Trends in Food Science & Technology 69 (2017) 25–35

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: http://www.journals.elsevier.com/trends-in-food-science-and-technology

Review

Hyperspectral imaging technique for evaluating food quality and safety during various processes: A review of recent applications

Yuwei Liu [a, b, c], Hongbin Pu [a, b, c], Da-Wen Sun [a, b, c, d, *]

[a] School of Food Science and Engineering, South China University of Technology, Guangzhou 510641, China
[b] Academy of Contemporary Food Engineering, South China University of Technology, Guangzhou Higher Education Mega Center, Guangzhou 510006, China
[c] Engineering and Technological Research Centre of Guangdong Province on Intelligent Sensing and Process Control of Cold Chain Foods, Guangzhou Higher Education Mega Centre, Guangzhou 510006, China
[d] Food Refrigeration and Computerized Food Technology, University College Dublin, National University of Ireland, Agriculture and Food Science Centre, Belfield, Dublin 4, Ireland

A R T I C L E I N F O

Article history:
Received 8 November 2016
Received in revised form
8 August 2017
Accepted 20 August 2017
Available online 24 August 2017

Keywords:
Imaging spectroscopy
Cooking
Drying
Chilling
Freezing
Curing

A B S T R A C T

Background: The quality of products depends on their processing. Effective way of monitoring and controlling these processes will ensure the quality and safety of products. Since traditional measurement methods cannot achieve on-line monitoring, imaging spectroscopy, as a fast, accurate and non-destructive detection tool, has been widely used to evaluate quality and safety attributes of foods undergoing various processes.
Scope and Approach: In the current review, detailed applications of hyperspectral imaging (HSI) system in various food processes are outlined, including cooking, drying, chilling, freezing and storage, and salt curing. The study emphasized the ability of HSI technique to detect internal and external quality parameters in different food processes. Also, the advantages and disadvantages of HSI applications on these food processes are discussed.
Key Findings and Conclusions: The literature presented in this review clearly demonstrate that HSI has the ability to inspect and monitor different food manufacturing processes and has the potential to control the quality and safety of the processed foods. Although still with some barriers, it can be expected the HSI systems will find more useful and valuable applications in the future evaluation of food processes.

1. Introduction

Cooking (Han, Li, Yu, & Sun, 2016), drying (Delgado & Sun, 2002; Ma, Sun, Qu, & Pu, 2017; Pu & Sun, 2016, 2017; Qu et al., 2017; Sun, 1999; Yang, Sun, & Cheng, 2017), cooling (McDonald, Sun, & Kenny, 2000, 2001; Sun, 1997; Sun & Brosnan, 1999; Sun & Zheng, 2006; Wang & Sun, 2004; Zheng & Sun, 2004), freezing (Cheng, Sun, & Pu, 2016; Cheng, Sun, Zhu, & Zhang, 2017; Kiani, Zhang, Delgado, & Sun, 2011; Ma et al., 2015; Pu, Sun, Ma, & Cheng, 2015; Xie, Sun, Xu, & Zhu, 2015; Xie, Sun, Zhu, & Pu, 2016) and storage, curing, and fermentations are common techniques for processing foods. The monitoring and controlling of these processes can affect the quality and safety of the final products. Traditional quality measurement methods or instruments, such as the oven method for measuring moisture content, the colorimeter for color, and the textural profile analyzer for texture, cannot realize on-line monitoring of a food process. Therefore, the development of non-contact, non-destructive on-line detection tools is required.

Emerging non-destructive analytical instruments and approaches have been investigated for food processing, including spectroscopy, computer vision (Du & Sun, 2005; Jackman, Sun, & Allen, 2009, 2011; Sun & Brosnan, 2003; Xu, Riccioli, & Sun, 2017; Xu & Sun, 2017) and hyperspectral imaging (Cheng & Sun, 2015, 2017; Cheng, Sun, Pu, & Zhu, 2015; Cheng et al., 2016; ElMasry, Sun, & Allen, 2013; Feng et al., 2013; Feng & Sun, 2013b; Kamruzzaman, ElMasry, Sun, & Allen, 2013; Li, Sun, Pu, & Jayas, 2017; Ma, Sun, & Pu, 2016; Pu, Kamruzzaman, & Sun, 2015; Su, He, & Sun, 2017; Wu & Sun, 2013; Xiong et al., 2015;

* Corresponding author. Food Refrigeration and Computerized Food Technology, University College Dublin, National University of Ireland, Agriculture and Food Science Centre, Belfield, Dublin 4, Ireland.
E-mail address: dawen.sun@ucd.ie (D.-W. Sun).
URL: http://www.ucd.ie/refrig, http://www.ucd.ie/sun

http://dx.doi.org/10.1016/j.tifs.2017.08.013
0924-2244/

Xu, Riccioli, & Sun, 2016). Spectroscopy, as a kind of optical method, can provide the information of interaction of electromagnetic radiation with atoms and molecules, thus to determine multiple quality parameters simultaneously in a fast and non-invasive way (Magwaza et al., 2012; Scotter, 1997). In the last few years, near infrared (NIR) spectroscopy has been widely used for the assessment of quality attributes of various foods, such as beverage, dairy products, fruits, vegetables, meat and meat products (Andrés et al., 2008; Cen & He, 2007; Prieto, Andrés, Giráldez, Mantecón, & Lavín, 2008, 2009). However, it cannot obtain spatially distributed spectral responses of the specimen. As for computer vision, it analyzes digital images for rapid visual evaluations, thereby receives spatial information of the tested materials, including size, shape, color, and texture, which has been developed as a useful tool for physical properties assessment and quality inspection of a variety of food products (Brosnan & Sun, 2004; Du & Sun, 2006; Sun, 2000). Unfortunately, computer vision cannot provide chemical composition data, and thus it cannot be used for determining internal quality attributes (ElMasry, Barbin, Sun, & Allen, 2012a). As a combination and extension of spectroscopy and computer vision, HSI goes far beyond these two techniques. On one hand, by recording the spectral characteristics of samples, the HSI system can identify the spectral signatures that are related to molecular overtones and combinations of these fundamental vibrations due to the stretching and bending of N–H, O–H, and C–H groups, thus can be used for quantitative and qualitative analyses. On the other hand, HSI obtains the overall scene of the sample, providing much more detailed spatial information, thus it has the ability for classifying objects in the scene based on their spectral properties. By acquiring two-dimensional spectral information and one-dimensional spatial information, HSI has the capability and ability to determine both internal and external quality attributes, and generate chemical maps to visualize the distribution of quality parameters in foods. HSI has therefore been used as a technique for food analysis and classification in real-time as compared with traditional time-consuming, destructive, and expensive methods associated with inconsistency and variability, thus opening up new possibility for rapidly and nondestructively analyzing foods (ElMasry et al., 2012a).

The capability of the HSI technique has been primarily developed for food quality evaluation and inspection. The research activities are mainly divided among (a) agricultural products (such as apple, peach, strawberry, cucumber, mushroom), whose key attributes are firmness, presence of bruises, defects, and chilling injury (ElMasry, Kamruzzaman, Sun, & Allen, 2012b; Liu, Zeng, & Sun, 2015; Lorente et al., 2011); (b) seafood (such as salmon, cod fillet, oyster), focusing on color, texture and fat (Cheng & Sun, 2014); and (c) meat and meat products, which are studied for chemical, microbiological, sensory (color, marbling, tenderness), and technological (pH, water holding capacity) attributes (ElMasry et al., 2012a; Xiong, Sun, Zeng, & Xie, 2014).

Beside the foregoing applications, research activity in HSI applications has been extended to study the quality and safety attributes of food products as affected by processing, such as cooking, drying, chilling, freezing and storage, curing, and fermentations. However, up to now, no review has been published addressing this aspect. This review intends to provide detailed information on applying hyperspectral imaging for evaluating the quality and safety aspects of foods undergoing processing, thus leading to rapid and non-destructive on-line process control. It is hoped that the review will encourage more applications of HSI in the food industry.

2. Recent applications of HSI in various food processes

2.1. Cooking process

Industrial cooking is a widely used thermal process for enhancing sensory attributes of food products. The main effects of industrial cooking on the food materials lie in four aspects: microbial activity, enzymes, nutritional components, and sensory quality. Both positive and negative influences of industrial cooking on food are illustrated in Table 1. Among the advantages and disadvantages of the cooking processes, the monitoring of cooking conditions using a fast and non-contact method should be investigated, and HSI has therefore been studied for the assessment of food products during the industrial cooking process.

2.1.1. Moist heating method

Moist heating means cooking food using water or steam. Using hot water to process food also refers to boiling, or water bath immersion, which ensures that food can be heated relatively uniformly. In recent years, the HSI system has found its potential for predicting core temperature and cooking loss of meat and meat products that were boiled in a water bath (ElMasry & Nakauchi, 2015; Pu, Sun, Ma, & Cheng, 2015; Xie, Sun, Xu, & Zhu, 2015). In relation to temperature monitoring for detecting biochemical reactions in food during thermal treatment, ElMasry and Nakauchi (2015) used HSI for non-destructively predicting the core temperature (T_C) and thermal history (TH) of a Japanese seafood product in the spectral range of 900–2500 nm. Partial least square regression (PLSR) was applied to build the prediction model and it generated a reasonable accuracy with $R_P^2 = 0.86$ and 0.83 for T_C and TH, respectively. In addition, a linear discriminant analysis (LDA) algorithm was used to distinguish samples with the T_C reaching 65 °C, which indicated the cut-off limit of “cooked” and “uncooked” samples, yielding a classification accuracy of 93.8%. In another study by Nguyen Do Trong et al. (2011), the HSI technique combined with chemometrics was used to detect the cooking front (the interface between the raw and fully cooked part) of potatoes in a water bath. In the hyperspectral images of the potatoes, the pixels of the raw part, cooked part, and background were assigned value of 2, 1, and 0, using partial least squares discriminant analysis (PLSDA). Fig. 1 shows the chemical images of these samples, in which the cooking front of the potatoes heated from 0 to 30 min could be clearly observed, which could help to monitor the cooking process.

Steam heating cooks food at 100 °C. In comparison with traditional boiling, steaming is superior in achieving a better capacity of heat transfer. However, conventional instrumental procedures such as differential scanning calorimetry (DSC) and microscopy for determining contents or structural changes of certain chemical component are time-consuming and laborious (Bertram, Wu, Straadt, Aagaard, & Aaslyng, 2006a, b). For this reason, ElMasry, Iqbal, Sun, Allen, and Ward (2011) employed a HSI system in the NIR region of 900–1700 nm to evaluate the quality of different steam-cooked turkey hams based on their spectral data. Subsequently, Iqbal, Sun, and Allen (2013) attempted to simultaneously predict the moisture, color (a^*), and pH of steam-cooked, pre-sliced turkey hams by using the same HSI system. PLSR was used to establish the calibration model while a regression coefficient (RC) was used to select the optimum wavelengths, yielding R^2 of 0.88, 0.74, and 0.81 with RMSECV of 2.51, 0.35, and 0.02 for moisture content, color and pH, respectively.

2.1.2. Dry heating

Baking, grilling, and roasting are the main dry heating methods. For roasting, the heat treatment of coffee and cocoa generates

Table 1
The positive and negative influence of industrial cooking on food materials.

Positive influence	1. Prolonging the shelf-life of food products by: (a) restraining or killing microbes, such as pathogenic bacteria, putrefying bacteria and other detrimental microorganism; (b) inactivation of enzyme, such as peroxidase (Dewanto, Wu, Adom, & Liu, 2002) 2. Destroying unnecessary or harmful components in the raw materials (Mora, Curti, Vittadini, & Barbanti, 2011) 3. Improving palatability of products by generating special and favorable flavor, fragrance and texture (Mora et al., 2011) 4. Increasing utilization and digestibility of some nutritional components (Dewanto et al., 2002)
Negative influence	1. Loss of some nutritional contents, especially degradation of heat-sensitive ingredients (Kong, Tang, Rasco, & Crapo, 2007) 2. Undesirable changes of quality attributes, such as non-enzymatic browning or over-cooking (Rattanathanalerk, Chiewchan, & Srichumpoung, 2005) 3. Consumption of excessive energy (Sun, 2014)

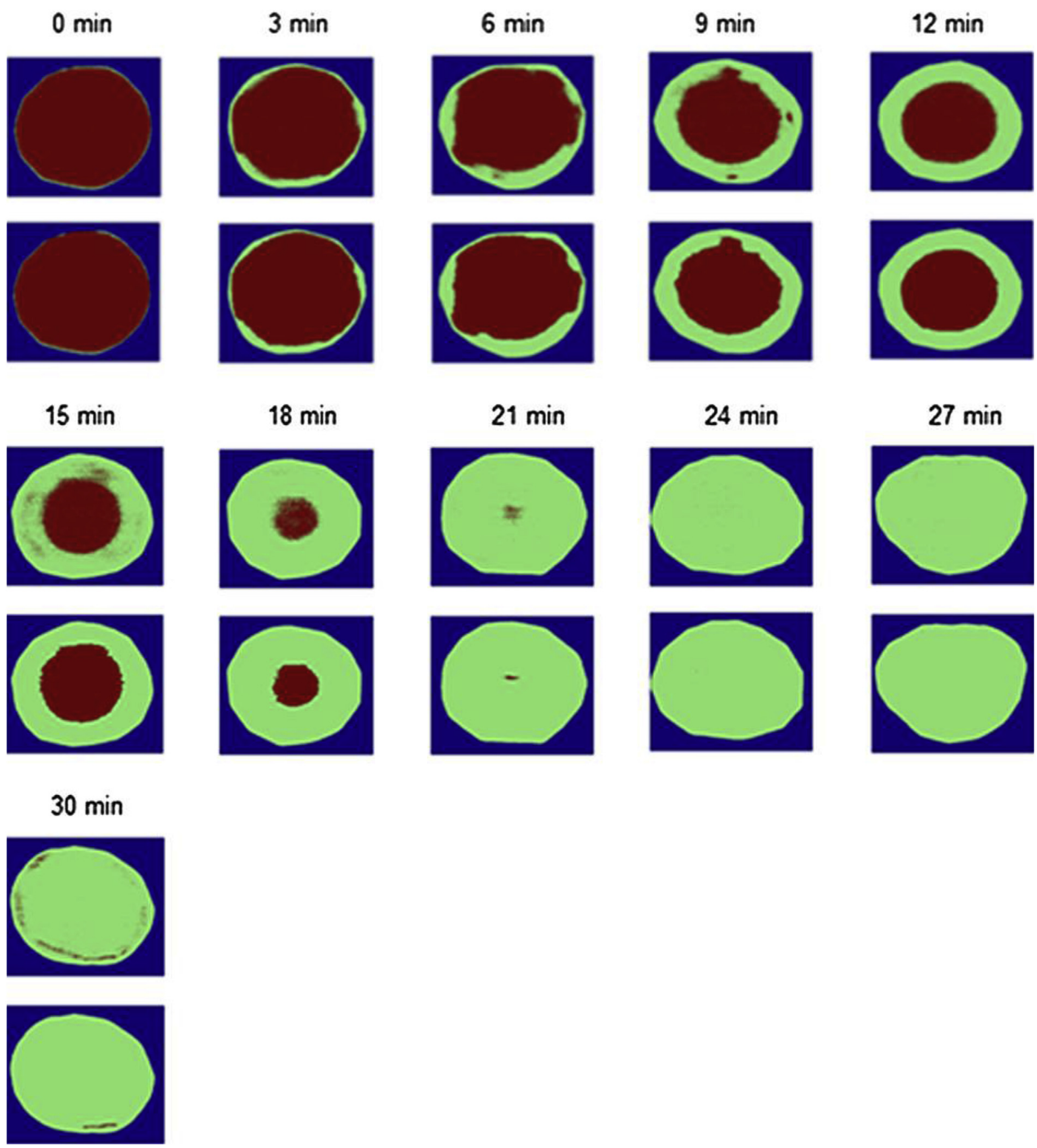

Fig. 1. PLSDA images of potatoes with different cooking times predicted by the PLSDA model (first row) and corresponding false color images resulting from image processing (second row).

special aroma and color. Baking and grilling are usually used for preparing cake, bread, meat or vegetables. In grilling and roasting meat and meat products, a large number of internal and external quality attributes change, including tenderness, which is the most important sensory attribute (Rødbotten, Nilsen, & Hildrum, 2000). For assessing tenderness, the Warner-Bratzler shear force (WBSF) and the slice shear force (SSF) are two common instrumental methods (Chen et al., 2015; Fu et al., 2015). As for the sensory evaluation of tenderness, it is usually conducted by trained panelists with sensory scores. However, neither instrumental nor sensory evaluation of tenderness of meat and meat products is suitable for fast and on-line monitoring. Therefore, attempts have been made using HSI for the tenderness assessment of various heat-treated meats (Table 2). Barbin, ElMasry, Sun, and Allen (2012) and Kamruzzaman, Elmasry, Sun, and Allen (2013), respectively, used hyperspectral imaging in the NIR region (900–1700 nm) for evaluating tenderness of grilled pork and lamb meat, which were successfully correlated with tenderness scores obtained from experienced panelists. However, subsequent PLSR models yielded a poor relationship between the spectral information and the sensory tenderness, possibly due to the small range of response values. Although the sensory tenderness could not be predicted by the acquired PLSR model, the classification ability was excellent when the tested samples were split into two sub-groups: tough with sensory scores <5.0 and tender with sensory scores ≥5.0, with the overall classification accuracy of 91% and 97% for lamb and pork, respectively. As for instrumental tenderness, Naganathan et al. (2008a) examined the possibility of applying a HSI system (400–1000 nm) for predicting SSF as the indicator of tenderness of roasted beef steak. A canonical discriminant analysis (CDA) model was established to predict three beef tenderness categories: tender, intermediate, and tough, with an excellent accuracy of 96.4%.

2.2. Drying process

Food drying, or food dehydration, is a conventional food processing and preservation method. Drying involves the removal of water from food materials to reduce water activity, thus decreasing the rate of microbial spoilage. There are different drying methods, mainly including convective drying, spray-drying, vacuum-drying, and freeze-drying. Improper drying conditions can have negative impacts on food products, leading to unpleasant physical changes (dry shrinkage, dry crack, and case-hardening) and chemical changes (destruction of certain nutritional ingredients and pigments, and loss of some flavor compounds) (Mujumdar & Law, 2010).

In monitoring the drying process, color and moisture content (MC) are two main parameters. Traditionally, color can be assessed by a colorimeter, while MC can be measured using the oven drying method. However, these traditional instrumental methods are time-consuming, laborious, and destructive. For food with a non-uniform color and MC distribution, these methods can only be used for measuring their average values by mincing the samples. Thus, HSI has been investigated to rapidly and non-destructively determine these two parameters in drying processes. Table 3 summarizes these relevant studies, including hot-air drying, microwave-vacuum-drying (MVD) and freeze-drying.

2.2.1. Hot-air drying process

Hot-air drying is a convective process, where food samples are put in a convective dryer or oven and the air is the heat source and the carrier of moisture. Xie, Li, Shao, and He (2014) studied the feasibility of applying the HSI technique for the non-destructive measurement of color components (ΔL^*, Δa^*, and Δb^*) and the classification of tea leaves during different drying periods. Successive projections algorithm (SPA) was used to select the effective wavelengths, and the least squares-support vector machine (LS-SVM) model was established, giving encouraging results with correlation coefficients (r_p) of 0.929, 0.849, and 0.917 for ΔL^*, Δa^*, and Δb^*, respectively. For foods of animal origin, Wu et al. (2012) have successfully developed a HSI system based on multiple linear regression (MLR) for predicting MC of hot-air dried prawns. They (Wu et al., 2013) also used time series hyperspectral imaging (TS-HSI) for drying kinetic analysis based on the spectral changes during the drying of beef, leading to an encouraging coefficient of determination (r_V^2) of 0.953. Besides, Yang, Sun, and Cheng (2017) explored a simplified model for detecting TVB-N value of cured pork slices during drying process based on the HSI system (400–1000 nm). By selecting 9 key wavelengths, it was shown that the best simplified model was MLR, with an R^2_P of 0.861 and RMSEP of 4.73. The above studies demonstrated that the HSI technique has the potential to monitor the quality changes of both animal origin and plant origin foods during hot-air-drying process.

2.2.2. Microwave-vacuum-drying process

Microwave-vacuum-drying (MVD) is a novel and attractive technique combining the advantages of both microwave and vacuum drying, with a faster drying rate and more efficient energy utilization compared to conventional drying (Cui, Xu, & Sun, 2003, 2008). Furthermore, some thermally-sensitive components in foodstuffs can be maintained at the maximum extent due to a relatively low temperature (Clary, Mejia-Meza, Wang, & Petrucci, 2007). However, because of the non-uniformity of microwave heating, different regions of the sample may be under-dried or over-dried, causing a non-uniform distribution of MC, which is undesirable for food produce (Pitchai, Birla, Subbiah, Jones, & Thippareddi, 2012; Vadivambal & Jayas, 2010). Consequently, demand is growing for the development of a fast and non-invasive technique to predict MC of food materials during the MVD process, especially with a distribution map.

The studies of Pu and Sun (2015, 2016) have demonstrated that HSI in different spectral ranges was a promising tool for measuring and visualizing the MC of mango slices during the drying process. Before hyperspectral datacube analysis, Pu and Sun (2015) employed seven thin-layer drying models to investigate the drying kinetics. Based on the adjusted coefficients of determination (adjusted R^2), the sum of squares due to error (SSE), and the root mean square errors (RMSE), the Page and the two-term thin-layer drying models were chosen to describe the relationship between moisture ratio (MR) and drying time (t). In addition, the overall

Table 2
Applications of hyperspectral imaging system for the assessment of tenderness of industrial cooked processed food.

Processing method	Food material	Spectral range (nm)	Parameters	Data analysis	Accuracy	Reference
Water bath	Lamb	900–1700	WBSF	PLSR	0.84	Kamruzzaman et al., 2013
Roasting	Beef	400–1000	SSF	CDA	96.4%	Naganathan et al., 2008a
Roasting	Beef	900–1700	SSF	CDA	77.0%	Naganathan et al., 2008b
Grilling	Pork	900–1700	Sensory attributes	PLSDA	97%	Barbin et al., 2012
Grilling	Lamb	900–1700	Sensory tenderness	PLSR, PLSDA	0.69, 91%	Kamruzzaman et al., 2013

Table 3
Applications of hyperspectral imaging system for the assessment of color and moisture content of dried processed food.

Processing method	Food material	Spectral range (nm)	Parameters	Data analysis	Accuracy	Reference
Hot-air drying	Tea leaves	380–1030	Color (ΔL^*, Δa^*, Δb^*)	LS-SVM	0.929, 0.849, 0.917	Xie et al., 2014
Hot-air drying	Beef	380–1700	Water content	MLR	0.953	Wu et al., 2013
Hot-air drying	Prawn	380–1100	Moisture content	MLR	0.962	Wu et al., 2012
Hot-air drying	White button mushroom	400–1000	Moisture content	PLSR	0.83	Taghizadeh, Gowen, & O'Donnell, 2009
Hot-air drying	Cured pork	400–1000	TVB-N	MLR	0.861	Yang et al., 2017
PSMVD	Soybean	400–1000	Color Moisture content	PLSR	0.862 0.971	Huang, Wang, Zhang, & Zhu, 2014
PSMVD	Maize kernel	400–1000	Moisture content uniformity	PLSR	0.848	Huang, Zhao, Wang, Zhang, & Zhu, 2015
MVD	Mango slices	400–1000 880–1720	Moisture distribution	PLS	0.959 0972	Pu & Sun, 2015
MVD	Mango slices	951–1630	Moisture content uniformity	MLR	0.993	Pu & Sun, 2016

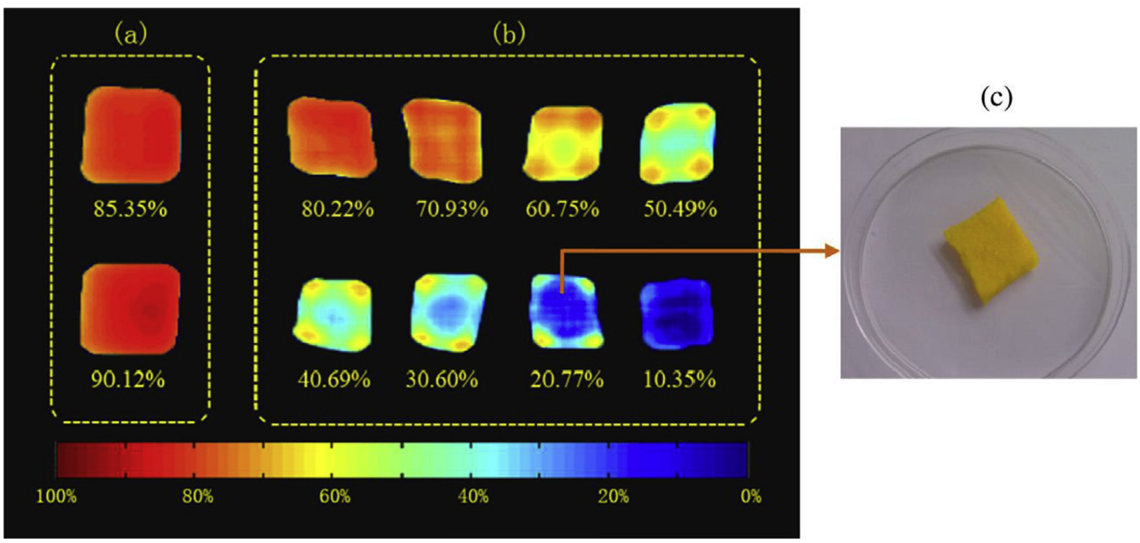

Fig. 2. Moisture content visualization map of mango slices. (a) Raw mango slice samples; (b) Representative mango slice samples during MVD; (c) RGB image of the mango slice with 20.8% of moisture content.

optimal HSI model established had the highest prediction accuracy of $R_p^2 = 0.972$ and RMSEP = 4.611% for MC of mango slices, and based on the visualization map generated by the model, it was found that MC in the middle part of each mango slice was lower than those at the four corners of the visualization map (Fig. 2). This phenomenon could be explained by the non-uniform heating property of the microwave drying process, leading to the uneven temperature distribution on the mango slices. Later, the effect of different shapes of mango slices (square, rectangle, round shape, and regular triangle) on MC during the MVD process using HSI in the region of 951–1630 nm was also investigated (Pu & Sun, 2016). Then, MLR was successfully applied to build a quantitative relationship between spectral data and the reference MC values, achieving an excellent result with $Rp^2 = 0.993$ and RMSEP = 1.282%. In order to compare the moisture distribution in all shapes of mango samples during MVD, a histogram was constructed to study which sample shape performed better in drying, and the result showed that round-shaped slices had better MC uniformity than other shapes of samples which had three or four corners.

2.2.3. Freeze-drying process

Freeze-drying is a two-step process, in which the food material is first frozen and then the water is removed by sublimation (Krokida, Karathanos, & Maroulis, 1998). Freeze-drying is one of the best drying methods for maintaining better sensory quality, higher level of nutrients and better rehydration properties (Pei et al., 2014) However, it is also one of the most expensive techniques with high energy-consumption (Donsi, Ferrari, & Matteo, 2001). Little effort has been made to analyze freeze-dried food products in a non-destructive way. Recently, Hernández-Hierro et al. (2014) evaluated the potential of HSI technology in two different wavelength regions (Vis/NIR and NIR) for the quantitative screening and localization of total glucosinolates in freeze-dried broccoli. It was observed that the best result was achieved in the spectral region of 950–1650 nm with the standard error of cross-validation (SECV) = 1.75, as this region contains little information about color variations among the broccoli samples. The visualization map generated by the best model developed showed that the total glucosinolates were mainly located in the external part of freeze-dried broccoli florets.

2.3. Chilling, freezing, and storage processes

Chilling, freezing, and storage are common food preservation processes during which a series of changes occur inside or on the

Table 4
The specific changes of food subjected to chilling, freezing, and storage processes.

During refrigeration or cold storage	1. Water evaporation (Wang & Sun, 2001) 2. Chilling injury and cold contraction (Watkins et al., 2004) 3. Changes of components, such as loss of vitamin C in fruits and vegetables, increasing of amino acid in meat (Cheng, Sun, & Cheng, 2016a) 4. Undesirable changes of color, flavor, or taste (Cheng et al., 2015a; Xiong et al., 2015)
During freezing process	1. Change of volume (Ballin & Lametsch, 2008) 2. Redistribution of water (Erickson & Hung, 2012) 3. Mechanical damage (Ballin & Lametsch, 2008) 4. Non-aqueous phase components being concentrated (Erickson & Hung, 2012)
During frozen storage	1. Recrystallization (Ballin & Lametsch, 2008) 2. Freezer burn (Watkins et al., 2004) 3. Oxidation and degradation of lipids (Cheng et al., 2015a) 4. Decrease in protein solubility (Erickson & Hung, 2012) 5. Other changes in pH, color, flavor, and nutritional components, and so on (Erickson & Hung, 2012)

surface of the food. Table 4 illustrates the specific changes during these processes. Recently, a number of studies have been conducted using HSI techniques for assessing internal and external quality attributes of foods associated with these processes.

2.3.1. Chilling

Chilling lowers the temperature of food products in order to maintain their quality and safety. During chilling, chilling injury can occur in fruits and vegetables when the chilling temperature is too low, which can destroy their normal metabolism. The injury appears with a slight browning discoloration of the flesh or the core, which can be easily ignored by inexperienced inspectors (Watkins, Nock, & Lime, 2004). While conventional methods can hardly determine the external and internal quality attributes at the same time, the HSI system can provide a solution for this difficulty. In a study conducted by ElMasry, Wang, and Vigneault (2009), p. 84 apples were used in the experiment, half of which were stored at room temperature while the other half were kept at −1 °C for 24 h and then room temperature for another 24 h. After acquiring the hyperspectral images and measuring color and firmness, five optimal wavelengths were selected to establish the artificial neural network (ANN) model, which was then used to distinguish normal apples from chilling-injured ones with an overall classification accuracy of 98.4%. Similar studies were conducted on cucumbers (Cheng et al., 2004; Liu, Chen, Wang, Chan, & Kim, 2005, 2006) and citrus fruits (Menesatti, Urbani, & Lanza, 2004), proving that HSI was able to identify chilling injury of fruits and vegetables.

2.3.2. Freezing and thawing processes

Fresh meat and seafood are highly perishable, and are often frozen for long-term storage. Due to the similar appearance of fresh and freeze-thawed products, it becomes a challenge to identify fresh meat or fish from frozen-thawed samples. A HSI system has been investigated for its capability in classifying them (Barbin, Sun, & Su, 2013b; Ma et al., 2015; Pu et al., 2015, 2014; Qu et al., 2015; Zhu, Zhang, He, Liu, & Sun, 2013). Barbin et al. (2013b) and Pu, Sun, Ma, Liu, and Cheng (2014) used spectral data related to color, pH, and thawing loss of pork meats to build classification models, and these models generated high accuracy. Moreover, in order to extract textural features, gray level co-occurrence matrix (GLCM) is commonly used as a statistical analysis method in order to calculate the frequency of pixel pairs expressing the same gray level in the image (Arebey, Hannan, Begum, & Basri, 2012). Nearly all the studies built the classification models based on physical indices, therefore future research could utilize chemical parameters for differentiating fresh meat from frozen-thawed ones.

2.3.3. Cold storage process

Besides evaluating chill-injured fruit and vegetables, and frozen-thawed meat and fish products, HSI has been studied for evaluating quality attributes of various food products during cold storage, in particular meat and seafood. These quality attributes include MC, color, pH, texture, and total soluble solids (ElMasry, Wang, ElSayed, & Ngadi, 2007; Gowen et al., 2008; Huang & Lu, 2010; Peng and Lu, 2008). Table 5 lists the applications of HSI systems for assessing the freshness of meat and seafood during cold storage. For expressing freshness, both chemical and microbial properties are two main indices for foodstuffs of animal origin during cold storage (Korel, Luzuriaga, & Balaban, 2001; Zhang, Tong, Chen, & Lan, 2008).

Thiobarbituric acid (TBA), and biogenic amines (BAI), and total volatile basic nitrogen (TVB-N) are degradation products of polyunsaturated fatty acids and protein, respectively (Rodtong, Nawong, & Yongsawatdigul, 2005; Ruiz-Capillas & Jiménez-Colmenero, 2005), and the K value is calculated from the quantification of adenosine-5′-triphosphate (ATP) and its corresponding series of breakdown products (Lowe, Ryder, Carragher, & Wells, 1993). All of them can be used as chemical indicators of meat freshness during cold storage (Cheng, Sun, Pu, Wang, & Chen, 2015a, b; 2016a, b; Li, Chen, Zhao, & Wu, 2015; Xiong et al., 2015). Cheng et al. (2015a, b) made attempts to use HSI for assessing TBA value and K value of grass carp stored at 4 °C for various periods. For correlating spectral information with measured TBA and K values, it was found that the RC-MLR model and the SPA-PLSR model based on selected optimal wavelengths were the two most effective models for predicting TBA and K values with an accuracy of $R^2_P = 0.840$ and 0.936, respectively. In another study, Cheng, Sun, Pu, and Liu (2016b) used the date fusion technique to analyze spectral and spatial information simultaneously. Compared to the prediction models using spectral data or textural data only, it was found that the data fusion achieved a more robust model in predicting the K value of pork, with an improvement of accuracy by at least 17.5%. Similar methodology was used by Li et al. (2015), who combined the HSI system with colorimetric sensors for the measurement of TVB-N content of pork during cold storage, and the data fusion method also generated good results with a correction coefficient (R) of 0.932 and a ratio of prediction to deviation (RPD) of 2.885.

Although the activity of microorganisms is reduced at low temperature, food spoilage still happens at a slow rate during cold storage. Consequently, it becomes necessary to identify, classify, and quantify microbial growth on food which would allow early detection of microbial contamination (Gowen, Feng, Gaston, & Valdramidis, 2015). Therefore, a number of studies have been conducted using HSI to estimate the total viable count (TVC) of microbes on beef, pork meat, chicken breast, and salmon fillets during cold storage (Barbin, ElMasry, Sun, Allen, & Morsy, 2013a; Feng & Sun, 2013a; Peng et al., 2011; Wu & Sun, 2013). Feng and Sun (2013a) used a pushbroom HSI system (910–1700 nm) to

Table 5
Applications of hyperspectral imaging system for assessment of freshness of meat and sea food during cold storage.

Sample	Spectral range (nm)	Parameters	Data analysis	Accuracy	Reference
Grass carp	400-1000, 1000-2500	Color (L^*, a^*, b^*)	LS-SVM	0.912, 0.891, 0.731	Cheng, Sun, Pu, & Zeng, 2014
Rainbow trout	400-1000, 1000-2500	Freshness	PCA	0.98, 0.67	Khojastehnazhand et al., 2014
			PLSDA	100%, 75%	
Grass carp	400–1000	TBA	MLR	0.8395	Cheng et al., 2015a
Chicken	328–1115	TBARS	PLSR	0.801	Xiong et al., 2015
Grass carp	400–1000	K	PLSR	0.935	Cheng, Sun, Pu, & Zhu, 2015b
Pork	400–1000	K	PLSR	0.924	Cheng et al., 2016b
Pork	400–1000	BAI	MLR	0.957	Cheng et al., 2016a
Pork	430–960	TVB-N	BP-Adaboost	0.932	Li et al., 2015
Salted pork	430–960	TVB-N	BP-ANN	0.8334	Chen, Zhang, Zhao, & Hui, 2013
Smoked salmon	400–1000	Freshness	PLSDA	82.7%	Ivorra et al., 2013
Beef	400–1100	TVC	PLSR	0.95	Peng et al., 2011
Chicken breast fillet	910–1700	TVC	PLSR	0.94	Feng & Sun, 2013a
Pork	900–1700	TVC	PLSR	0.81	Barbin et al., 2013a
		PPC		0.81	
Salmon	400–1700	TVC	PLSR	0.985	Wu & Sun, 2013
Chicken	930–1450	Enterobacteriaceae loads	PLSR	0.87	Feng et al., 2013
Grass carp	400–1000	*Escherichia coli* loads	MLR	0.870	Cheng & Sun, 2015
Chicken breast fillet	900–1700	*Pseudomonas* loads	PLSR	0.88	Feng & Sun, 2013b
Salmon	900–1700	LAB	LS-SVM	0.925	He et al., 2014

investigate its potential in predicting TVC in raw chicken breast stored at 4 °C. The hyperspectral images obtained in reflectance and absorbance and in Kubelka–Munck (K–M) units were compared and finally the best simplified prediction model was established based on K–M spectra, with a correlation coefficient (R_C) of 0.96 and RMSEC of 0.40 $\log_{10}$ CFU/g for calibration. Apart from TVC, total Enterobacteriaceae, *Escherichia coli* loads, *Pseudomonas* loads, and lactic acid bacteria (LAB) in various poultry and fish products have also been successfully investigated using the HSI technique (Cheng & Sun, 2015; Feng & Sun, 2013b; Feng et al., 2013; He, Sun, & Wu, 2014).

2.4. Salt-curing process

Curing allows salt to permeate into food, decreasing water activity and increasing osmotic pressure, which has an antimicrobial and preservative effects, thus significantly prolonging shelf-life. Salt can be used in various food products, including vegetables (as a preservative, a softening agent, or for fermentation), dairy products (mainly involving the use of salt in cheese, to influence the growth of microbes and supply special flavor), and meat and fish products (for activating enzymes, generating ripening pigment, and controlling microbial safety) (Puolanne, Ruusunen, & Vainionpää, 2001; Rowney, Roupas, Hickey, & Everett, 2004).

One representative of the brined-vegetables is whole pickles. Brined cucumbers of good quality are characterized by perfect external attributes (color, size, and shape), as well as internal attributes (free from bloater damage). Since a hollow center is hidden inside pickles, it is challenge to detect the internal state using traditional analytical methods, making it more difficult to measure the external and internal parameters at the same time. HSI has been investigated for overcoming such difficulties. For non-destructive sensing of surface color and bloater damage of brined pickles, Ariana and Lu (2010) integrated reflectance (400–675 nm) and transmittance (675–1000 nm) modes into one HSI system and they were able to achieve an overall classification accuracy of 86% for normal pickled cucumbers when using principal component analysis (PCA). As for cured meat or fish products, a series of experiments on salted pork meat was conducted by Liu, Qu, Sun, Pu, and Zeng (2013, 2014a, b) who used the HSI technique to detect several parameters associated with pork meat quality during different salting stages. Treated with NaCl from 0 to 150 min, the salt content, water activity, and pH of pork slices were then measured, as these attributes can be good indicators of palatability and flavor. The results showed that HSI was effective for predicting salted meat quality. It should be noted that in the study of Liu et al. (2014a), the pork meat was immersed into a 30% (w/w) NaCl brine solution, thus was wet-curing meat, while in the work of Liu et al. (2013, 2014b), 30% analytical pure NaCl (w/w) was directly employed on the meat and therefore the samples were dry-cured: HSI proved to be effective in both processes. Investigation on other dry-cured foodstuffs was also carried out using the HSI system, including salted salmon fillets (Segtnan et al., 2009), dry-cured ham slices (Gou et al., 2013), and dried salted coalfish (Wold et al., 2006), confirming the potential of HSI in evaluating the salt-curing process.

2.5. Other processes

Fermentation is an old processing technology, which depends largely on the biochemical activity of specific microorganisms for the production of a series of metabolites (Ross, Morgan, & Hill, 2002). Fermentation encompasses breakdown processes of nutrient substances, such as carbohydrate, protein, and fat, in an aerobic or anaerobic environment (Caplice & Fitzgerald, 1999) and plays an important role in the food industry. In recent years, progress has been made in combining the HSI technique with the fermentation process. Serranti (2012) first applied HSI to detect anaerobic digestion process of wine waste, and found that HSI in the NIR range could be utilized to monitor the biogas production process in real-time. In another work reported by Zhu et al. (2016), total acid content (TAC) and MC were chosen as monitoring parameters during solid-state fermentation (SSF) of vinegar culture samples by using HSI in the region of 430–960 nm. After extracting spectral and spatial data, a genetic algorithm (GA) optimization combined with PLSR was employed to construct the prediction model, achieving R^2_P for TAC and MC of 0.857 and 0.816, respectively. Furthermore, Verdú, Ivorra, Sánchez, Barat, and Grau (2015) used short-wave NIR imaging (SW-NIR) to study the characterization of wheat flour during the fermentation process, and a relationship between the SW-NIR spectra of wheat flours and their behavior during fermentation process was successfully obtained.

Packaging is used in the food industry to extend shelf-life and maintain the quality of food products. HSI has also been studied for evaluating packaged foodstuffs. Sone, Olsen, Sivertsen, Eilertsen, and Heia (2012) used three methods to package salmon fillets: traditional overwrap (AIR), modified atmosphere packaging (MAP), and 90% vacuum packaging (VAC). During storage at 4 °C, total bacterial count (TBC) and thiobarbituric acid-reactive substances (TBARS) were measured in order to acquire hyperspectral images. The results showed that the spectral changes of three packaging types of salmon could be observed at wavelengths of 606 and 636 nm, possibly attributing to different states of heme proteins in the salmon fillets. Along with another three optimal wavelengths, it was demonstrated that the K nearest-neighbor classifier could facilitate classifying salmon fillets under various packaging conditions, with a successful classification accuracy of 88.3 ± 4.5%. Another study reported by Taghizadeh, Gowen, Ward, and O'Donnell (2010) also confirmed that it was possible to apply the HSI technique in the Vis–NIR spectral range (400–1000 nm) for evaluating the shelf-life of white button mushrooms packaged using different polymer top-films during cold storage. In addition, Karimi, Maftoonazad, Ramaswamy, Prasher, and Marcotte (2009) exploited the potential of hyperspectral reflectance systems for the color classification of avocados, which were subjected to different coating materials, with the final stepwise discrimination procedure showing an accuracy of more than 92%.

3. Challenges and future trends

In spite of the foregoing studies confirming that the hyperspectral imaging system is a powerful technique for the rapid and non-destructive evaluation of food quality and safety as affected by manufacturing processes, some barriers still limit its application. Although the cost of the HSI instrument is decreasing, it is still expensive compared to some conventional analytical methods (Gowen, O'Donnell, Cullen, Downey, & Frias, 2007), even though there is only a minor barrier. In addition, due to the limited capabilities of hardware and software of the HSI system, the speed of image acquisition, processing, and analysis is relatively slow, especially with a vast number of hyperspectral data. Therefore, it remains difficult to use the HSI system for widespread implementation in on-line real-time industrial applications (Cheng & Sun, 2014). Other difficulties arise from data processing and analysis. Because the spectral and spatial information is obtained simultaneously, the HSI system overcomes the disadvantages of the individual techniques of computer vision and spectroscopy. However, this capacity also encounters a biggest barrier, which is the high dimensional nature of hyperspectral data with redundant information: thus, extracting useful information with the least possible data is a challenging task. As such, efficient and emerging algorithms and chemometric methods are needed to reduce the dimensionality of hyperspectral data, speed up the computation process, and improve model performance and robustness by avoiding redundancies and irrelevant variables (ElMasry et al., 2012a). At present, selection of key wavelengths is the most common way to simplify the calibration and prediction model. However, extracting optimal wavebands in the laboratory is off-line and manual, thus reducing processing efficiency (Chen, Sun, Cheng, & Gao, 2016). In addition, improper algorithms may sometimes lead to critical information being missed. On the other hand, most current studies concentrate on extracting and utilizing the spectral information, thus ignoring the spatial information (Xiong et al., 2014). As mentioned above, several researchers have demonstrated that combining spatial data with spectral data provide better and more accurate results. Therefore, future studies should focus on data fusion to provide superior and more robust prediction.

The above drawbacks are mainly concerned with the HSI system itself and its algorithms and models building. In respect of its application for evaluating food processes, more development needs to be explored. Taking the industrial cooking process as an example, most of related studies involve the assessment of meat and meat products, with only a small fraction of agricultural products. This is because the inactivation of pathogenic and spoilage microorganisms and the improving of palatability have a greater influence on meat than on vegetables or fruits when using an industrial cooking process. For meat, industrial cooking can generate changes in physical properties and produce flavor compounds, but it can also develop toxic substances: therefore, future studies should concentrate more on the assessment of appropriate chemical properties. As for chilling, freezing, and storage processes, a considerable number of researchers have studied the growth and distribution of microorganisms on the surface of foods during cold storage. However, little research is available on monitoring the sterilization process with the HSI technique: thus, studies should be conducted on this area in the near future.

The rapid, non-invasive and accurate nature of the HSI system facilitates the need for its mobility from laboratories to processing lines. Unfortunately, few applications of HSI systems have been implemented in the industry for both quantitative and qualitative on-line real-time analysis of raw food materials or food products. Currently HSI technology is not capable of fulfilling automatic and simultaneous inspection and evaluation of quality and safety parameters. In addition, research activities up to now have mainly focused on individual food items, but not on a category of food products. Therefore, extensive studies are still required to develop HSI or multi-spectral imaging systems as a more routine and comprehensive technique to inspect and monitor food manufacturing processes.

4. Conclusions

HSI combine the advantages of traditional spectroscopy and computer vision to provide three-dimensional information for the simultaneous measurement of external and internal quality and safety attributes. In this review, representative applications of HSI in evaluating quality and safety attributes of food products undergoing various manufacturing processes are summarized. These include industrial cooking, drying, chilling, freezing and storage, salt-curing and other processes. All of these studies prove that HSI is a competent tool for the evaluation of these quality and safety attributes as affected by processing procedures, which could lead to on-line real-time process control. However, HSI systems also suffer from some obstacles, which need to be overcome in future studies, including the limitations of system hardware, massive redundant data and outdated image processing algorithms, leading to challenges for further industrial applications. Therefore, there is much more research opportunities for the development of this technique, and it can be envisaged that HSI systems will find many useful and valuable applications in food processing operations.

Acknowledgements

The authors are grateful to the International S&T Cooperation Program of China (2015DFA71150) for its support. This research was also supported by the Collaborative Innovation Major Special Projects of Guangzhou City (201508020097, 201604020007, 201604020057), the Guangdong Provincial Science and Technology Plan Projects (2015A020209016, 2016A040403040), the Key Projects of Administration of Ocean and Fisheries of Guangdong Province (A201401C04), the National Key Technologies R&D Program (2015BAD19B03), the International and Hong Kong – Macau - Taiwan Collaborative Innovation Platform of Guangdong Province on Intelligent Food Quality Control and Process Technology &

Equipment (2015KGJHZ001), the Guangdong Provincial R & D Centre for the Modern Agricultural Industry on Non-destructive Detection and Intensive Processing of Agricultural Products, the Common Technical Innovation Team of Guangdong Province on Preservation and Logistics of Agricultural Products (2016LM2154) and the Innovation Centre of Guangdong Province for Modern Agricultural Science and Technology on Intelligent Sensing and Precision Control of Agricultural Product Qualities. In addition, the authors wish to acknowledge the contribution of Paul B McNulty, Emeritus Professor of Biosystems Engineering, University College Dublin, Ireland, who assisted in editing this manuscript.

References

Andrés, S., Silva, A., Soares-Pereira, A. L., Martins, C., Bruno-Soares, A., & Murray, I. (2008). The use of visible and near -infrared reflectance spectroscopy to predict beef m. longissimus thoracis et lumborum quality attributes. *Meat Science, 78*, 217–224.

Arebey, M., Hannan, M., Begum, R. A., & Basri, H. (2012). Solid waste bin level detection using gray level co-occurrence matrix feature extraction approach. *Journal of Environmental Management, 104*, 9–18.

Ariana, D. P., & Lu, R. (2010). Evaluation of internal defect and surface color of whole pickles using hyperspectral imaging. *Journal of Food Engineering, 96*, 583–590.

Ballin, N. Z., & Lametsch, R. (2008). Analytical methods for authentication of fresh vs. thawed meat – a review. *Meat Science, 80*, 151–158.

Barbin, D. F., ElMasry, G., Sun, D.-W., & Allen, P. (2012). Predicting quality and sensory attributes of pork using near-infrared hyperspectral imaging. *Analytica Chimica Acta, 719*, 30–42.

Barbin, D. F., ElMasry, G., Sun, D.-W., Allen, P., & Morsy, N. (2013a). Non-destructive assessment of microbial contamination in porcine meat using NIR hyperspectral imaging. *Innovative Food Science & Emerging Technologies, 17*, 180–191.

Barbin, D. F., Sun, D.-W., & Su, C. (2013b). NIR hyperspectral imaging as non-destructive evaluation tool for the recognition of fresh and frozen–thawed porcine longissimus dorsi muscles. *Innovative Food Science & Emerging Technologies, 18*, 226–236.

Bertram, H. C., Wu, Z., Straadt, I. K., Aagaard, M., & Aaslyng, M. D. (2006a). Effects of pressurization on structure, water distribution, and sensory attributes of cured ham: Can pressurization reduce the crucial sodium content? *Journal of Agricultural and Food Chemistry, 54*, 9912–9917.

Bertram, H. C., Wu, Z., van den Berg, F., & Andersen, H. J. (2006b). NMR relaxometry and differential scanning calorimetry during meat cooking. *Meat Science, 74*, 684–689.

Brosnan, T., & Sun, D.-W. (2004). Improving quality inspection of food products by computer vision––a review. *Journal of Food Engineering, 61*, 3–16.

Caplice, E., & Fitzgerald, G. F. (1999). Food fermentations: Role of microorganisms in food production and preservation. *International Journal of Food Microbiology, 50*, 131–149.

Cen, H., & He, Y. (2007). Theory and application of near infrared reflectance spectroscopy in determination of food quality. *Trends in Food Science & Technology, 18*, 72–83.

Chen, L., Zhou, G.-H., & Zhang, W.-G. (2015). Effects of high oxygen packaging on tenderness and water holding capacity of pork through protein oxidation. *Food and Bioprocess Technology, 8*, 2287–2297.

Cheng, X., Chen, Y., Tao, Y., Wang, C., Kim, M., & Lefcourt, A. (2004). A novel integrated PCA and FLD method on hyperspectral image feature extraction for cucumber chilling damage inspection. *Transactions of the ASAE, 47*, 1313.

Cheng, J.-H., & Sun, D.-W. (2014). Hyperspectral imaging as an effective tool for quality analysis and control of fish and other seafoods: Current research and potential applications. *Trends in Food Science & Technology, 37*, 78–91.

Cheng, J.-H., & Sun, D.-W. (2015). Rapid quantification analysis and visualization of Escherichia coli loads in grass carp fish flesh by hyperspectral imaging method. *Food and Bioprocess Technology, 8*, 951–959.

Cheng, Jun-Hu, & Sun, Da-Wen (2015). Rapid and non-invasive detection of fish microbial spoilage by visible and near infrared hyperspectral imaging and multivariate analysis. *LWT-Food Science and Technology, 62*, 1060–1068.

Cheng, Jun-Hu, & Sun, Da-Wen (2017). Partial least squares regression (PLSR) applied to NIR and HSI spectral data modeling to predict chemical properties of fish muscle. *Food Engineering Reviews, 9*, 36–49.

Cheng, W., Sun, D.-W., & Cheng, J.-H. (2016a). Pork biogenic amine index (BAI) determination based on chemometric analysis of hyperspectral imaging data. *LWT - Food Science and Technology, 73*, 13–19.

Cheng, Jun-Hu, Sun, Da-Wen, & Pu, Hongbin (2016). Combining the genetic algorithm and successive projection algorithm for the selection of feature wavelengths to evaluate exudative characteristics in frozen-thawed fish muscle. *Food Chemistry, 197*, 855–863.

Cheng, W., Sun, D.-W., Pu, H., & Liu, Y. (2016b). Integration of spectral and textural data for enhancing hyperspectral prediction of K value in pork meat. *LWT - Food Science and Technology, 72*, 322–329.

Cheng, J.-H., Sun, D.-W., Pu, H.-B., Wang, Q.-J., & Chen, Y.-N. (2015a). Suitability of hyperspectral imaging for rapid evaluation of thiobarbituric acid (TBA) value in grass carp (Ctenopharyngodon idella) fillet. *Food Chemistry, 171*, 258–265.

Cheng, J.-H., Sun, D.-W., Pu, H., & Zeng, X.-A. (2014). Comparison of visible and long-wave near-infrared hyperspectral imaging for colour measurement of grass carp (Ctenopharyngodon idella). *Food and Bioprocess Technology, 7*, 3109–3120.

Cheng, J.-H., Sun, D.-W., Pu, H., & Zhu, Z. (2015b). Development of hyperspectral imaging coupled with chemometric analysis to monitor K value for evaluation of chemical spoilage in fish fillets. *Food Chemistry, 185*, 245–253.

Cheng, Jun-Hu, Sun, Da-Wen, Pu, Hongbin, & Zhu, Zhiwei (2015). Development of hyperspectral imaging coupled with chemometric analysis to monitor K value for evaluation of chemical spoilage in fish fillets. *Food Chemistry, 185*, 245–253.

Cheng, Jun-Hu, Sun, Da-Wen, Qu, Jia-Huan, Pu, Hong-Bin, Zhang, Xiao-Chao, Song, Zhongxiang, et al. (2016). Developing a multispectral imaging for simultaneous prediction of freshness indicators during chemical spoilage of grass carp fish fillet. *Journal of Food Engineering, 182*, 9–17.

Cheng, Lina, Sun, Da-Wen, Zhu, Zhiwei, & Zhang, Zi (2017). Emerging techniques for assisting and accelerating food freezing processes: A review of recent research progresses. *Critical Reviews in Food Science and Nutrition, 57*, 769–781.

Chen, Y.-N., Sun, D.-W., Cheng, J.-H., & Gao, W.-H. (2016). Recent advances for rapid identification of chemical information of muscle foods by hyperspectral imaging analysis. *Food Engineering Reviews*, 1–15.

Chen, Q., Zhang, Y., Zhao, J., & Hui, Z. (2013). Nondestructive measurement of total volatile basic nitrogen (TVB-N) content in salted pork in jelly using a hyperspectral imaging technique combined with efficient hypercube processing algorithms. *Analytical Methods, 5*, 6382–6388.

Clary, C. D., Mejia-Meza, E., Wang, S., & Petrucci, V. E. (2007). Improving grape quality using microwave vacuum drying associated with temperature control. *Journal of Food Science, 72*, E023–E028.

Cui, Z.-W., Sun, L.-J., Chen, W., & Sun, D.-W. (2008). Preparation of dry honey by microwave–vacuum drying. *Journal of Food Engineering, 84*, 582–590.

Cui, Z.-W., Xu, S.-Y., & Sun, D.-W. (2003). Dehydration of garlic slices by combined microwave-vacuum and air drying. *Drying Technology, 21*, 1173–1184.

Delgado, A. E., & Sun, D.-W. (2002). Desorption isotherms and glass transition temperature for chicken meat. *Journal of Food Engineering, 55*, 1–8.

Dewanto, V., Wu, X., Adom, K. K., & Liu, R. H. (2002). Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. *Journal of Agricultural and Food Chemistry, 50*, 3010–3014.

Donsi, G., Ferrari, G., & Matteo, D. (2001). Utilization of combined processes in freeze-drying of shrimps. *Food and Bioproducts Processing, 79*, 152–159.

Du, C. J., & Sun, D.-W. (2005). Pizza sauce spread classification using colour vision and support vector machines. *Journal of Food Engineering, 66*, 137–145.

Du, C.-J., & Sun, D.-W. (2006). Learning techniques used in computer vision for food quality evaluation: A review. *Journal of Food Engineering, 72*, 39–55.

ElMasry, G., Barbin, D. F., Sun, D.-W., & Allen, P. (2012a). Meat quality evaluation by hyperspectral imaging Technique: An overview. *Critical Reviews in Food Science and Nutrition, 52*, 689–711.

ElMasry, G., Iqbal, A., Sun, D.-W., Allen, P., & Ward, P. (2011). Quality classification of cooked, sliced Turkey hams using NIR hyperspectral imaging system. *Journal of Food Engineering, 103*, 333–344.

ElMasry, G., Kamruzzaman, M., Sun, D.-W., & Allen, P. (2012b). Principles and applications of hyperspectral imaging in quality evaluation of agro-food products: A review. *Critical Reviews in Food Science and Nutrition, 52*, 999–1023.

ElMasry, G., & Nakauchi, S. (2015). Noninvasive sensing of thermal treatments of Japanese seafood products using imaging spectroscopy. *International Journal of Food Science & Technology, 50*, 1960–1971.

ElMasry, Garnal, Sun, Da-Wen, & Allen, Paul (2013). Chemical-free assessment and mapping of major constituents in beef using hyperspectral imaging. *Journal of Food Engineering, 117*, 235–246.

ElMasry, G., Wang, N., ElSayed, A., & Ngadi, M. (2007). Hyperspectral imaging for nondestructive determination of some quality attributes for strawberry. *Journal of Food Engineering, 81*, 98–107.

ElMasry, G., Wang, N., & Vigneault, C. (2009). Detecting chilling injury in Red Delicious apple using hyperspectral imaging and neural networks. *Postharvest Biology and Technology, 52*, 1–8.

Erickson, M., & Hung, Y.-C. (2012). *Quality in frozen food*. Springer Science & Business Media.

Feng, Y.-Z., ElMasry, G., Sun, D.-W., Scannell, A. G. M., Walsh, D., & Morcy, N. (2013). Near-infrared hyperspectral imaging and partial least squares regression for rapid and reagentless determination of Enterobacteriaceae on chicken fillets. *Food Chemistry, 138*, 1829–1836.

Feng, Y.-Z., & Sun, D.-W. (2013a). Determination of total viable count (TVC) in chicken breast fillets by near-infrared hyperspectral imaging and spectroscopic transforms. *Talanta, 105*, 244–249.

Feng, Y.-Z., & Sun, D.-W. (2013b). Near-infrared hyperspectral imaging in tandem with partial least squares regression and genetic algorithm for non-destructive determination and visualization of Pseudomonas loads in chicken fillets. *Talanta, 109*, 74–83.

Fu, Q.-Q., Liu, R., Zhang, W.-G., Li, Y.-P., Wang, J., & Zhou, G.-H. (2015). Effects of different packaging systems on beef tenderness through protein modifications. *Food and Bioprocess Technology, 8*, 580–588.

Gou, P., Santos-Garcés, E., Høy, M., Wold, J. P., Liland, K. H., & Fulladosa, E. (2013). Feasibility of NIR interactance hyperspectral imaging for on-line measurement of crude composition in vacuum packed dry-cured ham slices. *Meat Science, 95*, 250–255.

Gowen, A. A., Feng, Y., Gaston, E., & Valdramidis, V. (2015). Recent applications of hyperspectral imaging in microbiology. *Talanta, 137*, 43–54.

Gowen, A. A., O'Donnell, C. P., Cullen, P. J., Downey, G., & Frias, J. M. (2007). Hyperspectral imaging – an emerging process analytical tool for food quality and safety control. *Trends in Food Science & Technology, 18*, 590–598.

Gowen, A. A., O'Donnell, C. P., Taghizadeh, M., Gaston, E., O'Gorman, A., Cullen, P. J., et al. (2008). Hyperspectral imaging for the investigation of quality deterioration in sliced mushrooms (Agaricus bisporus) during storage. *Sensing and Instrumentation for Food Quality and Safety, 2*, 133–143.

Han, Z., Li, H., Yu, X.-C., & Sun, Da-Wen (2016). Effects of low temperature cooking on the retention of 4-(methylthio)-3-butenyl isothiocyanate (MTBITC) of Chinese white radish (Raphanussativus L.). *Food and Bioprocess Technology, 9*(10), 1640–1647.

Hernández-Hierro, J. M., Esquerre, C., Valverde, J., Villacreces, S., Reilly, K., Gaffney, M., et al. (2014). Preliminary study on the use of near-infrared hyperspectral imaging for quantitation and localisation of total glucosinolates in freeze-dried broccoli. *Journal of Food Engineering, 126*, 107–112.

He, H.-J., Sun, D.-W., & Wu, D. (2014). Rapid and real-time prediction of lactic acid bacteria (LAB) in farmed salmon flesh using near-infrared (NIR) hyperspectral imaging combined with chemometric analysis. *Food Research International, 62*, 476–483.

Huang, M., & Lu, R. (2010). Apple mealiness detection using hyperspectral scattering technique. *Postharvest Biology and Technology, 58*, 168–175.

Huang, M., Wang, Q., Zhang, M., & Zhu, Q. (2014). Prediction of color and moisture content for vegetable soybean during drying using hyperspectral imaging technology. *Journal of Food Engineering, 128*, 24–30.

Huang, M., Zhao, W., Wang, Q., Zhang, M., & Zhu, Q. (2015). Prediction of Moisture content uniformity using hyperspectral imaging technology during the drying of maize kernel. *International Agrophysics, 29*, 39–46.

Iqbal, A., Sun, D.-W., & Allen, P. (2013). Prediction of moisture, color and pH in cooked, pre-sliced Turkey hams by NIR hyperspectral imaging system. *Journal of Food Engineering, 117*, 42–51.

Ivorra, E., Girón, J., Sánchez, A. J., Verdú, S., Barat, J. M., & Grau, R. (2013). Detection of expired vacuum-packed smoked salmon based on PLS-DA method using hyperspectral images. *Journal of Food Engineerin, 117*, 342–349.

Jackman, Patrick, Sun, Da-Wen, & Allen, Paul (2009). Automatic segmentation of beef longissimus dorsi muscle and marbling by an adaptable algorithm. *Meat Science, 83*, 187–194.

Jackman, Patrick, Sun, Da-Wen, & Allen, Paul (2011). Recent advances in the use of computer vision technology in the quality assessment of fresh meats. *Trends in Food Science & Technology, 22*, 185–197.

Kamruzzaman, M., Elmasry, G., Sun, D.-W., & Allen, P. (2013). Non-destructive assessment of instrumental and sensory tenderness of lamb meat using NIR hyperspectral imaging. *Food Chemistry, 141*, 389–396.

Karimi, Y., Maftoonazad, N., Ramaswamy, H. S., Prasher, S. O., & Marcotte, M. (2009). Application of hyperspectral technique for color classification avocados subjected to different treatments. *Food and Bioprocess Technology, 5*, 252–264.

Khojastehnazhand, M., Khoshtaghaza, M. H., Mojaradi, B., Rezaei, M., Goodarzi, M., & Saeys, W. (2014). Comparison of visible–near infrared and short wave infrared hyperspectral imaging for the evaluation of rainbow trout freshness. *Food Research International, 56*, 25–34.

Kiani, Hossein, Zhang, Zhihang, Delgado, Adriana, & Sun, Da-Wen (2011). Ultrasound assisted nucleation of some liquid and solid model foods during freezing. *Food Research International, 44*, 2915–2921.

Kong, F., Tang, J., Rasco, B., & Crapo, C. (2007). Kinetics of salmon quality changes during thermal processing. *Journal of Food Engineering, 83*, 510–520.

Korel, F., Luzuriaga, D. A., & Balaban, M.Ö. (2001). Objective quality assessment of raw Tilapia (Oreochromis niloticus) fillets using electronic nose and machine vision. *Journal of Food Science, 66*, 1018–1024.

Krokida, M., Karathanos, V., & Maroulis, Z. (1998). Effect of freeze-drying conditions on shrinkage and porosity of dehydrated agricultural products. *Journal of Food Engineering, 35*, 369–380.

Li, H., Chen, Q., Zhao, J., & Wu, M. (2015). Nondestructive detection of total volatile basic nitrogen (TVB-N) content in pork meat by integrating hyperspectral imaging and colorimetric sensor combined with a nonlinear data fusion. *LWT - Food Science and Technology, 63*, 268–274.

Li, Jiang-Lin, Sun, Da-Wen, Pu, Hongbin, & Jayas, Digvir S. (2017). Determination of trace thiophanate-methyl and its metabolite carbendazim with teratogenic risk in red bell pepper (Capsicumannuum L.) by surface-enhanced Raman imaging technique. *Food Chemistry, 218*, 543–552.

Liu, Y., Chen, Y.-R., Wang, C. Y., Chan, D. E., & Kim, M. S. (2005). Development of a simple algorithm for the detection of chilling injury in cucumbers from visible/near-infrared hyperspectral imaging. *Applied Spectroscopy, 59*, 78–85.

Liu, Y., Chen, Y., Wang, C., Chan, D., & Kim, M. (2006). Development of hyperspectral imaging technique for the detection of chilling injury in cucumbers; spectral and image analysis. *Applied Engineering in Agriculture, 22*, 101–111.

Liu, D., Ma, J., Sun, D.-W., Pu, H., Gao, W., Qu, J., et al. (2014a). Prediction of color and pH of salted porcine meats using visible and near-infrared hyperspectral imaging. *Food and Bioprocess Technology, 7*, 3100–3108.

Liu, D., Pu, H., Sun, D.-W., Wang, L., & Zeng, X. A. (2014b). Combination of spectra and texture data of hyperspectral imaging for prediction of pH in salted meat. *Food Chemistry, 160*, 330–337.

Liu, D., Qu, J., Sun, D.-W., Pu, H., & Zeng, X.-A. (2013). Non-destructive prediction of salt contents and water activity of porcine meat slices by hyperspectral imaging in a salting process. *Innovative Food Science & Emerging Technologies, 20*, 316–323.

Liu, D., Zeng, X.-A., & Sun, D.-W. (2015). Recent developments and applications of hyperspectral imaging for quality evaluation of agricultural products: A review. *Critical Reviews in Food Science and Nutrition, 55*, 1744–1757.

Lorente, D., Aleixos, N., Gómez-Sanchis, J., Cubero, S., García-Navarrete, O. L., & Blasco, J. (2011). Recent advances and applications of hyperspectral imaging for fruit and vegetable quality assessment. *Food and Bioprocess Technology, 5*, 1121–1142.

Lowe, T., Ryder, J., Carragher, J., & Wells, R. (1993). Flesh quality in snapper, Pagrcrs auratus, affected by capture stress. *Journal of Food Science, 58*, 770–773.

Ma, J., Pu, H., Sun, D.-W., Gao, W., Qu, J.-H., & Ma, K.-Y. (2015). Application of Vis–NIR hyperspectral imaging in classification between fresh and frozen-thawed pork Longissimus Dorsi muscles. *International Journal of Refrigeration, 50*, 10–18.

Ma, Ji, Sun, Da-Wen, & Pu, Hongbin (2016). Spectral absorption index in hyperspectral image analysis for predicting moisture contents in pork longissimus dorsi muscles. *Food Chemistry, 197*, 848–854.

Ma, Ji, Sun, Da-Wen, Qu, Jia-Huan, & Pu, Hongbin (2017). Prediction of textural changes in grass carp fillets as affected by vacuum freeze drying using hyperspectral imaging based on integrated group wavelengths. *LWT-Food Science and Technology, 82*, 377–385.

Magwaza, L. S., Opara, U. L., Nieuwoudt, H., Cronje, P. J., Saeys, W., & Nicolaï, B. (2012). NIR spectroscopy applications for internal and external quality analysis of citrus fruit – A review. *Food and Bioprocess Technology, 5*, 425–444.

McDonald, K., Sun, D.-W., & Kenny, T. (2000). Comparison of the quality of cooked beef products cooled by vacuum cooling and by conventional cooling. *Lebensmittel-Wissenschaft und-Technologie-Food Science and Technology, 33*, 21–29.

McDonald, K., Sun, D.-W., & Kenny, T. (2001). The effect of injection level on the quality of a rapid vacuum cooled cooked beef product. *Journal of Food Engineering, 47*, 139–147.

Menesatti, P., Urbani, G., & Lanza, G. (2004). Spectral imaging Vis-NIR system to forecast the chilling injury onset on citrus fruits. *V International Postharvest Symposium, 682*, 1347–1354.

Mora, B., Curti, E., Vittadini, E., & Barbanti, D. (2011). Effect of different air/steam convection cooking methods on Turkey breast meat:Physical characterization, water status and sensory properties. *Meat Science, 88*, 489–497.

Mujumdar, A. S., & Law, C. L. (2010). Drying technology: Trends and applications in postharvest processing. *Food and Bioprocess Technology, 3*, 843–852.

Naganathan, G. K., Grimes, L. M., Subbiah, J., Calkins, C. R., Samal, A., & Meyer, G. E. (2008a). Visible/near-infrared hyperspectral imaging for beef tenderness prediction. *Computers and Electronics in Agriculture, 64*, 225–233.

Naganathan, G. K., Grimes, L. M., Subbiah, J., Calkins, C. R., Samal, A., & Meyer, G. E. (2008b). Partial least squares analysis of near-infrared hyperspectral images for beef tenderness prediction. *Sensing and Instrumentation for Food Quality and Safety, 2*, 178–188.

Nguyen Do Trong, N., Tsuta, M., Nicolaï, B. M., De Baerdemaeker, J., & Saeys, W. (2011). Prediction of optimal cooking time for boiled potatoes by hyperspectral imaging. *Journal of Food Engineering, 105*, 617–624.

Pei, F., Shi, Y., Mariga, A. M., Yang, W.-j, Tang, X.-Z., Zhao, L.-Y., et al. (2014). Comparison of freeze-drying and freeze-drying combined with microwave vacuum drying methods on drying kinetics and rehydration characteristics of button mushroom (agaricus bisporus) slices. *Food and Bioprocess Technology, 7*, 1629–1639.

Peng, Y., & Lu, R. (2008). Analysis of spatially resolved hyperspectral scattering images for assessing apple fruit firmness and soluble solids content. *Postharvest Biology and Technology, 48*, 52–62.

Peng, Y., Zhang, J., Wang, W., Li, Y., Wu, J., Huang, H., et al. (2011). Potential prediction of the microbial spoilage of beef using spatially resolved hyperspectral scattering profiles. *Journal of Food Engineering, 102*, 163–169.

Pitchai, K., Birla, S., Subbiah, J., Jones, D., & Thippareddi, H. (2012). Coupled electromagnetic and heat transfer model for microwave heating in domestic ovens. *Journal of Food Engineering, 112*, 100–111.

Prieto, N., Andrés, S., Giráldez, F. J., Mantecón, A., & Lavín, P. (2008). Ability of near-infrared reflectance spectroscopy (NIRS) to estimate physical parameters of adult steers (oxen) and young cattle meat samples. *Meat Science, 79*, 692–699.

Prieto, N., Roehe, R., Lavín, P., Batten, G., & Andrés, S. (2009). Application of near infrared reflectance spectroscopy to predict meat and meat products quality: A review. *Meat Science, 83*, 175–186.

Pu, Hongbin, Kamruzzaman, Mohammed, & Sun, Da-Wen (2015). Selection of feature wavelengths for developing multispectral imaging systems for quality, safety and authenticity of muscle foods–A review. *Trends in Food Science & Technology, 45*, 86–104.

Puolanne, E. J., Ruusunen, M. H., & Vainionpää, J. I. (2001). Combined effects of NaCl and raw meat pH on water-holding in cooked sausage with and without added phosphate. *Meat Science, 58*, 1–7.

Pu, Y. Y., & Sun, D.-W. (2015). Vis-NIR hyperspectral imaging in visualizing moisture distribution of mango slices during microwave-vacuum drying. *Food Chemistry, 188*, 271–278.

Pu, Y.-Y., & Sun, D.-W. (2016). Prediction of moisture content uniformity of microwave-vacuum dried mangoes as affected by different shapes using NIR hyperspectral imaging. *Innovative Food Science & Emerging Technologies, 33*, 348–356.

Pu, Yuan-Yuan, & Sun, Da-Wen (2017). Combined hot-air and microwave-vacuum drying for improving drying uniformity of mango slices based on hyperspectral imaging visualisation of moisture content distribution. *Biosystems Engineering, 156*, 108–119.

Pu, H., Sun, D.-W., Ma, J., & Cheng, J.-H. (2015). Classification of fresh and frozen-thawed pork muscles using visible and near infrared hyperspectral imaging and textural analysis. *Meat Science, 99*, 81–88.

Pu, H., Sun, D.-W., Ma, J., Liu, D., & Cheng, J.-H. (2014). Using wavelet textural features of visible and near-infrared hyperspectral image to differentiate between fresh and frozen–thawed pork. *Food and Bioprocess Technology, 7*, 3088–3099.

Qu, J.-H., Cheng, J.-H., Sun, D.-W., Pu, H., Wang, Q.-J., & Ma, J. (2015). Discrimination of shelled shrimp (Metapenaeus ensis) among fresh, frozen-thawed and cold-stored by hyperspectral imaging technique. *LWT - Food Science and Technology, 62*, 202–209.

Qu, Jia-Huan, Sun, Da-Wen, Cheng, Jun-Hu, et al. (2017). Mapping moisture contents in grass carp (Ctenopharyngodon idella) slices under different freeze drying periods by Vis-NIR hyperspectral imaging. *LWT-Food Science and Technology, 75*, 529–536.

Rattanathanalerk, M., Chiewchan, N., & Srichumpoung, W. (2005). Effect of thermal processing on the quality loss of pineapple juice. *Journal of Food Engineering, 66*, 259–265.

Rødbotten, R., Nilsen, B., & Hildrum, K. (2000). Prediction of beef quality attributes from early post mortem near-infrared reflectance spectra. *Food Chemistry, 69*, 427–436.

Rodtong, S., Nawong, S., & Yongsawatdigul, J. (2005). Histamine accumulation and histamine-forming bacteria in Indian anchovy (Stolephorus indicus). *Food Microbiology, 22*, 475–482.

Ross, P. R., Morgan, S., & Hill, C. (2002). Preservation and fermentation: Past, present and future. *International Journal of Food Microbiology, 79*, 3–16.

Rowney, M. K., Roupas, P., Hickey, M. W., & Everett, D. W. (2004). Salt-induced structural changes in 1-day old Mozzarella cheese and the impact upon free oil formation. *International Dairy Journal, 14*, 809–816.

Ruiz-Capillas, C., & Jiménez-Colmenero, F. (2005). Biogenic amines in meat and meat products. *Critical Reviews in Food Scince and Nutrition, 44*, 489–599.

Scotter, C. N. (1997). Non-destructive spectroscopic techniques for the measurement of food quality. *Trends in Food Science & Technology, 8*, 285–292.

Segtnan, V. H., Høy, M., Sørheim, O., Kohler, A., Lundby, F., Wold, J. P., et al. (2009). Noncontact salt and fat distributional analysis in salted and smoked salmon fillets using x-ray computed tomography and NIR interactance imaging. *Journal of Agricultural and Food Chemistry, 57*, 1705–1710.

Serranti, S. (2012). Hyperspectral imaging techniques applied to the monitoring of wine waste anaerobic digestion process. *Optical Engineering, 51*, 111708.

Sone, I., Olsen, R. L., Sivertsen, A. H., Eilertsen, G., & Heia, K. (2012). Classification of fresh Atlantic salmon (Salmo salar L.) fillets stored under different atmospheres by hyperspectral imaging. *Journal of Food Engineering, 109*, 482–489.

Su, Wen-Hao, He, Hong-Ju, & Sun, Da-Wen (2017). Non-Destructive and rapid evaluation of staple foods quality by using spectroscopic techniques: A review. *Critical Reviews in Food Science and Nutrition, 57*, 1039–1051.

Sun, D.-W. (1997). Solar powered combined ejector vapour compression cycle for air conditioning and refrigeration. *Energy Conversion and Management, 38*, 479–491.

Sun, D.-W. (1999). Comparison and selection of EMC ERH isotherm equations for rice. *Journal of Stored Products Research, 35*, 249–264.

Sun, D.-W., & Brosnan, T. (1999). Extension of the vase life of cut daffodil flowers by rapid vacuum cooling. *International Journal of Refrigeration-Revue Internationale du Froid, 22*, 472–478.

Sun, D.-W., & Brosnan, T. (2003). Pizza quality evaluation using computer vision – Part 2-Pizza topping analysis. *Journal of Food Engineering, 57*, 91–95.

Sun, D.-W., & Zheng, L. Y. (2006). Vacuum cooling technology for the agri-food industry: Past, present and future. *Journal of Food Engineering, 77*, 203–214.

Sun, D.-W. (2000). Inspecting pizza topping percentage and distribution by a computer vision method. *Journal of Food Engineering, 44*, 245–249.

Sun, D.-W. (2014). *Emerging Technologies for food processing* (2nd ed.). San Diego, California, USA: Academic Press/Elsevier.

Taghizadeh, M., Gowen, A., & O'Donnell, C. P. (2009). Prediction of white button mushroom (Agaricus bisporus) moisture content using hyperspectral imaging. *Sensing and Instrumentation for Food Quality and Safety, 3*, 219–226.

Taghizadeh, M., Gowen, A., Ward, P., & O'Donnell, C. P. (2010). Use of hyperspectral imaging for evaluation of the shelf-life of fresh white button mushrooms (Agaricus bisporus) stored in different packaging films. *Innovative Food Science & Emerging Technologies, 11*, 423–431.

Vadivambal, R., & Jayas, D. (2010). Non-uniform temperature distribution during microwave heating of food materials—a review. *Food and Bioprocess Technology, 3*, 161–171.

Verdú, S., Ivorra, E., Sánchez, A. J., Barat, J. M., & Grau, R. (2015). Study of high strength wheat flours considering their physicochemical and rheological characterisation as well as fermentation capacity using SW-NIR imaging. *Journal of Cereal Science, 62*, 31–33.

Wang, L., & Sun, D.-W. (2001). Rapid cooling of porous and moisture foods by using vacuum cooling technology. *Trends in Food Science & Technology, 12*, 174–184.

Wang, L. J., & Sun, D.-W. (2004). Effect of operating conditions of a vacuum cooler on cooling performance for large cooked meat joints. *Journal of Food Engineering, 61*, 231–240.

Watkins, C., Nock, J., & Lime, S. U. H. (2004). SmartFreshTM (1-MCP)—the good and bad as we head into the 2004 season. *New York Fruit Quarterly, 12*, 3–8.

Wold, J. P., Johansen, I., Haugholt, K. H., Tschudi, J., Thielemann, J., Segtnan, V. H., et al. (2006). Non-contact transflectance near-infrared imaging for representative on-line sampling of dried salted coalfish (bacalao). *Journal of Near-infrared Spectroscopy, 14*, 59.

Wu, D., Shi, H., Wang, S., He, Y., Bao, Y., & Liu, K. (2012). Rapid prediction of moisture content of dehydrated prawns using online hyperspectral imaging system. *Analytica Chimica Acta, 726*, 57–66.

Wu, D., & Sun, D.-W. (2013). Potential of time series-hyperspectral imaging (TS-HSI) for non-invasive determination of microbial spoilage of salmon flesh. *Talanta, 111*, 39–46.

Wu, Di, & Sun, Da-Wen (2013). Advanced applications of hyperspectral imaging technology for food quality and safety analysis and assessment: A review – Part II: Applications. *Innovative Food Science & Emerging Technologies, 19*, 15–28.

Wu, D., Wang, S., Wang, N., Nie, P., He, Y., Sun, D.-W., et al. (2013). Application of time series hyperspectral imaging (TS-HSI) for determining water distribution within beef and spectral kinetic analysis during dehydration. *Food and Bioprocess Technology, 6*, 2943–2958.

Xie, C., Li, X., Shao, Y., & He, Y. (2014). Color measurement of tea leaves at different drying periods using hyperspectral imaging technique. *Plos One, 9*(12).

Xie, A., Sun, D.-W., Xu, Z., & Zhu, Z. (2015). Rapid detection of frozen pork quality without thawing by Vis-NIR hyperspectral imaging technique. *Talanta, 139*, 208–215.

Xie, Anguo, Sun, Da-Wen, Zhu, Zhiwei, & Pu, Hongbin (2016). Nondestructive measurements of freezing parameters of frozen porcine meat by NIR hyperspectral imaging. *Food and Bioprocess Technology, 9*, 1444–1454.

Xiong, Z., Sun, D.-W., Pu, H., Xie, A., Han, Z., & Luo, M. (2015). Non-destructive prediction of thiobarbituric acid reactive substances (TBARS) value for freshness evaluation of chicken meat using hyperspectral imaging. *Food Chemistry, 179*, 175–181.

Xiong, Z., Sun, D.-W., Zeng, X.-A., & Xie, A. (2014). Recent developments of hyperspectral imaging systems and their applications in detecting quality attributes of red meats: A review. *Journal of Food Engineering, 132*, 1–13.

Xu, Jun-Li, Riccioli, Cecilia, & Sun, Da-Wen (2016). Development of an alternative technique for rapid and accurate determination of fish caloric density based on hyperspectral imaging. *Journal of Food Engineering, 190*, 185–194.

Xu, Jun-Li, Riccioli, Cecilia, & Sun, Da-Wen (2017). Comparison of hyperspectral imaging and computer vision for automatic differentiation of organically and conventionally farmed salmon. *Journal of Food Engineering, 196*, 170–182.

Xu, Jun-Li, & Sun, Da-Wen (2017). Identification of freezer burn on frozen salmon surface using hyperspectral imaging and computer vision combined with machine learning algorithm. *International Journal of Refrigeration-Revue Internationale du Froid, 74*, 151–164.

Yang, Q., Sun, D.-W., & Cheng, W. (2017). Development of simplified models for nondestructive hyperspectral imaging monitoring of TVB-N contents in cured meat during drying process. *Journal of Food Engineering, 192*, 53–60.

Zhang, Z., Tong, J., Chen, D.-H., & Lan, Y.-B. (2008). Electronic nose with an air sensor matrix for detecting beef freshness. *Journal of Bionic Engineering, 5*, 67–73.

Zheng, L. Y., & Sun, D.-W. (2004). Vacuum cooling for the food industry – A review of recent research advances. *Trends in Food Science & Technology, 15*, 555–568.

Zhu, F., Zhang, D., He, Y., Liu, F., & Sun, D.-W. (2013). Application of visible and near-infrared hyperspectral imaging to differentiate between fresh and frozen–-thawed fish fillets. *Food and Bioprocess Technology, 6*(10), 2931–2937.

Zhu, Y., Zou, X., Shen, T., Shi, J., Zhao, J., Holmes, M., et al. (2016). Determination of total acid content and moisture content during solid-state fermentation processes using hyperspectral imaging. *Journal of Food Engineering, 174*, 75–84.