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Classification and characterization of blueberry mechanical damage with time evolution using reflectance, transmittance and interactance imaging spectroscopy

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ABSTRACT

The aim of this work was to evaluate the performance of hyperspectral data coupled with chemometrics methods in characterizing and detecting the non-visible mechanical damage of blueberries with time evolution. Reflectance and transmittance as well as interactance hypercubes were automatically segmented by the region growing based algorithms. The maximum-normalized spectra were pretreated by the Standard Normal Variate algorithm, and subsequently the Competitive Adaptive Reweighted Sampling algorithm was applied to extract the damage-specific wavelengths. Based on confusion matrices and area under Receiver Operating Characteristics curves, transmittance showed relatively superior performance to reflectance and interactance. Application of new sample set subjected to impact tests with time evolution, results demonstrated that it was especially difficult to distinguish fresh damage in blueberry. At 2 days after impacted, several transmittance-based classifiers obtained satisfactory accuracies for classifying damaged (sound) blueberries: logistic regression 79.1% (85.7%), multilayer perceptron-back propagation 74.4% (92.1%) and logistic function tree 72.1% (95.2%). Furthermore, the physical property preliminarily proved to be more pronounced than the absorbed impact energy for damage incidence and severity of blueberry via the use of multiple comparison.

1. Introduction

Fruits can be injured during a complete farm-to-table chain such as harvesting, handling, transport and storage (Li and Thomas, 2014; Van Zeebroeck et al., 2007). The presence of mechanical damage will accelerate fruit softening (Zhou et al., 2007) and even increase fruit susceptibility to fungal spoilage (Mehra et al., 2013), which in turn reduce the income of fruit industry and bring the possible hazard to the consumer (Opara and Pathare, 2014). Blueberry belongs to a small soft fruit, and its production has greatly expanded these years due to the health-promoting and antimicrobial attributes (Elks et al., 2013; Retamales, 2012; Shen et al., 2014); however, the highly perishable nature of blueberry makes it particularly prone to mechanical damage and afterward leads to amount of economic loss (Li et al., 2010). To improve blueberry quality, it is necessary to prevent the damaged blueberries for marketing.

Non-destructive measurements in conjunction with chemometrics methods are attempted to estimate fruit damage, instead of labor-intensive and fallible manual inspection. Opara and Pathare (2014) elaborated the progresses in applications of non-destructive defect detection approaches, containing machine vision system (Zhang et al., 2015), visible and near infrared (vis/NIR) spectroscopy (Martinsen et al., 2014; Wu and Wang, 2014), hyperspectral imaging (Pu et al., 2015), thermal imaging (Baranowski et al., 2009), magnetic resonance imaging (Mazhar et al., 2015; Patel et al., 2015). Among these techniques, hyperspectral imaging treats spectral data as a series of images, and therefore it has been viewed as the combination of machine vision and spectroscopy techniques (Manley, 2014; Wu and Sun, 2013). Compared with thermal imaging and MRI approaches, hyperspectral imaging has less temperature influence and is more suitable for online detection (Van Zeebroeck et al., 2007). Thus, the majority of investigators had applied the hyperspectral imaging for detecting fruit mechanical damage (ElMasry et al., 2008; Xing et al., 2005). Siedliska et al. (2014) detected apple bruise based on supervised classification models which were also utilized by Baranowski et al. (2013, 2012) to classify the bruised apple using hyperspectral and thermal imaging techniques. The time evolution of apple bruise was taken into account by the above investigators (Baranowski et al., 2013). In regard to damage time evolution,

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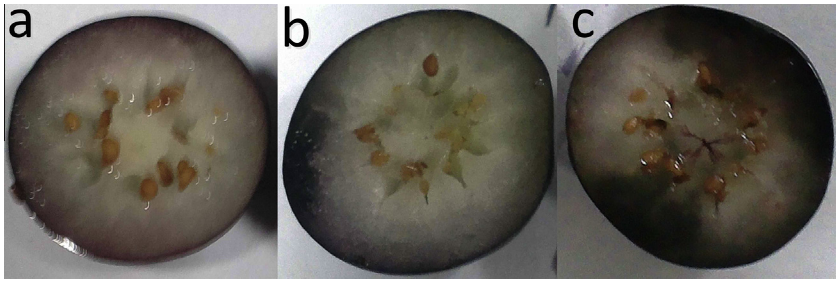

Fig. 1. The definition of blueberry damage degrees: (a) sound; (b) minor damage; and (c) (major) damage.

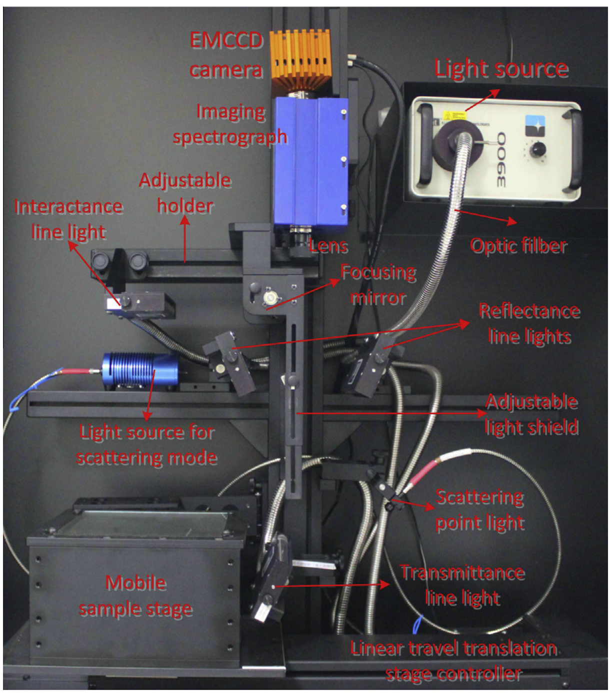

Fig. 2. Photographs of hyperspectral reflectance/transmittance/interactance imaging system.

Jimenez-Jimenez et al. (2013) used digital camera to conduct temporal evolution assessment of table olive damage. Huang et al. (2015) developed an online multispectral imaging system for apple bruise detection. H. Lee et al. (2014) used support vector machine (SVM) to classify hyperspectral morphological features for recognizing crack in tomato. In the publication of K.Q. Yu et al. (2014), the crack in the surface of fresh jujube was discriminated by the combined use of vis/NIR hyperspectral imaging and least-squares SVM. The feasibility of using hyperspectral imaging for the early detection of mechanical damage in mango had been proved by the previous study of Rivera et al. (2014), and their results demonstrated that the k-Nearest Neighbors was superior to supervised classification models. W.-H. Lee et al. (2014) used NIR hyperspectral imaging combining with *F*-value based band ratio algorithm to detect pear bruise. A novel hyperspectral imaging system based on two liquid crystal tuneable filters was developed for the inspection of citrus fruit decay (Gomez-Sanchis et al., 2014).

Previous literature on determining fruit mechanical damage usually applied hyperspectral imaging technique in reflectance mode. The potential use of the other sensing modes, such as transmittance and interactance, is required to be discussed for the detection of fruit mechanical damage. Transmittance mode had been effectively used to perform the detections of pickling cucumber internal defect (Cen et al., 2014) and parasite in cooked clam (Coelho et al., 2013) as well as insect-damaged soybean (Huang et al., 2013; Ma et al., 2014). For interactance, despite being advantageous over the other modes (Wu and Sun, 2013), few studies had been reported to conduct this mode for food quality evaluation (ElMasry and Wold, 2008; Gou et al., 2013; Sivertsen et al., 2012) due to the relatively complicated imaging architecture (Leiva-Valenzuela et al., 2014). The successful application of these modes had been achieved in the studies of spectroscopy (Nicolaï et al., 2007; Wang et al., 2013), owing to no or low spatial resolution.

In the case of non-destructive techniques for blueberry quality control, Li et al. (2014) and Yang et al. (2014) used traditional computer vision and hyperspectral imaging to identify the blueberry mature stages, respectively. Leiva-Valenzuela et al. (2014) correlated the hyperspectral reflectance and transmittance data with the soluble solids content and firmness of blueberry by partial least squares regression. In order to recognize visible mechanical damaged blueberries, Leiva-Valenzuela and Aguilera (2013) proposed the classifiers based on a traditional computer vision system, and the average classification accuracy was beyond 85%. However, the mechanical damage underneath the blueberry skin was undetectable when using these classifiers. The principle of optical nondestructive method is based on the fact that the change of fruit (micro) structure will accompany the change of fruit optical properties (Allan-Wojtas et al., 2001; Mollazade et al., 2012). Apart from the optical measurements, Li et al. (2010) used electronic nose to identify the fungal disease of blueberry. The study of using electronic nose in classifying the impacted blueberries was carried out by Demir et al. (2011), and one of their results showed that blueberry impacted damage was invisible to the naked eye. Unlike optical methods, the testing principle of electronic nose is on the basis of the changes in volatile characteristics. From the above literature evidences, very limited research work had been conducted on the hyperspectral imaging for detecting the invisible mechanical damage of blueberry.

The objectives of current study are to: (1) establish the classification models based on the hyperspectral reflectance and transmittance as well as interactance modes for distinguishing blueberry mechanical damage; (2) verify the main factors of the impact damage incidence, e.g. mechanical properties and absorbed energy, and characterize the spectral behavior during cold storage; and (3) use the established classification models to identify blueberry impact damage with respect to the time evolution.

2. Materials and methods

2.1. Blueberry sample preparation

A total of 737 blueberries (*Vaccinium corymbosum*) were collected from Frutera San Fernando S.A., Chile during December 2014 to January 2015. After transported to the lab, the blueberries were stored at environmental temperature of 4 °C and relative