Recent Developments in Hyperspectral Imaging and Chemometrics for Food Quality Assessment - A Review

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Abstract: By leveraging the technologies of imaging and spectroscopy, hyperspectral imaging has been widely studied and developed. Hypersepctral Imaging concept is adopted as non-destructive, real-time detection tool for assessment of food quality. Hyperspectral imaging helps in simultaneously obtaining spatial and spectral information of the objects being studied. This has resulted in many successful applications in the food industry for quality and safety evaluation and inspection. These applications are categorized in to 4 main groups – Fruits and Vegetables, Meat, Dairy Products and Grains. In this review paper, the principle of the technique is introduced, followed by detailed discussion on some typical application examples to illustrate the advantages of applying the technique in the food industry. The potential and future work of hyperspectral imaging for effective food quality assessment is also discussed. Besides the paper also outlines the need of Chemometrics and its importance to overcome the challenges of Hyperspectral Imaging.

Keywords: Hyperspectral imaging; Image processing; Food quality and safety; Image analysis; Spectrum; spectroscopy; Imaging spectroscopy, Chemometrics

1. Introduction

Quality is the foremost key factor in modern food industry. Food Industry and Suppliers needs to cater to the current growing need for low production and operating costs with zero tolerance to the quality and safety aspects. Adherence to quality standards and assurance of food safety is always takes the foremost priority irrespective of many other challenges. Meeting these challenges is significance to grade food products for different markets. These factors demand the need for efficient, low-cost, and non-invasive quality and safety inspection technologies to gain customers confidence, market share, sustainability and competitiveness.

Assessment of Quality of food is usually recognized by:

- Physical attributes - Texture, color, tenderness etc.,
- Chemical attributes - Fat content, moisture, protein content, pH etc.,
- Biological attributes - Bacterial count etc.,

Human Visual Inspection of assessment of quality and safety is tedious, inefficient and prone to errors. It also requires skilled analyst. Adopting Chemical and Biological experiments are even tedious, time and effort consuming, destructive, and may have adverse effects on environment and objects being studied. These challenges warranted the need for accurate, fast, real-time and non chemical detection technologies, in order to optimize quality and assure safety of food hence the Hyperspectral imaging techniques was absorbed and received much attention for food quality and safety evaluation and inspection. However Hyperspectral Imaging results in tremendous data volumes which lead to high data storage, processing time and transmission bandwidth. To address these challenges Chemometrics techniques are adopted.

In this paper, a wide-ranging review of the recent developments in hyperspectral imaging systems, Chemometrics and applications in food and food products are outlined.

2. Principles of HyperSpectral Imaging System (HSI)

2.1 Fundamentals of Hyperspectral Imaging

The combination of image processing and spectral processing techniques is what we call as hyperspectral imaging. In this hyperspectral imaging technique, the interaction between light and a specimen are measured in terms of the optical properties of both incident light and the specimen in study, and such interactions are used to characterize the material.

This technique involves illumination of Far-infrared rays on the specimen under investigation. The first interaction that we can observeis on the surface of specimen where a small part of the light is reflected. This partly reflected light containsa little information about the specimen under study, since medium isgoverned by the difference between refractive index of the media.

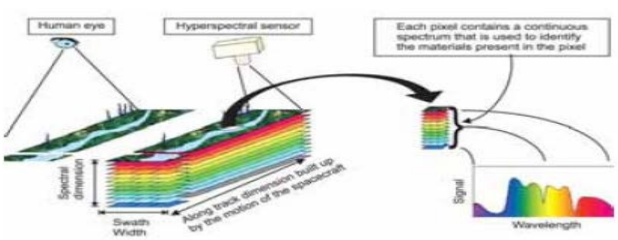

Figure 2.a Hyperspectral Imaging concept (courtesy: HyperMed Imaging)

Once the rays penetrate the material, the light can be scattered or absorbed partly or fully. Scattering is the process of change in the direction of incident lightdue to interactions with the molecular structure of the specimen under study. This scattering depends on the wavelength of the incident light, size of the particles and the refractive indices of the media. Here, we can see elastic scattering and inelastic scattering. Majority of the scattered light is identical to the wavelength of the incident lightwhich we call as elastic scattering. A small fraction of Inelastic scattering also known as "Raman scattering" also can be observed. This inelastic scattering cause wavelength shifts with respect to the vibration states of the molecules of the specimen under study. Raman scattering can be used to measure and analyze the chemical compositions and their properties of the specimen under study.

For any chemical compound, its absorption property is dependent on the wavelength of the incident light spectrum. If there is an absorption in the visible wavelength range, it corresponds to the electronic states of the molecule, while absorption in the NIR and IR is determined by the vibrational modes. When the molecules return to the ground state from excitedstate, molecules release energy in the form of radiation viz., heat or photoluminescence (transfer energy to other molecules). So,these two spectral absorptions and any presence of induced photoluminescence are measured and used to identify the chemical contents of a specimen using hyperspectral cameras in reflectance, or transmission mode. However, the Quantitative analysis is complicated because the length of the path travelled by the incident light depends on the optical properties of the specimen.

2.2 Acquisition of Hyperspectral Images

Hyperspectral images are analogous to a stack of images;where each image is acquired at a narrow spectral band. The data set thus obtained is a three-dimensional block of data, called the hypercube. Each data set has two spatial (x,y) dimensions and one wavelength (λ) dimension. Using this hypercube, images for each wavelength (λi) and a spectrum from each individual pixel (xj,yk) can be obtained. Since hyperspectral images are stack of image data set, obtaining information in all three dimensions of a hypercube simultaneously is currently not feasible; instruments can only capture two dimensions at a time. Temporal scanning is done to create a three-dimensional hypercube by stacking the two-dimensional data in sequence. There are three different methods of acquiring a hypercube, commonly known as point scanning,line scanning and area scanning. These temporal scanning methodologies refer to the hardware methodology used to acquire the hypercube.

In a point scanning method, a complete spectrum is obtained at a single point. The Light from this single point enters the objective lens which is then taken by a spectrometer to separate the point light into different wavelengths. This spectrum is detected by a linear array detector. Once the spectral of one point is obtained, thespectrum of another point can be recorded. Scanning has to be performed in both the spatial directions to complete the hypercube.

In line scanning method, the spectra of all pixels contained in one line of the image are acquired simultaneously. Thus acquired spectra are dispersed onto a two dimensional charge coupled device detector. This way, a two dimensional data matrix with the spectral dimension and one spatial dimension is acquired. The second spatial dimension is acquired by scanning across the specimen surface in a direction perpendicular to the imaging line. This vertical and horizontal scanning of imaging lines says that there should be a relative movement between the object and detector, which can be achieved either by moving the specimen and keeping the hyperspectral camera in a fixed position or vice versa.

An area scanning method also acquires a two-dimensional data matrix which represents a more conventional image with two spatial axes. A complete hypercube can be obtained by collecting a sequence of these images for one wavelength band at a time. The wavelength of incoming light in this configuration is typically modulated using a tunable filter.

3 CHEMOMETRICS

3.1 Overview and Importance of Chemometrics

For each pixel, a whole spectrum is obtained and this is the differentiate factor of a hyperspectral image with respect to other imaging. The resulting huge quantity of data poses many challenges while processing the images as pointed out by Amigo in the framework of pharmaceutical preparations. The main challenge is extracting useful and meaningful information from the raw images. High dimensionality of the data will result in huge storage, processing and transmission bandwidth. In this context, Chemometrics is an appealing tool to reduce the dimensionality of the data, retain essential spectral information and classify or quantify important areas of a scene.

3.2 Grouping of Chemometrics Methods

Chemometric methods can be classified based on the information desired from applications in scope:

- Qualitative/exploratory analysis: Examples includePrincipal Component Analysis (PCA), Fixed Size Image Window–Evolving Factor Analysis (FSIW–EFA).
- Supervised and unsupervised classification: Examples include PCA, K-means and fuzzy clustering, Linear Discriminant Analysis (LDA), Partial Least Squares-Discriminant Analysis (PLS-DA), and fisher discriminant analysis (FDA), Artificial Neural Networks (ANN).
- Resolution and quantization: Examples include multivariate curve resolution (MCR), partial least squares regression (PLSR), ANN for regression, multi-linear

regression (MLR), and classical least squares (CLS).

There have been many applications of chemometrics and HSI to foodstuffs fordifferent purposes. They can be divided into four main groups: Fruits and vegetables, meat, dairy products, and grains. Chemometrics helps to attain the optimum performance for Digital Image Processing. Hyperspectral Imaging and Chemometrics is a perfect combination for quality assessment of food items. Section (4) describes different Chemometrics techniques that can be applied for effective food quality assessment. There is a lot of traction in analysis, design and critical evaluation of different Chemometrics techniques. This is the way forward to reduce the dimensionality of the data for quicker and easy digital Image and video processing.

4. Applications of Hyper Spectral Imaging in Food Analysis

Hyperspectral imaging techniques have received much attention for food quality and safety evaluation and inspection. Many approaches and applications have shown the usefulness of hyperspectral imaging and chemometrics in the food industry. They can be divided into four main groups: Fruits and vegetables, meat, dairy products, and grains. In each group the needs are different, as can be appreciated in Table 1. For instance, the main applications in fruits, vegetables and meat are to find external defects/properties; whereas sorting is one of the main applications in grains. Table 1 shows a comprehensive view of the main applications in the four groups mentioned.

TABLE 1 Main Applications of HIS and Chemometrics in Foodstuff

Sample	Application	Analytical technique	Chemometrics technique
Apples	Detection of bruises	Vis–NIR HSI	PCA, ANN, MLR
	Detection of bitter pit defects	NIR HSI	PLS
	Prediction of the firmness and soluble solids content	Vis–NIR HSI	ANN, MLR
	Detection of chilling injury	Vis–NIR HSI	ANN
	Detection of physical properties	Vis–NIR HSI	PCA
	Detection of defects on the surface	UV–vis–NIR HSI	ANN
	Quantization of starch distribution	Vis–NIR HSI	PLS
	Quantization of starch content	NIR HSI	PLS-DA
	Ripening	Vis–NIR HSI	PLS-DA
	Quantization of sugar content	NIR HSI	PLS
Cucumbers	Detection of chilling injury	Vis–NIR HSI	PCA, FLD (k-NN)
	Detection of internal defects	Vis–NIR HSI	PLS-DA
	Detection of defects on the surface	Vis–NIR HSI	PCA
Citruses	Detection of skin defects	RGB and NIR HSI, fluorescence imaging	LDA
	Detection of rottenness caused by bacteria	Vis–NIR HSI	LDA
	Detection of bruises	Vis–NIR HSI	PCA

TABLE 1 Main Applications of HIS and Chemometrics in Foodstuff—Cont'd

Sample	Application	Analytical technique	Chemometrics technique
Pork	Prediction of the quality grade	Vis–NIR HSI	ANN
	Detection of bacterial spoilage	Vis–NIR HSI	SVM
Chicken	Detection of skin tumours on chicken carcasses	Fluorescence HSI	FCM, ANN, SVM, PCA, DWT, KDA
	Detection of faecal contaminants	Vis–NIR HSI	PCA
Fish	Detection of parasites and blood spots on the surface	Vis–NIR HSI	PLS-DA, SIMCA
	Monitoring moisture distribution in dried salted fish	NIR HSI	PLS
	Prediction of water and fat content	NIR HSI	PLS
Sample	Application	Analytical technique	Chemometrics technique
Cheese	Quantization of sugar, citric acid and salycilic acid in different cheeses	NIR HSI	PLS
	Classification of cheeses according to protein, fat and carbohydrate content	NIR HSI	
Grain	Classification and identification of grain specific classes	SWNIR HSI, NIR HSI and Vis–NIR HSI	PCA, PLS, LDA, ANN
	Prediction of chemical composition	NIR HSI	PLS
	Classification of grains according to hardness	Vis–NIR hyperspectral imaging	PCA, PLS-DA
	Detection of bacterial spoilage	Fluorescence HSI, NIR HSI	LDA, QDA, MDC

4.1 Fruit – Bruise Detection of Apples and Citrus fruit Inspection

Consumers would like to pay more for prime fruit with superior quality and safety guaranteed. Hyperspectral imaging has been proved its great capability for the quality and safety assessment of fruits targeting apple, citrus, pear, peach, oranges, almond nut, blueberry, citrus, grape seed, grape skin, and strawberry. The defects such as contamination, bruises, surface defects, starch index, firmness, SSC, sugar content, bitter pit, and chilling injury/freeze damage are the major research quality attributes.As a main external defect, bruise damage is a main cause for the quality loss and degradation of fruit, which usually occurs during the harvest or transport process.

Bruise Detection of Apples

Apple is the main research object for the detection of bruise damage using hyperspectral

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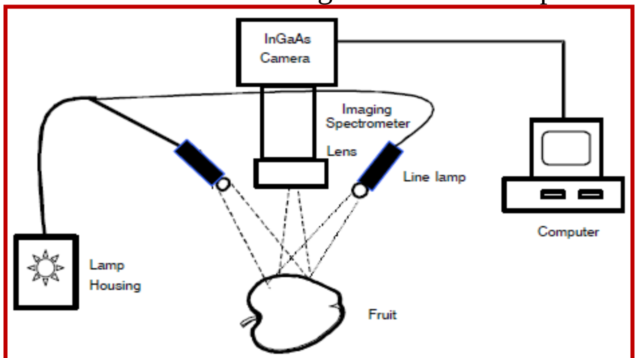
imaging in the last decade (Lorente et al., 2012; Nicolai et al., 2007; Sun, 2010). The study were carried out in reflectance mode and in the VIS-NIR range (about 900–1,700 nm).

The bruise damages of apples are normally due to impact,compression, vibration, or abrasion during handling. The impact bruise may not be visible immediate. The symptom appears after a certain period of time. Therefore Early detection of such impact bruise is needed in order to on to improve the product quality.

Figure 4.a Bruises in Apple

The system mainly consisted of :

- An InGaAs area array camera covering the spectral range between 900 nm and 1700 nm.
- An imaging spectrograph attached to the camera.
- A 25 mm focal length TV Lens Computer



Schematic of the near–infrared hyperspectral imaging system for detecting bruises on apples.

Figure 4.b Systems block diagram

Course Of Events:

- The light beam entered the spectrograph.It was dispersed into different directions according to wavelength.
- The dispersed light was then mapped onto the InGaAs detector resulting in a two–dimensional image, one dimension representing the spectral axis and the other the spatial information for the scanning line.
- By scanning the entire surface of the fruit, three–dimensional hyperspectral image cube was created, where two dimensions represented the spatial information and the third represented the spectral information

Flowchart :

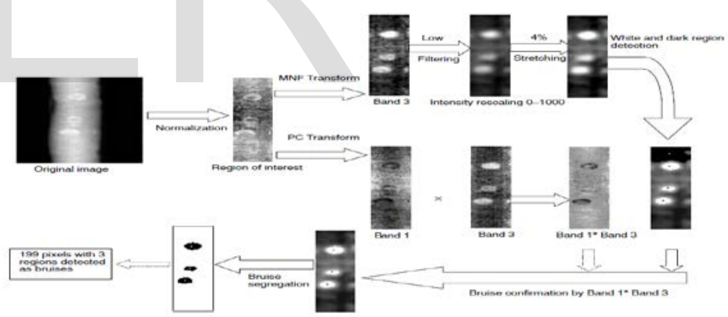


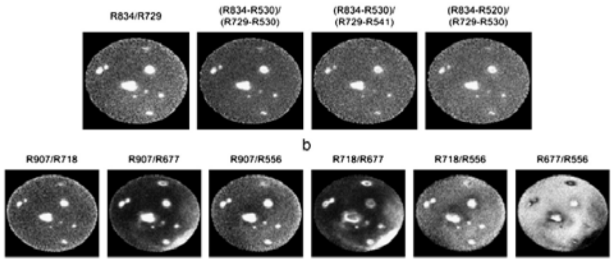
Figure 4.c Procedure used to detect bruises on apples

This is an example of how Principal Component transform (PC) and Minimum Noise Fraction transform (MNF) are used in combination to detect spectral region and band resolution that are appropriate for detection of bruises regardless of bruise age. However the algorithm development and procedure are discussed in the literature [17].

Citrus Fruit Inspection:

Citrus fruit is another type of fruits that require early detection of fungal infections using

Hyperspectral imaging. A small number of fruit that infected by fungi can spread the infection to a whole consignment of citrus fruit.



Citrus canker is a serious disease affecting most commercial citrus species that is caused by the bacterium Xanthomonas axonopodis. In recent years, more efforts were made on selecting critical bands of the hyperspectral image data for developing multispectral methods to inspect citrus canker. The two-band ratio (R834 nm/R729 nm) selected by Correlation Analysis (CA) gave the maximum absolute correlation value of 0.811 in the correlation analysis. Two-band ratio images based on these two wavelengths had the classification accuracies in the range of 93.3–96.7% for each month (Zhao, Burks, Qin, & Ritenour, 2010b). Fig. 4.d shows band ratio images of a cankerous grapefruit based on wavelengths selected by CA and PCA. Two-band ratio (R834 nm/R729 nm) outperformed the PCA-selected bands (R907 nm/R718 nm) in terms of classification performance owing to its supervised nature (Qin, Burks,Zhao, Niphadkar, & Ritenour, 2011). On the basis of the identified two important bands, a one-line commercial fruit sorting machine was developed with a speed of 5 fruits/s, and achieved an overall classification accuracy of 95.3% (Qin, Burks, Zhao, Niphadkar, & Ritenour, 2012). [18]

4.2 Vegetables

A series of works have been conducted on detecting defects of vegetables such as cucumber, potatos, tomato, mugbean, soyabean etc. However the application of Hyperspectral Imaging (HSI) systems are well suited for bulk sorting of potatoes. Since the work with the complex nature of information of HSI-data and huge data volumes are recognized to be quite challenging, a new camera system technology called EVK Chemical Color Camera (EC3) is used as a bridging of spectroscopy and industrial image processing.

Sugar-End growth defect:

Sugar-Ends (SE), also known as ”Translucent-Ends” or ”Jelly-Ends” are a wide spread growth disorder. Affected potatoes show a difference of fructose, glucose, sucrose and starch concentration between proximal and distal end. SE- affected potatoes (figure1) fry, caused by the Maillard-Reaction, to an undesirable dark brown color at the proximal- and an acceptable golden tan color at the distal end. As this growth disorder is recognizable at a spectral wavelength range of around 1300nm and not in visual light range (380nm-780nm), a NIR System like Helios-EC3 with a wavelength range of 1100 nm to 1700nm turned out to be an accurate choice.[19]

Measurement System

To enable the detection of Sugar-Ends a HELIOS-EC3 NIR system . This system allows the measurement of chemical or physical properties in the wavelength region 0.9-1.7 _m described in a standardized color format (RGB) per spatial point (pixel). The chemical color information is processed using image processing algorithms (like classification, object detection, etc..) that are standard in EVK sensor systems for bulk sorting. The system is scanning transported potatoes across a line illuminated by a halogen light source (Fig. 4.e). By concatenating scanned lines, a chemical color image is gained, visualizing objects transported through the inspection line. The idea of chemical coloring is to reduce the amount of spectral data generated by hyperspectral imaging systems (HSI) via transformation into color information and by this means making a chemical-color-line camera out of a hyperspectral imaging system. Scanning an object with a HIS system leads, depending on scan rate and resolution, to a large amount of data as every single spatial point has spectral information behind it. The preprocessing and transformation from spectral to color-information is done by the Helios System itself providing fast data throughput and making it possible to use the system in an inline application. Constraining colors to chemical information is done with the

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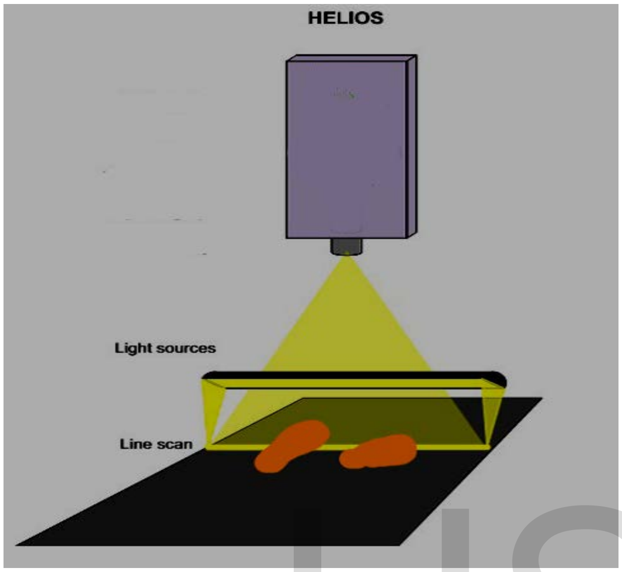
Helios EC3-Configurator by teaching the systematical spectral variations observed in referenced spectra.

Steps for Assessment:

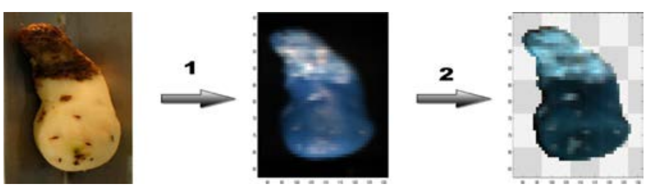
Step 1 : Steam peeled potatoes with a speed of 1.2 m/s were scanned with a rate of 330 frames per second to get the HSI-Data.



HELIOS EC3 NIR system (EVK DI Kerschhaggl GmbH/Raaba)

Figure 4.f

Step 2 : The appropriate preprocessing method has to be chosen. To eliminate light interferences caused by the geometrical or environmental influences the HSI data was normalized and a foreground-background segmentation was applied.



Applying preprocessing of HSI-Data

Figure 4.g

Step 3 : Some preprocessed spectra can be seen. With these spectra and those spectra taken over a long period of time a chemical color transformation was calculated. The quality and robustness of such an EC3-model depends on the variety and quantity of spectra available. As it is the goal of the EC3-model to describe the entire abundance of the searched defect, many spectra were chosen. An example of the result of the applied chemical color transformation can be seen .

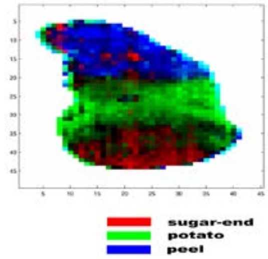


Figure 4.h

The resulting image of a chemical color transformation

4.3 *Fish freshness*

Quality analysis and evaluation for fish and other seafoods is playing an important role in providing products of superior quality in consideration of human health and international trade. Currently, it is necessary to look for effective and rapid techniques to monitor quality changes and safety indices due to the vulnerability and perishability of aquatic products.

Nematode infection is a common problem occurring in fishing nations, and it is also a severe issue of food safety. These incidents about nematodes such as parasites in fish muscle to a great extent result in an instant negative response from consumers towards the product, and further generate disbelief in fish as a healthy and nutritious product as well as the noteworthy reduction of fish international trade and consumption (Heia et al., 2007). Therefore, it is important for the fish processing industry to avoid the occurrence of parasites in fish products and detect them on-line. Currently, commercial means of detecting parasites commonly depends on manual and candling inspection with a white light table. However, the efficiency of recognition by traditional method is relatively low (Heia et al.,2007; Sivertsen, Heia, Stormo, Elvevoll, & Nilsen, 2011). Hyperspectral imaging has been developed to detect parasite contamination. In an early study, Wold, Westad, and Heia (2001) investigated the multispectral imaging technique in the visible and near infrared spectral region in alliance with soft independent modeling by class analogy (SIMCA) approach for automatic detection of parasites in cod fillets. It was observed that the spectral features of parasites obtained from the images were different from those of fish muscles free of parasites and this technique was capable of detecting parasites at the depths of 6 mm into the fish flesh, which created fairly good classification evidence and benefited to on-line assessment. It was in concurrence with the study reported by Heia et al. (2007) using the imaging spectroscopy to discriminate good fish muscle from those with parasites for the same cod species. The only difference was that in this study, Partial Least Squares Discriminant Analysis (PLS-DA) and image filtering techniques were used to analyse the spectral information. Encouragingly, the measuring depth has also been extended to8 mm below the fillet surface that was 2 or 3 mm deeper than the depth observed by manual inspection of fish fillets (Petursson, 1991). It has also proved that this technique has the potential to identify parasites located both on the outside and inside of the fillets for on-line industrial purposes.[20]

4.4 Grains

Some research work also has been conducted for detection of damage and contaminants of grains. Williams et al. [96] developed the NIR hyperspectral imaging system (1,000–2,498 nm) to track changes in fungal contamination of whole maize kernels. PLS regression models were established to assess the changes over time. The results indicated the possibility of the early detection of fungal contamination and activity. NIR hyperspectral imaging technology has also been applied to detect damaged wheat kernels. A NIR hyperspectral imaging system in the range of wavelengths 1,000–1,600 nm was developed for detection of insect-damaged wheat kernels [103]. LDA and QDA were employed to classify healthy and insect-damaged wheat kernels and the classification accuracy was 85%–100%. Later, another NIR hyperspectral imaging system (700–1,100 nm) was established to discriminate healthy and midge-damaged wheat kernels by the same research team [92]. Statistical features and histogram features were extracted from hyperspectral images at significant wavelengths. Three statistical classifiers were used for classification. The high average accuracy (95.3%–99.3%) strongly indicated the potential of NIR hyperspectral imaging for detection of damaged wheat kernels.[21]

4.4 Other applications- Biofilm Detection

Recently, Jun et al. [107] reported the utilization of macro-scale fluorescence hyperspectral imaging to evaluate the potential detection of pathogenic bacterial biofilm formations on five types of food-contact surface materials: stainless steel, high density polyethylene (HDPE), plastic laminate (Formica), and two variations of polished granite. These materials are commonly used to process and handle food, and sometimes cause biofilm pollution on food surface. Spots of biofilm (E. coli O157:H7 and Salmonella biofilm) growth were produced on sample surfaces and stored and scanned by fluorescence hyperspectral imaging system using ultraviolet-A excitation (421–700 nm, including a C-mount object lens, F1.9 35 mm). PCA was used to reduce the dimensionality of hyperspectral images and an image processing method was developed based on single-band and two-band ratio techniques to select the wavebands appropriate for differentiating biofilm spots form different backgrounds. The suitable spectral fluorescence band for detecting microbial biofilm on stainless steel surfaces was 559 nm, with overall detection rate of 95%. For HDPE and granite, ratios between different two bands provided the most efficient results. For Formica, the results were not accurate enough to detect biofilms effectively. The result of this study showed the hyperspectral imaging could also be used to develop portable hand-held devices for sanitation inspection of food packaging, which has been a big issue for food processing. It was also noted that low cell population density may influence the accuracy of biofilm inspection of food processing surfaces. More studies could be conducted on the hyperspectral imaging biofilm detection, especially in low cell population density.

5 CONCLUSION

Hyperspectral imaging is a complex, highly multidisciplinary field with the aim of realizing efficient and reliable measurement of bothcontents and spatial distributions of multiple chemical constituents and physical attributes simultaneously without monotonous samplepreparation, and therefore offering the possibility of designing inspection systems for the automatic grading and nutrition determinationof food products. The various applications outlined in this review show the capability of using hyperspectral imaging for sample classificationand grading, defect and disease detection, distribution visualization of chemical attributes in chemical images, and evaluations of overall quality of meat, fruits, vegetables, and other food products. Moreover, currently some practical implementations for real-time monitoring are already available. It is anticipated that real-time food monitoring systems with this technique can be expected to meet the requirements of the modern industrial control and sorting systems in the near future.

The full potential of hyperspectral imaging on grading and classification of all varieties of food items would be explored in the future works.Feasibility of Hyperspectral Imaging for quality assessment of food items which are of liquid forms (Ex - Cooking Oil, Fruit juice, Milk) can be investigated.

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