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Review

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

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ABSTRACT

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;

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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