

Review Article

## Potential Application of Laser-Based Imaging Technology in the Quality Evaluation of Agricultural Products: A Review

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**Abstract:** Non-destructive quality evaluation of agricultural products particularly during postharvest stage has been a primary concern in recent years. The laser-based imaging technology is one of the most promising non-invasive tools which demonstrate potential ability to replace the conventional methods of quality monitoring that are time-consuming, expensive, laborious, inaccurate and most of all destructive. Hence, in this paper, we briefly reviewed the potential application of laser-light backscattering imaging technique (LLBI) as a non-destructive quality evaluation tool applied in agricultural products. This review mainly reports the current knowledge on the successful implementations of the LLBI in measuring the various quality-related attributes of agricultural products under different postharvest conditions such as in drying, storage, sorting, maturity identification and defect detection. The basic components, uses and considerations of the techniques are highlighted in this paper. Moreover, the advantages, drawbacks, measurement methods, data analysis applied as well as the accuracies obtained are briefly summarized.

**Keywords:** agricultural products; laser-based imaging; non-destructive; postharvest; quality evaluation

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### 1. Introduction

In recent years, the high demand for fresh, healthy and defect-free agricultural products is associated with the corresponding demand of rapid and non-destructive quality

evaluation techniques. In most cases, the quality of the fresh productions are more important for consumers and food processors rather than its cost (Sanchez *et al.*, 2020a). In fact, the market sales of ready-to-use fresh fruits and vegetables have grown rapidly due to the changes in consumers' attitude in accepting or rejecting the product (Rico *et al.*, 2007). Thus, it is necessary to monitor regularly and control the quality of fresh productions in order to meet the quality standards as well as the consumer requirements (Ruiz-Altisent *et al.*, 2010). However, the quality evaluation of fresh productions are still being approached using conventional procedures. These procedures were reportedly time consuming, inefficient, laborious, costly and destructive in nature (Chen *et al.*, 2013; Sanchez *et al.*, 2020a). As a matter of fact, one of the most devastating effects of destructive measurement is that the produce is lost after the measurement has been carried out (Nicolai *et al.*, 2009). Thus, to overcome the drawbacks and challenges of destructive methods, non-destructive optical based technologies have been adopted and developed for the quality inspection of various agricultural and food products based on the optical measurements in the visible or near-infrared (NIR) regions (Abbott, 1999). These optical-based methods can be used with high precision, minimum labor and low operating cost (Rady & Guyer, 2015).

One of the most promising non-destructive optical-based technologies is the laser-light backscattering imaging (LLBI) technique. LLBI is an emerging spectral imaging tool that is known for an effective monitoring capability without touching the samples and offering low instrumentation cost at high accuracy (Mollazade & Arefi, 2017). LLBI technique can acquire spectral information from a sample through a deep penetration of light which makes it unique among other imaging methods. Aside from that, other optical-based imaging techniques have not been commercially and industrially utilized as compared with LLBI due to various limitations such as unsatisfactory performance, adaptability issues, and high cost of instrumentations (Adebayo *et al.*, 2016; Mollazade & Arefi, 2017). Moreover, LLBI has been reportedly efficient and potentially alternative machine vision technique with powerful spectral readings (Hashim *et al.*, 2013; Lorente *et al.*, 2013). Hence, the application of LLBI in agricultural and food industries is of growing interest in recent decades.

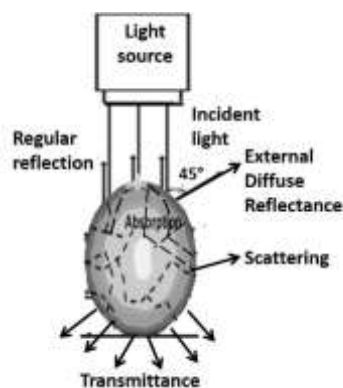
Over the past 10 years, LLBI has been approached by several research groups in monitoring the quality indices of various agricultural and food products. In fact, there have been numerous comprehensive reviews published complementary with this work who reported the potential applicability of diverse imaging methods in the non-destructive quality inspection of various horti-food products. However, the said reviews critically discussed the application of different imaging techniques on a specific food product/s with less discussions about LLBI. Say for instance, Chen *et al.* (2013) focused on the description, differences and trends of various optical imaging techniques. Adebayo *et al.* (2017) widely discussed the applications of laser light, multispectral, and hyperspectral backscattering imaging techniques in different food products while Rady & Guyer (2015) focused mainly in potato,

Mohd Ali *et al.* (2017a) in watermelons and Sanchez *et al.* (2020a) in potatoes and sweet potatoes. Thus, it is the primary objective of the current work to report the current knowledge on the successful implementations of LLBI in various agricultural products. This paper will be of great help in the agricultural sector particularly in the marketing chain of fresh produce wherein proper sorting and grading is required. Likewise, this specific review in LLBI will be beneficial for the food processing and research institutions working on the developments of the technology for further online implementations.

## 2. Laser-light backscattering imaging (LLBI)

### 2.1 Basic concepts of LLBI

Generally, the backscattering imaging technology adopts the principle of capturing the scattered light of photons projected into the food material (Figure 1). According to Mireei *et al.* (2010), a turbid or semi-transparent material like agricultural products will allow the passage of light through its body at a specific wavelength. This occurrence manifests that when a light hits a crop tissue, 4 % of the light will be reflected back to the atmosphere while the rest will penetrate and is being absorbed, transmitted or scattered back (diffuse reflectance) to the incident point (Birth, 1976). Mohd Ali (2017) mentioned that the reflected light is distributed into three (3) types such as the regular, external diffuse, and scattering (Figure 1). The interaction of light during penetration in the crop tissue carries useful information about the structure of the material which is essential in measuring the quality of the produce (Hashim *et al.*, 2014; Mollazade *et al.*, 2012; Onwude *et al.*, 2018). In other words, this method possessed a simultaneous estimation of the absorption and scattering coefficients of the captured light from the material being examined.



**Figure 1.** Schematic representation of the distribution of light in agricultural products (Mohd Ali, 2017).

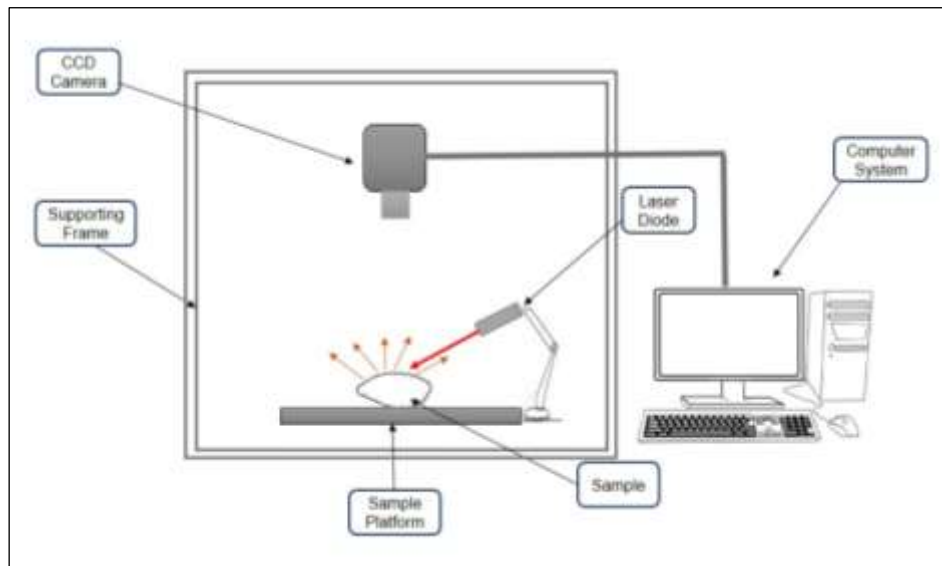
Absorption coefficient ( $\mu_a$ ) and reduced scattering coefficients ( $\mu_s'$ ) are two of the most important optical properties of the backscattering technique (Zude-Sasse *et al.*, 2019).

The decreasing rate of the light intensity when passing through the surface of a food material corresponds to the measure of the absorption coefficient while the fraction of scattered light per unit distance in the material belongs to the scattering coefficient (Mollazade *et al.*, 2012). Absorption and scattering coefficients uphold the principle that when a scattered light returns to its point of origin, it can only be described by considering the interference effects. Irimpan *et al.* (2008) added that the scattered lights with theme-reversed paths will interfere constructively and these interfering occurrences will enhance the photon projection and reduces the diffusion effect. The enhanced photons will later be extracted for the quantification of the physicochemical attributes of the material.

According to Mollazade & Arefi (2017), the backscattering imaging technique can acquire thousands of spectra per sample and based on the light source and imaging unit used, it can be divided into three categories which include laser-light backscattering imaging (LLBI), hyperspectral backscattering imaging (HBI), and multispectral backscattering imaging (MBI). Each of these imaging techniques is differentiated based on the illumination source and imaging set-up (Adebayo *et al.*, 2017). Theoretically, the use of LLBI is similar to that of HBI and MBI but only differs with the number of wavelengths applied. However, the LLBI technique is utilized for quantifying the scattering light at a specific wavelength rather than considering a wide range of wavebands (Mollazade *et al.*, 2012). With this particular reason, the LLBI is more advantageous and recommended to use since a single light source is always coherent and the system becomes easy to adjust and assemble. Thus, the LLBI is possible for the quality evaluation of various agricultural products utilizing the scattering and absorption effects.

## 2.2 Basic components of LLBI

An LLBI system is basically consist of two (2) major components: a light source and an imaging unit. A light source is designed to provide continuous light beam while the imaging unit is intended to acquire high quality of backscattered images. In the light source, the size of the laser beam and the incident angle between the sample and the beam have to be considered to provide distortion-free images (Hashim *et al.*, 2013; Lorente *et al.*, 2015). Meanwhile, the imaging unit is primarily provided with a camera; charge-coupled device (CCD), complementary metal oxide (CCMO) and monochromatic are three (3) of the most commonly adopted cameras in the LLBI system (Mohd Ali, 2017). As a whole, the basic parts of an LLBI system as shown in Figure 2 includes a computer system, camera, laser emitting diode, sample platform, supporting frame, and the sample being examined.



**Figure 2.** Schematic diagram of the basic components of an LLBI system (Sanchez *et al.*, 2020b).

According to Adebayo *et al.* (2017), one of the most important considerations in using the LLBI technique for non-invasive quality evaluation of food products is the appropriate selection of laser wavelength. Choosing the appropriate wavelength for a particular food product is of uppermost importance in order to obtain a more precise measurement (Gunasekaran *et al.*, 1985). On the report of Adebayo *et al.* (2017), they have found that the food product quality could be quantified by utilizing the laser wavelengths from visible to NIR (400-1,000) as established in several former studies. It is then suggested that the 620 nm to 1,010 nm wavelength exhibited good potential for soluble solids content (SSC) and texture property measurements while 900 nm is suitable for moisture content (MC) measurement.

Another part that has to be considered in the application of LLBI technique is the laser beam size. Lasers with the larger beam size are known to provide good light distribution but could be disadvantageous for the backscattering properties as photons do not travel along the same path ways (Lu, 2004). Likewise, the light distribution from smaller beam sizes are concentrated but the light intensities are reduced which may result to a poor scattering area. Thus, proper selection of laser source sizes is important. Zulkifli *et al.* (2019) added that vigilant selection of laser source wavelength must be highly considered to obtain a good light signal.

Also, the incident angle between the food material and the laser source must be appropriately considered. The reason behind this is to minimize the oversaturation effect of the light intensity and to refrain the irrelevant reflection back to the camera. Based on review,

an incident angle of 15° to 22° has been applied in the former LLBI studies which resulted to an easier image processing procedure (Adebayo *et al.*, 2016) and distortion-free images (Hashim *et al.*, 2013; Hashim *et al.*, 2014; Lorente *et al.*, 2013; Mohd Ali *et al.*, 2017b; Onwude *et al.*, 2018; Zulkifli *et al.*, 2019). Thus, proper LLBI configuration must be of high regard to have soft and precise quality-based optical measurements that are free from uncertain variations.

### 3. Applications of LLBI in Various Agricultural Products

In this part, the practical applications of LLBI technique across the various agricultural products are discussed. As shown in Table 1, the list of previous and recent literatures concerning the implementation of LLBI method under different study considerations applied such as the type of agricultural product, postharvest handling, wavelength selection range, data analyses applied and the corresponding accuracies obtained are summarized. It can be clearly seen that the exploitation of LLBI in the quality and safety evaluation of several agricultural products is paralleled with the different multivariate analytical methods. Multivariate analysis is a very crucial part in establishing the relationships between the extracted backscattering parameters and the reference quality parameters of the agricultural product being examined. Elmasry & Nakauchi (2016) stated that the mathematical, statistical, and modelling approaches are vital for the image-based analytical measurements. However, it is notable that the potential ability of LLBI technique has been viable across the different pre and post-harvest handling. Most applications of LLBI were concentrated on quantifying the quality of fruits and vegetables during fresh harvest, drying, storage, as well as in the decay detection and ripeness or maturity identification.

Say for instance, LLBI has been potentially approached by Hashim *et al.* (2013) in monitoring the chilling injuries of bananas when stored at a chilling temperature of 6 °C for a period of two days. The study showed a promising result as defined by the coefficient of determination ( $R^2$ ) of over 0.90 between the reference quality attributes (visual assessment, chlorophyll index and water content) and the extracted backscattering properties. This assessment was supported by a good classification analysis with over 90 % accuracy as established both from the Linear Discriminant Analysis (LDA) and Quadratic Discriminant Analysis (QDA). Zulkifli *et al.* (2019) expanded the analysis into prediction and classification of the ripening stages of the same crop (banana) during storage. Based on the results, a high correlation effect ( $R^2 > 0.90$ ) was also obtained between the measured total

soluble solids and color properties of banana against the LLBI parameters. The technique also showed a high classification ability in sorting the fruit into ripe and unripe groups with over 90 % accuracy as established both from the LDA and PCA. The two studies implemented in the same crop but of different data analysis used only implied that regardless of the multivariate data analysis employed, LLBI technique provided accurate and favorable results.

Likewise, the non-destructive quality detection of apples using LLBI has been investigated by Zude *et al.* (2006), Qing *et al.* (2008), and Mollazade *et al.* (2013). The authors examined the same quality parameters (SSC and firmness) of the fruit and multivariate data analysis (PLSR) but somehow differed on the wavelength of the laser source used (Table 1). As formerly stated, different laser wavelength may give dissimilar results in the analysis as LLBI mainly possessed light scattering properties. Accordingly, all of the laser source used with wavelength ranges from 600 to 1,100 nm gave a good indicative results in quantifying the firmness and SSC of apples establishing a correlation factors against the backscattering properties of  $R > 0.80$ . However, Qing *et al.* (2008) observed that the wavelength intensities in a range of 750 nm to 900 nm are less affected by the absorption of the fruit tissues while wavelength range between 780 nm to 880 nm will provide information mainly on the light scattering of the crop tissue. Thus, among all the three comparative results, the smaller wavelength used (660 nm) provided the highest correlation effect of  $R^2 = 0.887$  as found in the study of Mollazade *et al.* (2013). Recently, Wu *et al.* (2020) also demonstrated a good classification model in detecting the defects of apples based on their backscattering images. A convolutional neural network (CNN) theory was employed in analyzing the extracted properties achieving an accuracy of over 90 % recognition rate. Hence, these results showed that LLBI can be potentially applied in the non-invasive quality inspection of agricultural products particularly in apples.

Moreover, LLBI has also been explored in monitoring the quality changes of other fruits as affected by the postharvest handling such as during drying of papaya (Udomkun *et al.*, 2014), storage of plums (Mollazade *et al.*, 2013; Kalaj *et al.*, 2016), pears (Adebayo *et al.*, 2016; Zude-Sasse *et al.*, 2019) and watermelons (Mohd Ali *et al.*, 2017b). Other cases include the decay detection in citrus (Lorente *et al.*, 2013), estimating the maturity levels of cacao (Lockman *et al.*, 2019) and oil palm fresh fruit bunch (Mohd Ali *et al.*, 2020).

**Table 1.** Summary of LLBI applications in various agricultural products.

Product	Experimental Consideration	Quality Parameter	Data Analysis	Wavelength (nm)	Accuracy	Author/s
Apple	Fruit Maturity	SSC and Firmness	PLSR	400-1,100	R <sup>2</sup> > 0.80 Classification: > 90 %	Zude <i>et al.</i> (2006)
Apple	Storage	SSC and Firmness	PLSR	680-980	R <sup>2</sup> > 0.70	Qing <i>et al.</i> (2008)
Apple	Fresh Harvest	Defect Detection	CNN	635	Accuracy = 92.50 %	Wu <i>et al.</i> (2020)
Apple, Plum, Tomato, Mushroom	Storage	Firmness	PLSR	660	R <sup>2</sup> = 0.887 (Apple) R <sup>2</sup> = 0.790 (Plum) R <sup>2</sup> = 0.919 (Tomato) R <sup>2</sup> = 0.816 (Mushroom)	Mollazade <i>et al.</i> (2013)
Citrus	Storage	Decay Detection	GLP, LDA, PCA	532-1,060	R <sup>2</sup> = 0.998 Classification: > 90 %	Lorente <i>et al.</i> (2013)
Banana	Storage	Chilling Injury	MLR, LDA, QDA	660-785	R <sup>2</sup> > 0.90 Classification: > 90 %	Hashim <i>et al.</i> (2013)
Papaya	Drying	MC, Shrinkage, Color	MLR	532-780	R <sup>2</sup> > 0.90	Udomkun <i>et al.</i> (2014)
Plum	Storage	Firmness, SSC, Color, MC	MLR	532-785	R > 0.70	Kalaj <i>et al.</i> (2016)
Pears	Storage	Firmness, SSC	PLSR	532-830	R > 0.80	Adebayo <i>et al.</i> (2016)



Potato	Storage	MC, Firmness, Defect Detection	ANN	635	Classification: > 90 %	Babazadeh <i>et al.</i> (2016)
Potato	Fresh Harvest	Stones and Clods Discrimination	LDA	405-980	Classification: > 98 %	Geng <i>et al.</i> (2019)
Dry-cured Ham	Drying	MC and Texture	MLR	532-635	R > 0.60	Fulladosa <i>et al.</i> (2017)
Watermelon	Storage	Firmness, SSC, Color, pH, MC	PLSR	658	R <sup>2</sup> > 0.90	Mohd Ali <i>et al.</i> (2017b)
Sweet Potato	Drying	MC, Color	PCA, PLSR	658	R <sup>2</sup> > 0.70 Classification: > 90 %	Onwude <i>et al.</i> (2018)
Sweet Potato	Storage	MC, SSC, Color, Texture	MLR	658, 780	R > 0.85	Sanchez <i>et al.</i> (2020b)
Banana	Storage	Ripening/Maturity, Color, TSS	LDA, MLR, PCA	658	R <sup>2</sup> > 0.70 Classification: > 90 %	Zulkifli <i>et al.</i> (2019)
Pear	Storage	Firmness, MC, SSC	Regression	1,060	R <sup>2</sup> > 0.60	Zude-Sasse <i>et al.</i> (2019)
Cacao	Fresh Harvest	Firmness, Color	LDA, MLR	658, 705	R <sup>2</sup> > 0.755 Classification: >90 %	Lockman <i>et al.</i> (2019)
Oil Palm	Maturity Level	Oil Content, Color	PCA, PLSR	658	R <sup>2</sup> > 0.80 Classification: > 85 %	Mohd Ali <i>et al.</i> (2020)

**R**-correlation coefficient; **R<sup>2</sup>**- coefficient of determination; **MC**- moisture content; **SSC**- soluble solids content; **TSS**- total soluble solids; **pH**- titratable acidity; **ANN**- artificial neural network; **CNN**- convolutional neural network **GLP**-Gaussian Lorentzian Product; **LDA**-Linear discriminant analysis; **MLR**- multi-linear regression; **PLSR**- partial least squares regression; **PCA**- principal component analysis; **QDA**- quadratic discriminant analysis.

Similarly, the potential ability of LLBI has been extended in the quality monitoring of various vegetable crops. This include the classification, decay detection and discrimination of clods and stones in freshly harvested potatoes (Babazadeh *et al.*, 2016; Geng *et al.*, 2019) as well as during drying of sweet potatoes (Onwude *et al.*, 2018). In the case of sweet potato, the capability of LLBI technique as examined by Onwude *et al.* (2018) focused mainly on predicting the MC and color changes of the flesh during drying. However, monitoring the physicochemical properties of the whole sweet potato roots during storage is highly important considering particularly the differences in varieties (Md Saleh *et al.*, 2018). Thus, this has brought the further interest of Sanchez *et al.* (2020b) in investigating the feasibility of LLBI in evaluating the quality changes of different sweet potato varieties during storage. Based on the study conducted, it was found that the LLBI can adequately predict the quality parameters of different sweet potato varieties such as the MC, SSC, color and textural properties with  $R > 0.70$ . Results of the study also showed that the changes in the backscattering properties were related to that of the measured quality attributes and microstructural properties of the samples. Therefore, a baseline data was established concerning the potential ability of LLBI in quantifying the structural properties of an agricultural product.

Recently, Mohd Ali *et al.* (2020) investigated the potential of LLBI in combination with computer vision in rapidly determining the maturity levels of oil palm fresh fruit bunches. The study specifically determined the variations of color and oil content of the oil palm fruit at different maturity levels. Results of the study have indicated that the combined LLBI and computer vision (Red-Green-Blue imaging) methods were able to detect the quality changes of the oil palm fruit at different maturity levels as defined by the  $R^2 > 0.80$  for both oil content and color ( $L^*$ ,  $a^*$ ,  $b^*$ ) values. The combined optical techniques demonstrated a high potential in classifying the samples according to their maturity levels with over 90 % accuracies as described by the PCA. This review has emphasized the good potential of LLBI in combination with other optical-based methods for the non-destructive quality evaluation of agricultural products. Thus, it can be inferred that the LLBI technique has been proven effective and potentially viable in different implementations. However, the technique still has the room for advancements and developments for a more rapid and accurate quality measurements of agricultural and food products.

#### 4. Conclusion

This paper reviews and reports the available literatures relate to the application of LLBI technique in various quality-related measurements of agricultural products. The LLBI has the capability to replace the conventional methods of quality inspection that are mostly destructive and laborious in nature. The application of laser-based imaging technology in quantifying the quality-related indices of various agricultural products have shown potential ability of the method as a rapid non-destructive optical tool. Moreover, the integration of laser-based imaging in other optical imaging techniques are also feasible and can be further implemented for future developments. Thus, the non-destructive quality evaluation of several agricultural products can be potentially approached by means of LLBI method which is rapid, more accurate, user-friendly and economically viable.

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