of HSI for animal disease diagnosis and in dairy sector needs to be explored further. In spite of the fact that conventional methods for milk & milk products testing in the dairy industry could be complemented with HSI for more precise & rapid evaluation, only few applications of HSI have been explored so far in this direction. The technique holds promise for safety evaluation of dairy products during all stages of processing: from raw milk to value-added milk products, and to waste products classification. To conclude, the future of hyperspectral systems applied to animal industry is promising as the technology has shown a remarkable potential for animal products quality evaluation, apart from its applicability in animal disease diagnosis.

Abbreviations

HSI	Hyperspectral imaging
HIS	Hyperspectral imaging systems
TVC	Total viable count
WHC	Water holding capacity
IR	Infrared
NIR	Near infrared
PLSR	Partial least squares regression
WBSF	Warner-Bratzler shear force.

Conflict of interest

Authors would hereby like to declare that there is no conflict of interests that could possibly arise.

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