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An approach for monitoring the chilling injury appearance in bananas by means of backscattering imaging

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A B S T R A C T

The non-invasive detection of chilling injury (CI) symptoms in banana may potentially be approached by means of monitoring changes in the pigment contents and texture of the exocarp. In the present study, laser diodes emitting at 660 and 785 nm were applied to acquire images of backscattered light from intact banana fruits. The idea was to monitor chlorophyll and texture changes by means of relevant wavelengths, respectively. Bananas were stored for 2 days at 13 °C (control), 6 °C (chilling temperature), and subsequently 1 day at ambient temperature to allow the symptom development. Parameters obtained from the backscattering images and their combinations were applied for detecting chilling injury. Significant ($P < 0.05$) interaction of backscattering properties and treatment factors (temperature, ripening stage, and treatment time) were found. Classification of control and chill-injured samples in ripe fruits measured at 660 nm and 785 nm resulted in misclassification error as low as 6% and 8% for early detection, and 0.67% and 1.33% for detection after storage, respectively. The physiological relevance of the variation measured at the two wavelengths was pointed out by means of destructive pigment and water analyses.

1. Introduction

Visual assessment is the established method for the detection of chilling injury (CI) in bananas at each point of sale. Skog (1998) reported that the symptoms of CI are strongly dependent on the duration and temperature of chilling treatment. Symptoms may only develop when the produce is placed at higher temperatures and may appear immediately or the appearance may take several days. Such delayed appearance of CI symptoms creates economic losses during transportation, storage, and marketing. Thus, a non-destructive technology is needed that is capable to detect CI symptoms in an early stage. Potential fruit properties for detection of CI may be changes in the pigment contents as well as fruit texture. Advances in non-destructive methods for measuring fruit quality (Ruiz-Altisent et al., 2010) have been commercially made using computer vision regarding the external fruit appearance (Brosnan and Sun, 2002; Leemans et al., 2002; Blasco et al., 2003; Cubero et al., 2011), spectroscopy in the visible wavelength range for pigment detection (Olsen et al., 1969; Zude, 2003), and near-infrared spectroscopy (NIRS) aimed at prediction of soluble solids content (SSC) (Chen and Nattuvetty, 1980; Birth and Hecht, 1987; Bellon et al., 1993; Golic and Walsh, 2006; Miller and Zude, 2004; Nicolai et al., 2007). While the detection of pigment changes can be analyzed by means of vision systems and visible spectroscopy, the established methods are unable to provide reliable measurements of texture parameters such as fruit flesh firmness (Zude et al., 2006). The correlation between firmness using the NIRS and the conventional method – destructive Magness-Taylor test – is low when validating the calibration model with an independent test-set (McGlone and Kawano, 1998; Lu et al., 2000; Zude et al., 2006).

New approaches were introduced based on spatially-resolved readings, combining vision system and spectral readings. When light hits a fruit, light interactions will happen in which about 4% of the photons will be reflected at the fruit surface while the remaining part enters the fruit tissue and is absorbed, transmitted, or scattered back (diffuse reflectance) from the region close to the incident point (Birth, 1976). The apparent pathlength of the light, travelling in the fruit tissue from incidence point until total

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attenuation, provides information on the structural and chemical characteristics of the fruit. Chemical constituents in the fruit such as chlorophyll, soluble solids, and water influence light absorption, while fruit density, cell size, middle lamella, intra- and extracellular matrices are likely to affect scattering properties. While the absorption in the visible and NIR wavelength ranges can provide information on the chemical composition of the fruit, the structural and fine structure (texture) characteristics can be addressed by its scattering properties (McGlone et al., 1997; Qin and Lu, 2008) and effective pathlength of the photons (Zude et al., 2011). Consequently, during recent years absorption and scattering properties were studied. The scattering properties were approached by means of time-resolved (Torricelli, 2009) and spatially-resolved readings (Lu, 2004) of the photon attenuation in the fruit tissue. Spatially-resolved analyses were obtained by analyzing the backscattered images produced by hyper- and multispectral light sources that injects photons in the fruit tissue and a camera system. McGlone et al. (1997) reported that a correlation was found between firmness and backscattering measurements in the NIR using laser diode at 864 nm. Lu (2004) used multiple wavelengths in the visible and NIR range and found that combinations of four wavelengths – 680, 880, 905, and 940 nm – gave the best prediction of apple firmness. The highest correlation was found between reflectance at 680 nm and firmness in peach (Lu and Peng, 2006) and apples (Peng and Lu, 2008). The ratio of reflectance at 675 nm to that at 535 nm well classified three ripeness stages of tomatoes (Qin and Lu, 2008), addressing again the changes in pigment contents when the fruits turn from green to red, but certainly also changes in the scattering properties that result from the fruit texture variation. For understanding the physiological meaning of these calibrations, chemical reference analyses will be needed.

When analyzing the backscattering images, the size of the area in which photons are apparently backscattered (Peng and Lu, 2006), histogram of intensities (Qing et al., 2007, 2008), Lorentzian distribution function (Lu and Peng, 2006), modified Lorentzian function (Peng and Lu, 2006), and modified Gompertz function (Peng and Lu, 2007) were applied. Since the curvature of the fruit might affect the intensity values captured by the camera, the Lambertian cosine law was used for correcting the scattering profile (Peng and Lu, 2006; Qing et al., 2007). Results indicate correlations between the backscattering profiles with the reference values measured by the standard methods for fruit flesh firmness. Lorentzian distribution function with two parameters, i.e. peak value of the scattering profile and full width at half maximum (FWHM), were well correlated with the firmness of peach fruit (Lu and Peng, 2006). The peak value of the profile gave better prediction of fruit firmness than does its FWHM. The combination of both parameters provides improved results. A modified Lorentzian function provides four parameters to describe the profile of apparent photon backscattering with additional asymptotic and slope values. Results indicate that the advanced approach yielded better firmness predictions with the correlation coefficient and standard error of validation values being higher than 0.89 and lower than 6 N, respectively. However, the modified Lorentzian function with the combination of three parameters, i.e. slope, peak and FWHM, provided the highest performance for predicting both, fruit flesh firmness and SSC (Peng and Lu, 2008).

Research and development of laser-induced backscattering imaging have been done successfully considering the quality analyses of several fruit and vegetables such as apples (Peng and Lu, 2006; Qing et al., 2007; Qin and Lu, 2008), peaches (Lu and Peng, 2006), pear, plums, tomatoes, zucchini and cucumber (Qin and Lu, 2008) and kiwifruit (Qin and Lu, 2008; Baranyai and Zude, 2009). However, the knowledge on the capability of this technique is still limited for analyzing tropical fruit such as banana which is different in its physico-chemical properties. Reference analyses regarding the absorbing pigments and water – that cause the changes in the backscattering profile – have never been carried out.

The objectives of present work were (i) evaluating parameters to describe CI in bananas at two potentially synergistic wavelengths; (ii) evaluate the interaction of fruit pigment and water contents with parameters derived from backscattering images and (iii) classify the chill-injured and the control fruit considering storage time and visual assessment.

2. Materials and methods

2.1. Fruit samples

Musa cavendishii bananas in ripening stages two (R2-unripe), three (R3), four (R4), and five (R5-overripe) were obtained from a commercial banana ripening facility (FruchtExpress Import Export GmbH, Germany) importing bananas from Ecuador, Costa Rica, and Columbia. For each ripening stage 60 fruits ($n = 240$) were analyzed. For each stage, 30 bananas were grouped as chilled samples and 30 were grouped as control samples. The chilled and control samples were stored at 6 °C and 13 °C, respectively, for 2 days. Data collection spread over a period of 4 days. Day 1 is the day before treatment when all fruits were kept at 13 °C; on days 2 and 3 the samples were subjected to the temperature treatment; and on day 4, which is the day after the temperature treatments, all fruits were exposed to ambient temperatures. Backscattering imaging and visual assessment measurement were carried out on all samples at days 1, 3, and 4. One backscattering reading was taken at day 1, while five readings at 90-min intervals were taken on days 3 and 4 (16 measurements per fruit) to monitor the development of CI. Measurements at days 1 and 4 were carried out at ambient temperature (17.5 ± 2.5 °C). Pigment analysis was carried out at the beginning of the experiment destructively on a sub-sample of additional 20 fruits at each ripening stage and at the end of the experiment on control and chill-treated fruits. The fruits analyzed at the end of the experiment were the same fruits subjected to the backscattering analysis.

2.2. Laser-induced backscattering imaging system

Backscattering images of bananas were obtained by an in-house developed laser-induced backscattering imaging system in the Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB), Germany. The system mainly consisted of a high performance CCD camera (JVC KY-F50E) with zoom lens (F2.5 and focal lengths of 18–108 mm), a light source unit (solid-state laser diode emitting at two pass bands: 660 and 785 nm with 45 mW maximal power) and an in-house developed software to acquire the backscattering images (Baranyai and Zude, 2009). The backscattering images (720 × 576 pixels) were acquired in a dark-room and laser diode spot of 1 mm diameter provided a good signal to noise ratio of the profiles (Qing et al., 2007). The incident angle of light beam was set at 15° to get distortion free images and minimal direct reflection back to the camera.

Each banana was placed under the CCD camera with equal orientation and the acquisition of backscattering images was carried out using 660 and 785 nm laser-light source consecutively. A total of six images with three images per side of the banana were acquired to obtain the average value of the backscattering for each fruit.

2.3. Visual assessment, water content and pigments analyses

The visual assessment (VA) method captured a browning scale as described by Nguyen et al. (2003) and was performed immediately after the image acquisition. The browning scale was rated as follows: 1 – no chilling injury symptoms appears; 2 – mild chilling