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Mini Review

Optical parameters in food and agricultural processing

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Abstract

The non-destructive feature of optical techniques has gained interests for quality assessment of various agricultural produce as well as in food processing technology. The principle and interaction of light with food and agricultural produce provide essential information for quality assessment which promotes non-destructive inspection methods. This review encompasses the determination of optical properties associated with the evaluation of the quality of agricultural produce. The understanding of how light interacts with turbid agricultural produce is also presented, including light characteristics such as absorption and scattering. A brief overview of the estimation and application of the optical parameters in food and agricultural processing are discussed. The problems and implementation of optical parameters as well as its future trend are also included.

Introduction

The interaction of light with turbid agricultural produce is a fundamental concept in optical techniques, involving absorption and scattering light phenomena. The diffusion of photons that are typically scattered before being absorbed by a material indicates the absorption coefficient (μ_a) and the reduced scattering coefficient (μ'_s) (Jacques, 2013). Absorption and scattering are important parameters to determine the total reflected intensity in the particular region of the electromagnetic spectrum. The changes in microscopic state for the diffusion of light are due to the divergence of photon propagation, from the air vacuoles, membranes, or organelles of the material which can be related to the properties of the agricultural produce itself (Cubeddu *et al*., 2000). Since the optical characteristics are influenced by the physical state and chemical constituents, information of light interaction retrieved from the material is necessary for the quality evaluation of food and agricultural produce. It offers a non-invasive method to overcome the difficulties of subjective and destructive evaluation usually observed in the conventional method (Gunasekaran *et al*., 1985).

In addition, microscopic changes also rely on the scattering coefficient (μ_s) which can be described by the relationship of the angular probability distribution of scattered photon and interaction sites, based on the mean distance from both parameters (Cubeddu *et al*., 2000). A non-invasive optical technique using absorption and scattering coefficients has been applied in engineering research for the evaluation of crops and agricultural produce. This method ultimately relies on the measurement of absorption and scattering properties measurement of various types of turbid agricultural produce (Qin and Lu, 2008). The diversity of both optical parameters provides information about the samples and data quantification of the inside of the material. Information concerning the optical parameters which are dependent on the physiology of the sample tissue is required in chemometric techniques for extracting data using extrapolation method in optic-based applications. The optical techniques have been further developed in recent studies and are used for quality evaluation of numerous agricultural produce, especially when dealing with postharvest and processing technologies (Jha and Matsuoka, 2000).

Nonetheless, the measurement of optical properties requires the design of sophisticated instrumentation design and well-developed algorithms which could be a key limitation for postharvest processing regarding cost and speed of operation. The measurement of optical properties also varies as the external surfaces of agricultural produce are different from one another. The penetration of the light spectrum differs in terms of sensitivity level and performance of the imaging

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system for different types of samples. The external surface can only determine the optical properties based on the surface curvature of the agricultural produce due to the variation of surface area (Qin and Lu, 2008). The technique involving optical-based methods are also reported to be more feasible when used in real situations. The development of portable devices has gained interest in optical methods for their simplicity and advancement of the system. Thus, this paper discusses the fundamental concepts of the electromagnetic spectrum, the components of the optical properties as well as the applications and potential of the optical properties measurement for quality evaluation of various agricultural produce.

Estimation of optical parameters

The common types of agricultural produce are described as being turbid or opaque, as well as the ability of the substance to transmit light evenly at selected wavelengths judging from the optical properties (Mollazade *et al*., 2012). There is also the interaction between light and turbid agricultural produce if light propagation (absorption, reflectance, or transmittance) occurs during the process (Chen *et al.*, 2002). A reflection of light arising from the surface of the biological tissue is denoted as regular reflectance. The principle of reflection indicates that the external diffuse reflectance is reflected at an exact angle of 45° to the incident beam. In contrast, the angle at the point of reflection is similar to the incident angle from the external surface of the biological tissue (Shelby, 2005). In this case, light propagation is reflected by the internal attributes and scattered back to the external surface of the agricultural produce. Since the internal attributes of agricultural produce play a major role in the interaction with light, the backscattered photons act as an information carrier which is governed by the morphological and structural features of the material, such as mechanical, chemical, as well as physical properties (Peng and Lu, 2008).

Agricultural produce is a living thing which contains material, particularly morphological components and the structures of the cell tissue (Bot and Benites, 2005). The biochemical factors could be vital in quality changes including metabolic and hormone control during the development of maturity stages and the absorption of chemical constituents. The internal structure of the cell tissue carries information of the interior as well as exterior cell components of the biological tissue. The extracellular surface of a cell wall normally results in a light backscattering phenomenon in agricultural produce due to unexpected alteration of the reflection coefficients. However, small solid particles such as chloroplasts and starch are influenced by refraction based on the scattering properties of the external surface of the material (Mollazade *et al*., 2012). For this reason, the structural properties of agricultural produce could also absorb a specific region of the light spectrum that is associated with a wavelength region and light propagation depth. Likewise, the material can be categorised according to the optical parameters (absorption and scattering) that are particularly related to the material.

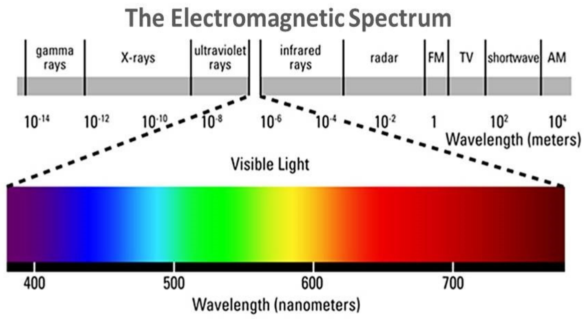

Figure 1. Electromagnetic spectrum radiation

As the light source for the imaging system is not necessarily monochromatic, there is a broad range of wavelength regions and colours, which consist of various intensities. The electromagnetic spectrum is denoted as the initial information governing optical techniques from different parts of the spectrum (Stedwell and Polfer, 2013). Generally, radiation is a basic type of propagation using transferring energy from one medium to another medium along the entire spectral region (Gunasekaran *et al.*, 1985). Light radiation is defined as blackbody radiation that is discharged by a non-reflective medium (opaque) at constant temperature (Gupta and Gupta, 2015). Consequently, light radiation defines its selected region of the wavelength spectrum and intensity depending on the blackbody temperature. Also, radiation propagates at the same speed beginning from the shortest gamma rays to the longest radio waves of the electromagnetic spectrum (Gunasekaran, 2000). Aside from the dependency of the wavelength in measuring optical properties, colour is an important attribute which relies on a selected respective wavelength spectrum. For instance, the visible spectrum is represented from red, at a wavelength range 620-750 nm to violet with a range between 380-450 nm (Figure 1). Meanwhile, the infrared spectrum ranges from 700 until 1000 nm in which the infrared wavelength band is subcategorized into five sections (near infrared, short-wavelength infrared, mid-wavelength infrared, long-wavelength infrared, far infrared) (Chen *et al*., 2002).

The optical properties (absorption and

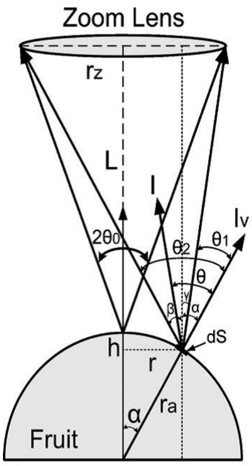

Figure 2. Correction for light intensity beam between imaging source and fruit sample (Qin and Lu, 2008)

scattering coefficients) of agricultural produce are normally measured from the physical state governing interaction of light with the material. The components of the optical parameters are often characterised according to several conditions such as wavelength, refractive index, reflection, absorption, transmission, and dispersion of light (Qin and Lu, 2008; Mollazade *et al*. 2012). The light source of a system is usually different in terms of wavelength band and implementation of the hardware. One of the important key points for optical measurements of agricultural produce is by the curvature of a sample (Baranyai, 2011). The whole process for determination of surface curvature of a sample should be considered due to the consistency of reflectance signals obtained from the sample. An illustration of correction for optical measurements based on the curvature of the sample is shown in Figure 2. The assumption made from the emission of reflectance at a curved surface follows the Lambertian Cosine Law, especially for turbid material, in which L is the distance of the object, r is the horizontal distance to the imaging source, ra is the radius of the sample (circular or cylindrical shape), r_z is the radius of the zoom lens, Iv is the normal component of the emitted reflectance at the curved surface, and I denotes an arbitrary reflectance intensity component passing through the imaging source (Kienle *et al*., 1996).

Applications in food and agricultural processing

In the food and agricultural processing industry, quality control is essential to monitor safety and to develop a checklist for inspection to obtain high-quality produce. In this case, determination of the optical properties could provide accurate results and is feasible for any specific application. The measurement of optical properties has been tested on several agricultural produce such as kiwifruit (Baranyai and Zude, 2009), wheat (Bürling *et al*., 2010), bananas (Hashim *et al*., 2012, 2013), apples (Beers *et al*., 2014), and citrus fruit (Lorente *et al*., 2015). The development of applications and food inspection techniques in automated systems and machine vision-based approaches for quality control is needed to achieve the targeted expected quality (Kodagali and Balaji, 2012). Postharvest technology focuses on the conservation and processing of food and agricultural produce, as well as to minimise postharvest losses during the harvesting process. As a continuous assessment of determination of optical properties in the food processing sector, several non-destructive techniques have been applied in advanced modern applications, such as near-infrared spectroscopy (Xu *et al*., 2007), spatially resolved spectroscopy (Madieta *et al*., 2010), backscattering imaging (Baranyai and Zude, 2009; Romano *et al*., 2010; Hashim *et al*., 2013, 2014; Lorente *et al*., 2014), and hyperspectral imaging (Erkinbaev *et al*., 2011). An overview of the evaluation of optical properties in agricultural produce is shown in Table 1.

Table 1. Evaluation of optical properties in agricultural produce

Agricultural produce	Quality parameters	Optical indices measurements	References
Apple	Chilling injury	Diffusion coefficient, D	(Baranyai, 2011)
Apple	Chilling injury	Absorption coefficient (μ_a), scattering coefficient (μ_s), anisotropy factor (g)	(Baranyai *et al*., 2009)
Kiwifruit	Laser light propagation	μ_a, μ_s, g	(Baranyai and Zude, 2009)
Apple	Ripeness, firmness, soluble solid contents, starch degradation	Streif index	(Beers *et al*., 2014)
Wheat	Leaf rust infection	Fluorescence parameter, Y(NO)	(Bürling *et al*., 2010)
Apple	Skin defects, depth of volume	μ_a, reduced scattering coefficient (μ'_s)	(Cubeddu *et al*., 2000)
Apple	Total soluble solids, firmness	μ_a, μ'_s	(Erkinbaev *et al*., 2011)
Citrus fruit	Decay	μ_a, μ'_s, relative refractive index, $R_f(r)$	(Lorente *et al*., 2015)
Citrus fruit	Decay	Gaussian–Lorentzian parameters	(Lorente *et al*., 2013)
Apple	Diffusion of photons	μ_a, μ'_s	(Madieta *et al*., 2010)
Pummelo fruit	pH, total soluble solids, turbidity	μ_a	(Shah *et al*., 2014)
Apple, peach, pear, kiwifruit, plum, cucumber, zucchini squash, tomato	Ripeness, firmness	μ_a, μ'_s, $R_f(r)$	(Qin and Lu, 2008)
Tomato	Leaf miner damage	Reflectance spectral parameters	(Xu *et al*., 2007)

Lorente *et al.* (2013) reported on the application of laser-light backscattering imaging for detection of early decay after infection with the pathogen *Penicillium digitatum*, prior to the formation of green mould in citrus fruit. Backscattered images of fruit samples were taken using a charge-coupled device (CCD) camera equipped with a zoom lens, five laser diodes at selected wavelengths (532, 660, 785, 830 and 1060 nm) within the visible and near-infrared range and a computer for data storage. The sample was placed manually and backscattered images were captured by the CCD camera. The images were stored on the computer. Backscattering profiles were obtained to evaluate the decay infection on the external surface of the fruit sample using the multivariate calibration model. The region of backscattered photon images was analysed by the changes of intensity in radial symmetry to the incident light point, in which the image was minimised to a one-dimensional profile with respect to radial averaging. The change of intensity was fitted to the mathematical expression of the Gaussian-Lorentzian (GL) function as denoted by Equation (1) (Peng and Lu, 2005):

$$I(x) = a + \frac{b}{\left[1 + e\left(\frac{x-c}{d}\right)^2\right]\exp\left[\left(\frac{1-e}{2}\right)\left(\frac{x-c}{d}\right)^2\right]} \quad (1)$$

Where I is the light intensity of each wavelength band after radial averaging, x is the scattering distance in pixels, a is the asymptotic value of light intensity, b is the peak value of light intensity at the centre point, c is the centre parameter, d is full scattering width at half maximum peak value, and e depends on the shape which varies from 0 to 1 (0 denotes pure Gaussian function; 1 denotes pure Lorentzian function).

The GL distribution function produces a backscattering profile as shown in Figure 3. The results indicated that the average coefficient of determination (R2) was approximately 0.998 for classification of fruit samples into two categories (good and decayed oranges) using linear discriminant analysis. Moreover, the findings achieved an average success rate of 80.4% with the application of laser light at 532 nm which showed a distinct relationship between the scattering properties of the infected sample and the carotenoid contents. The best results were obtained using five different laser wavelengths which achieved an average success rate of 96.1%, which highlighted the big potential of laser-light backscattering imaging for citrus grading. This approach is feasible for determination of optical properties, especially for rotating types of agricultural produce for implementation as part of a sorting and grading process.

Baranyai and Zude (2009) examined the propagation of laser light in kiwifruit using the Monte Carlo (MC) method with the application of a backscattering imaging system. The number of photons was obtained from simulation of the MC model, propagated from the radius of the beam and light intensity, below the noise level of the imaging source. The photon pulse consisted of 2.49×10^8 photons and included an integration time of 0.5-8.3 ms for the minimisation of the computation load with respect to the amount of emitted light. The measurement of the optical properties resulted in overall mean values of $\mu a = 0.9\ cm^{-1}$, $\mu_s = 40\ cm^{-1}$ and adjusted g= 0.8±20% using the Heyney-Greenstein phase function. The rotation of intensity profiles was evaluated to estimate the differences of changing the anisotropy factor value by deducting from the backscattered images. A significant difference with a p-value of less than 0.01 ($p<0.01$) was achieved using multi-factor ANOVA between the anisotropy of good-quality and overripe fruit samples, for monitoring of firmness properties. Three categories were chosen to find the best fit of mathematical functions (polynomial, exponential, trigonometric) to study the correlation between the slope of the logarithmic profile and the anisotropy factor using regression models with respect to $\mu_a = 0.9 cm^{-1}$ and $\mu_s = 40\ cm^{-1}$. Furthermore, the apparent intensity on the external part of homogenous fruit tissue was determined using several values of anisotropy within the range of 0 to 0.99. From this finding, the peak intensity increased with lower values of anisotropy. Thus, the approach used to define the optical parameters on the surface of a sample can be vital for classification and grading of agricultural produce in terms of rotation profile and discrimination analysis.

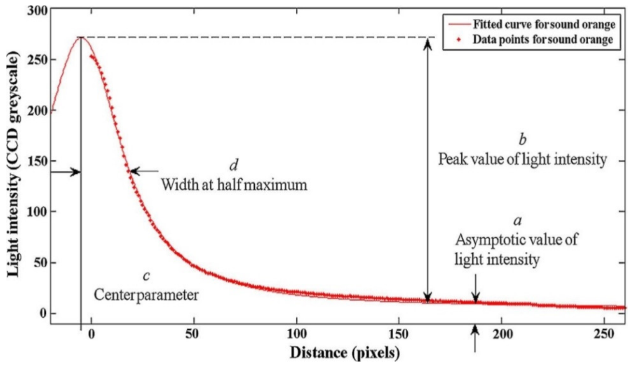

Figure 3. Gaussian-distribution model for backscattering profiles (Lorente *et al.*, 2013)

Erkinbaev *et al.* (2011) investigated optical property measurements using a hyperspectral imaging system to find a correlation between quality changes and the optical properties of an apple. Two types of apple samples (soft and hard apples) were studied. Three types of dimensional hypercubes consisting of one spectral axis and two spatial axes were obtained from the system based on selected wavelength spectrum. The sample achieved higher absorption values in the range of 650-670 nm as compared to the absorption values in the range of 500-600 nm (Figure 4). The implementation of a hyperspectral imaging system indicated that the technique could also be

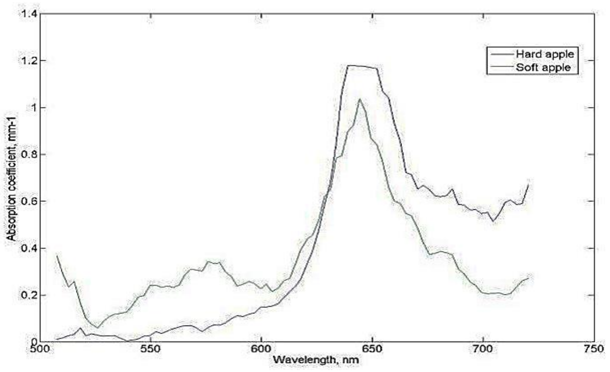

Figure 4. Absorption values of two types of apple samples at selected wavelength bands (Erkinbaev *et al*., 2011)

applied to an online detection system for various agricultural produce. Beers *et al.* (2014) discussed the potential of a hyperspectral scatter imaging system in evaluating the ripeness level of apples in the range of 550-1000 nm to detect a glowing spot due to the diffuse reflectance. Three quality parameters, which were firmness, soluble solids content, and starch degradation, were correlated with a Streif Index parameter using partial least squares. The result showed high correlation with an R^2 of 0.98 for the classification of ripeness of apple samples. The promising application of hyperspectral imaging is beneficial for using in optical sensor devices and automated harvesting systems.

Xu *et al.* (2007) studied the feasibility of near-infrared spectroscopy in detecting tomato leaf damage caused by the leaf miner. Leaf reflectance spectra were obtained to find the optimal wavelength region for classifying the leaf damage into five severity levels. The findings achieved a highest correlation coefficient value of 0.982 at wavelength bands of 1450 and 1900 nm. Hence, near-infrared spectroscopy has high potential for the application of an effective optical tool to evaluate the severity and early detection of plant disease. Madieta *et al.* (2010) compared photon diffusivity in apples with a finite element model and an analytical solution by means of spatially resolved spectroscopy. The diffusion equation was calculated apart from using Boltzmann transfer equation on μ_a= 0.0207 cm^{-1} and μ'_s=0.9952 cm^{-1}. The reduced scattering coefficient was proved to be higher than the absorption coefficient when tested using diffusion approximation. Further, the diffusion equation has also been measured in the Cartesian plane regardless of any curvature of the sample.

Problems and implementation of optical parameters

In the determination of optical parameters in food and agricultural processing industry, the main problem of this method is totally numerical. The entire analysis must be calculated numerically due to the analytical algorithms for determination of light propagation in the anisotropic medium are not accessible yet. For the time being, the numerical analysis is measured using the optical parameters as well as reflection and transmission information regarding the samples to find the accuracy of the analytical algorithms. However, the implementation of numerical analysis is impractical because the errors can only be obtained from the quadrature point of the light propagation medium. Also, the accuracy of tabulated values to generate validation model using anisotropic scattering is not available (Prahl *et al*., 1993). The two most commonly sources of experimental errors are the propagation of scattered light for the transmission measurements and the loss of travelled light within the edge of the samples. Hence, the non-destructive applications in determining optical parameters in agricultural produce might be the future thrust in the latter case of food and processing industry.

Future trend

The recent determination of optical parameters in food and agricultural processing leading to the enhancement of knowledge in light scattering properties for developing new and non-destructive techniques to overcome the limitations, especially for food quality inspection. The non-destructive techniques are expected to assist in acquiring the optical parameters information of various agricultural crops. This information is essential in providing insights on the quality assurance and biochemical reactions subjected to the light scattering properties. Future works should be conducted to develop postharvest technologies by means of light propagation knowledge to monitor quality attributes of agricultural produce and processing of food products. The optical parameter exhibits different understandings within the academic community since it is always referred as the reflectance and transmittance measurements. On the other hand, the optical technique based on those measurements are regarded as the extrinsic measurement to differentiate from other techniques based on the basic theory of radiation transfer.

There are a lot of studies on determination of optical parameters using commonly used non-destructive methods such as spectrophotometry and microscopy methods. Hence, considering the fact that non-destructive method is developed rapidly, one promising method is suggested for determination of optical parameters, which is biospeckle. Biospeckle is a non-invasive method that interprets an optical pattern produced by the laser illumination from the light scattering by diffusing medium. The advantage of using biospeckle is the ability of the optical pattern to be analysed using both numerical and graphical methods. Apart from that, the biospeckle method offers a fundamental approach for collecting data information in such a way that the quality attributes could be predicted based on the development of predictive models. Therefore, the development of new real-time optical method requires further advances in predicting quality changes of agricultural produce.

Conclusion

Generally, the quality control of food and agricultural produce is related to a description based on the characteristics of selected features or part of a material. For instance, during the ripening process of agricultural produce, the maturity indicator is assessed by colour inspection and direct visualisation assessment. Most of the agricultural produce exhibits different physiological and physicochemical changes during the ripening stages. For this reason, the optical properties are an option aside from colour inspection as colour alone is insufficient to thoroughly monitor the internal quality and defects. In addition, the non-destructive approach of optical property measurements can establish effective quality indices solely relying on the successfulness of optical parameters methods. There are two conditions that best describe the determination of optical parameters, which are the magnitude of relative measurement and the change in the measurement of maturity stages. In addition, the natural state of the evaluation benchmark should also be selected carefully since the optical property measurements are affected by the diversity of shape, size, light intensity, sensor sensitivity, and amplifier gain.

Optical properties of food and agricultural produce are very much related to certain conditions based on quality inspection to achieve accurate optical results. The estimation of those optical properties could provide an advantage in selecting appropriate applications according to the quality indices of the material. The non-invasive application of optical techniques basically emphasises the inspection of external and internal qualities in agricultural produce. Therefore, the determination of the optical properties is necessary since the differences in terms of geometric properties, size, and shape of agricultural produce are heterogeneous among different varieties. The interaction of light propagation by means of an engineering approach and mathematical representations should be considered in obtaining values of the optical properties. Nevertheless, with the arrival of spectroscopic and fibre optic techniques, the measurements of optical properties can be evaluated using high-speed operations at maximum capacity. Despite the existence of advanced approaches, further works are required to facilitate optimum usage of the determination of optical properties in the food and agricultural processing industry.

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