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Non-destructive analyses of apple quality parameters by means of laser-induced light backscattering imaging

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Abstract

Monitoring of apple fruit development is necessary to determine appropriate production measures. Furthermore, consumer acceptance of apples depends on internal quality especially regarding the soluble solids content (SSC) and fruit flesh firmness. In the present work, laser-induced light backscattering imaging was applied to analyze fruit SSC and firmness during apple development in different growing locations by means of non-destructive readings, showing potential for rapid site-specific fruit evaluation during production. Spectral images of the backscattering of light on the fruit surface were obtained from 'Elstar' and 'Pinova' apples using laser diodes emitting at five wavelengths (10 nm bandpass) between 600 and 1100 nm, addressing the fruit absorption and scattering properties. Different multivariate calibration methods were tested on the frequency of different intensities of backscattering each for the five wavelength bands to analyze SSC and firmness. The method was applied on two cultivars picked at weekly intervals during fruit development grown in sites with different plant water availability. During fruit development the mean values of SSC data of drought stressed and sufficiently irrigated regions of orchard ranged from 11.1 to 15.4 and 10.5 to 14.5 °Brix, respectively. The mean values of fruit firmness at the two different field regions developed from 130.9 to 71.6 and 116.1 to 68.3 N/cm^2, respectively.

Using partial least squares regression, calibration uncertainty in cross-validation ranged between 6 and 2% for SSC and firmness, while a validation on a test-set gave a percentage error of prediction in the range of 10% for SSC and 9% for firmness with respect to refractometrical SSC readings and the Magness–Taylor firmness test, respectively. Variation in fruit parameters due to slight drought stress was found in the range of 12–13%. A calibration on the specific fruit material is necessary for assessing the spatial distribution of fruit quality parameters in the orchard, however, laser-induced backscattering imaging is an inexpensive method for rapidly receiving relevant information for site-specific measures.

Keywords: Apple; Firmness; Fruit development; Imaging; Laser; Non-destructive; Scattering; SSC

1. Introduction

To provide high-quality apples for the market, the fruit have to be picked at the appropriate ripeness stage and quality. In this regard, internal fruit quality parameters are needed for process management along the entire supply chain. During production, environmental and physiological factors affect quality attributes in terms of firmness, taste, color, and shelf-life. Even among fruit grown in the same region, high variability in quality parameters may occur due to different environmental conditions such as plant water availability.

The common method for fruit flesh firmness analysis is the Magness–Taylor puncture test (M–T), a destructive method based on force-deformation characteristics of the fruit flesh mimicking the "mouth-feeling" during consumption by the consumer. Soluble solids content (SSC) is measured by means of refractometric reading of fruit juice addressing the fruit taste. While quality parameters are presently measured by means of destructive tests, non-destructive readings would provide a tool for on-site data collection.

Spectroscopic methods using the visible and near infrared (NIR) wavelength range provide data on absorbing compounds such as pigments as well as sugars (Kawano, 1994; Lammertyn et al., 1998; Peirs et al., 2005). Commercial non-destructive equipment, e.g. sorting line and portable devices, with regard to SSC is available based for NIR spectroscopy in the wavelength range of 800–1100 nm (Birth and Hecht, 1987; Bellon et al.,

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1993; Ji, 2000; McGlone et al., 2002; Temma et al., 2002; Miller and Zude, 2004). Changes in fruit absorption spectra caused by chlorophyll degradation provide an effective ripeness indicator for apples (Merzlyak et al., 1999; Zude-Sasse et al., 2002; Zude, 2003) or for measuring nutritionally valuable compounds such as carotenoids in carrots (Zude et al., 2007). Applications have been tested for precision horticulture by monitoring fruit pigments on tree (Herold et al., 2005). In commercial applications, the correlation of decrease in chlorophyll content and fruit flesh firmness has been discussed as a parameter for analyzing the firmness non-destructively using spectroscopy such as in SSC analysis. However, although a correlation between changes in chlorophyll and fruit flesh firmness obtained by the M–T test exists, robust calibrations on fruit flesh firmness by means of this correlation cannot be expected (Zude et al., 2006). In contrast, analysis of fruit scattering properties might provide a more reasonable approach for firmness analysis (Lu, 2004; Peng and Lu, 2006; Qing et al., 2007a). While spatial scattering data may provide information on fruit texture, the spectral information is still useful for SSC prediction. As a result, while near-infrared spectroscopy has been applied recently for non-destructively measuring and sorting apples taking into account SSC, wavelength-dependent laser-induced light backscattering methods might be able to predict SSC and firmness of apples simultaneously (Lu, 2004; Qing et al., 2007a). Regarding firmness analysis, this would provide an alternative to existing methods presently applied for predicting fruit mechanical properties (De Baerdemaeker, 1989; Abbott and Liljedahl, 1994; Felföldi et al., 2004).

In previous studies (Peng and Lu, 2006; Qing et al., 2007a), partial least squares regression (PLSR) was used to build calibration models. However, different methods were never used to test the feasibility of models. At present, firmness and SSC prediction models have been developed using PLSR, stepwise multiple linear regression (SMLR), and principal component regression (PCR). The objectives of the present study were to evaluate the feasibility of wavelength-dependent laser-induced light backscattering imaging to analyze internal quality of apples during fruit development in different growing conditions.

2. Materials and methods

2.1. Fruit samples

Malus x domestica ‘Elstar’ and ‘Pinova’ apples were obtained from a commercial orchard in Potsdam 52°22′N and 12°53′E, Germany, during the harvest season of 2006. The region provides semi-continental climate conditions with strong alterations in precipitation rate over the year. In the orchard a soil with loamy sand is dominant. Drip irrigation is installed in all sites, however, due to major variation in altitude the plant water supply was not equal. Irrigation took place two times per day. In sufficiently irrigated sites (+supply) in the plain area (51 m NN) the soil water potential ranged from 0 to −1.0 MPa (Tensiometer, Soilmoisture Equipment, USA) at 20 and 50 cm. In higher altitudes (64 m NN) the irrigation level was the same, but probably due to a more sandy soil structure with higher leakage rate as well as higher demands by the plants due to increased wind speed, the soil water potential ranged from 0 to −1.6 MPa, eventually providing conditions below the permanent wilting point. Trees grown in this site developed visually smaller leaves. As a result, a slight drought stress (−supply) can be assumed.

Forty ‘Elstar’ and ‘Pinova’ apples were harvested and measured once a week in the period from 1 August to 25 September. At each sampling date, for each cultivar, 20 samples were obtained from a drought stress zone of the orchard and 20 fruit from well-irrigated trees. Apples were stored at room temperature (24 °C) for at least 15 h before measurements were started. Each experiment was terminated within 2 days after harvest. Since seven harvest dates were used to measure samples, and a total of 40 apples for each cultivar were harvested on each measuring date, a total of 280 apples of each cultivar were measured for this study.

2.2. System set-up

A laser imaging system was assembled for this research, which consisted of a high performance CCD camera (Model TK-C1430EC, JVC Corporation, Japan) with a zoom lens (adjusting focal lengths of 1.4–11 mm). The light source was a solid-state laser diode module (RTR Optoelectronics Technology Co. Ltd., China) emitting at 680, 780, 880, 940, and 980 nm (±5 nm bandpass) alternately. On each fruit five images representing the five wavelengths bands (Qing et al., 2007b) were captured (Fig. 1a–e). After entering the fruit tissue, the portion of the light backscattered to the fruit surface was recorded by means of RGB images. The image sizes were 768 × 576 pixels. Dynamic range is full-well-depth (FWD) divided by the dark noise (DN), and the dynamic range of scattering images was defined as $\log_{10}$ of FWD/DN. The resulting dynamic range was 63:1. The divergence of laser diode modules was less than 1 mrad. The incident angle of the light beam was set at 15°, and the distance between the lens and the fruit sample was adjusted according to the focus of different laser source.

2.3. Backscattering image analysis

2.3.1. Image processing algorithms

The original color images of light scattering captured by CCD camera were transformed to monochrome images by calculating the luminescence (Eq. (1)), where I is the gray scale of light intensity; I_r, I_g and I_b are the light intensities of red, green and blue components of a true-color image (Gonzalez and Woods, 1992):

$$I = 0.3I_r + 0.59I_g + 0.11I_b \tag{1}$$

The gray scale of light intensity is expressed as the integer, which ranged from dark ($I = 0$) to white ($I = 255$). The gray values of pixels in scattering images were taken into account to obtain the histogram (Fig. 1f). As visible in Fig. 1f, the frequency increased at gray values less than 70 due to background noise as well as at values higher than 200 due to laser reflectance. The bimodal threshold algorithm was used to adjust global threshold