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Journal of Food Engineering 77 (2006) 254–260
JOURNAL OF FOOD ENGINEERING
www.elsevier.com/locate/jfoodeng

Non-destructive tests on the prediction of apple fruit flesh firmness and soluble solids content on tree and in shelf life

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Accepted 6 June 2005
Available online 9 August 2005

Abstract

Acoustic impulse resonance frequency sensor and miniaturized VIS/NIR spectrometer were applied on apple fruit *Malus domestica* 'Idared' and 'Golden Delicious' ($n = 800$) to predict fruit flesh firmness and soluble solids content (SSC) on tree and in shelf life. Partial least-squares calibration models on acoustic data and VIS spectra of 'Golden Delicious'/'Idared' apple fruits on tree were built for predicting the fruit flesh firmness: coefficients of determination (R^2) and standard errors of cross-validation (SECV) of $R^2 = 0.93/0.81$ and SECV = 7.73/10.50 [N/cm^2] were calculated. SSC prediction of freshly harvested apples using NIR spectrometry was obtained with $R^2 = 0.20/0.41$ and SECV = 1.29/0.94 [°Brix]. Prediction of SSC and fruit flesh firmness of stored 'Golden Delicious'/'Idared' apple fruits showed high errors or was not possible.

The fruit maturity stage on tree was predicted as classes based on calendar weeks for 'Golden Delicious'/'Idared' apple fruits with 64%/66% correct classification and 92%/84% correct plus neighboring class with SECV = 0.9/0.9 [weeks]. Classes of 'Golden Delicious'/'Idared' apple fruit at different quality levels due to different storage conditions were non-destructively discriminated with 77%/84% correctly classified fruits and 93%/99% correct plus neighboring class with SECV = 0.8/0.5 [classes].

The results show the potential of non-destructive sensors for predicting accepted fruit parameters enabling the determination of optimum harvest date and fruit quality in shelf life.

Keywords: Apple; Fruit quality; Fruit flesh firmness; Non-destructive sensing; OHD; Shelf life; Sensor fusion; Soluble solids content; Spectral analysis

1. Introduction

Measuring the apple fruit maturity stage on tree is not an easy task due to the various metabolic processes affected by the environmental conditions and production systems. However, decisions have to be made on the harvest date, which should be carried out during the optimum harvest window with respect to the desired fruit processing. In shelf life, the fruit quality maintenance is determined by the storage conditions and storage duration.

During the last few decades extensive research has been carried out on the development of non-destructive sensors (Abbott, 1999). None of the proposed particular approaches seems to provide all the information necessary to characterize fruit maturation and quality. Consequently different measuring principles addressing fruit flesh firmness, fruit sweetness, but also volatile

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0260-8774/$ - see front matter
doi:10.1016/j.jfoodeng.2005.06.027

compounds and pigment contents of fruit are recently used in parallel to improve the available information concerning the fruit maturity and quality (Di Natale et al., 2002).

However, commercial fruit quality inspection of freshly harvested as well as of stored fruit is often limited on measuring fruit flesh firmness and SSC, since at present the retail calls for minimum thresholds with regard to these quality parameters (Knee, 2001). At present destructive Magness–Taylor (MT) test and refractometer readings are applied to measure the fruit flesh firmness and SSC, respectively. Non-destructive methods for measuring those fruit parameters would be beneficial to ascertain the quality of an increased number of fruits individually as well as to monitor the fruit maturity and quality on individual fruit.

Fruit flesh firmness relates to texture properties, which can be judged either by humans—a sensory panel or market experts—or more objectively by mechanical tests. Destructive mechanical tests of texture include puncture, compression and shear tests, whereas non-destructive tests are related to impact, sonic and ultrasonic methods. Horticulturists tend to define firmness as the maximum force attained in the popular destructive MT penetrometer test. For six decades now, different non-destructive techniques have been developed for fruit excitation and signal analysis (Abbott, 1999; Chen, 1993; De Baerdemaeker, 1988; Finney, 1970). The acoustic impulse resonance frequency (AIF) technique uses the natural frequencies of the intact fruit obtained by recording the sound, which is produced by hitting the fruit and then performing a Fourier transformation on the signal. For spherical fruit a stiffness factor can be calculated using the frequency and mass of the fruit. The technique provides extremely useful information on apple fruit quality in shelf life. However, this method is not satisfactory for measuring the texture of fruit on tree (Huarng, Chen, & Upadhyaya, 1993; Landahl & De Baerdemaeker, 2002). Therefore in the present study optical spectral readings in the visible wavelength range were merged with the stiffness factor to achieve an improvement of the fruit flesh firmness prediction on tree as well as in shelf life.

Fruit SSC can non-destructively be determined with spectral–optical methods. Optical properties of fruit are based on reflectance, transmittance, absorbance, fluorescence or scatter of light by the product. The light recorded by means of light-protected glass fiber using a partial transmission mode is altered by extinction at various wavelengths due to absorption of responding molecules (Birth, 1978; Kawano, 1994; Olsen, Schomer, & Bartram, 1969). Within the visible (VIS) wavelength range the major absorbers in intact apples are the pigments: chlorophylls, carotenoids, and anthocyanins (Knee, 1972; Merzlyak, Gitelson, Chivkunova, & Rakitin, 1999; Zude-Sasse, Herold, & Geyer, 2000). Reflectance and transmittance spectra exhibit typical minima at the chlorophyll absorption band around 680 nm in the visible range. The maturity-dependent decrease of chlorophyll content (Knee, 1972; Matile, Hörtensteiner, & Thomas, 1999; Merzlyak et al., 1999; Olsen et al., 1969; Zude-Sasse, Truppel, & Herold, 2002) can be expressed by the shift of the inflection point (red-edge) on the wavelength scale (Gitelson, Merzlyak, & Lichtenthaler, 1996). This physical parameter has often been referenced by chemical analysis of fruit chlorophyll content (Gitelson et al., 1996; Knee, 1972; Merzlyak et al., 1999; Zude-Sasse et al., 2002; Zude, 2003a).

Wavelengths outside the visible spectrum have been used to measure the chemical composition of various agro-food products (Bellon, Vigneau, & Leclercq, 1993; Cael, Koening, & Blackwell, 1974; Kawano, 1994; Lammertyn, Nicolaï, Ooms, De Smedt, & De Baerdemaeker, 1998; Zude, 2003b). Currently, wavelength or whole-spectra analytical methods (Wise & Gallagher, 1996) are being developed for the non-destructive determination of SSC, acids, starches and overall maturity. Using the near infrared wavelength range up to 1700 nm, the SSC can be determined in intact produce (e.g. apple, banana, forages, kiwifruit, mango, melons, peach and potato) with $R^2 = 0.93$ and standard error of calibration (SEC) = 0.5 °Brix (Birth, 1978; Cael et al., 1974; Dull, Birth, & Leffler, 1989; Kawano, 1994). However, when using only the reduced wavelength range from 800 to 1100 nm sufficient results can still be expected (Bellon et al., 1993). In the present study, wavelengths are recorded in the visible (400–700 nm) and the very near infrared (700–1100 nm) range. This wavelength range has been used, because the corresponding sensors (Silicone CCD chips) are cheap enough for application in practise and the first results are promising (Bellon et al., 1993; Chen & Nattuvetty, 1980; Greensill & Walsh, 2000).

Non-destructive sensors were applied on *Malus domestica* Borkh., 'Golden Delicious' and 'Idared' apples. Linear multivariate fitting models were built using AIF analysis, VIS and NIR spectrometry. The feasibilities of the sensor data were tested to predict the well-accepted fruit flesh firmness and SSC. The fruit flesh firmness was addressed by AIF and VIS, while fruit SSC was predicted by NIRS. The information obtained with these methods is discussed, aiming at (i) determination of the optimum harvest date and (ii) fruit quality inspection in shelf life.

2. Experimental

2.1. Sampling and wet-chemical analysis

In a commercial orchard near Potsdam, Germany, apple fruits of the varieties 'Golden Delicious' and