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Supervised classification of bruised apples with respect to the time after bruising on the basis of hyperspectral imaging data

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ABSTRACT

Apple bruising, as a mechanical damage, occurs due to impact, compression, vibration or abrasion during handling. However, the symptoms of this damage, browning and softening of the tissue, appear not immediately but after a certain period of time after bruising. For sorting and grading systems, the information about how long the bruise exists in affected fruit can be valuable. VNIR (visible and near-infrared) and SWIR (short wavelength infrared) spectral characteristics of sound and bruised apple tissues were analyzed during a two week period after bruising. Supervised classification methods, including support vector machines, linear logistic regression, neural networks and decision trees, were used and compared to check their effectiveness for distinguishing time after bruising with respect to five varieties of apples. The detection system included hyperspectral cameras equipped with sensors working in the visible and near-infrared (400–1000 nm) and short wavelength infrared (1000–2500 nm) ranges. The results of supervised classification revealed good applicability of hyperspectral imaging in VNIR and SWIR spectral ranges for detecting the number of days after bruising. The linear logistic regression neural networks models were found to be the best classifiers in the majority of models developed. Prediction accuracies higher than 90% were obtained for classification models on spectral data pretreated with the second derivative.

1. Introduction

Bruise damage can be caused in apples from impact, compression, vibration, or abrasion (Leemans et al., 2002; Brosnan and Sun, 2004; Sun, 2008, 2010). In addition, the susceptibility of apples to bruise damage depends on the mechanical properties of the skin and flesh, which are cultivar dependent and can be modified by soil cultivation, nutrition and weather conditions in the field during fruit growth (Ferguson et al., 1999; Xing et al., 2007; Drogoudi and Pantelidis, 2011; Lleó et al., 2011; Grimm et al., 2012). Therefore, the location, shape and depth of bruising vary and damage detection is difficult, especially in case of dark skin colour or a small surface area of the bruise (Sun, 2008). Although bruising is the reason for rejecting the most fruit in sorting lines, the accuracy of the existing automatic sorting systems is still insufficient and a manual sorting method has still to be used (Leemans et al., 2002; Qin et al., 2009).

It is especially difficult to distinguish fruit bruises in the first hours/days after damage occurrence (Upchurch et al., 1994; Xing et al., 2005). Two basic effects of apple bruising, i.e. browning and softening of fruit tissue, develop gradually, depending on the storage conditions and physico-chemical properties of affected apples. The application of optical imaging in the visible and NIR regions for detection of early bruises is difficult due to multicolour backgrounds of particular cultivars (Wen and Tao, 2000; Xing et al., 2005). However, combining various wavelengths in differential reflectance improves detection and often identification of defects (Kleynen et al., 2003; Chen and Kim, 2004; Peng and Lu, 2006; Lee et al., 2008; Mendoza et al., 2011; Wang et al., 2011), and predicting fruit physical properties and biological variability (Lu, 2004; Lu and Peng, 2006; Nicolai et al., 2007; Peng and Lu, 2008; Bobelyn et al., 2010). A multispectral system was created (Mehl et al., 2002) which used the chlorophyll absorption wavelength at 685 nm and two wavelengths in the NIR range to separate defective areas in four cultivars of apples, with high spatial resolution between 0.5 mm and 1 mm. X-ray imaging was also tested for early apple bruise detection (Schatzki et al., 1997). However, the line-scan X-ray imaging experiment revealed inadequate separation of one day bruises in 'Golden Delicious' and 'Red Delicious' fruit (Shahin et al., 2002).

Baranowski et al. (2009) applied active thermal imaging for detection of early bruises in apples. The research was based on an hypothesis that internal defects and physiological disorders of fruit lead to changes inf tissue thermal properties. A comparison of pulsed-phase thermography (PPT) and visual inspection of bruising was performed, indicating high possibilities of the active thermography method for detecting defects up to several millimetres.

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There is an increasing number of studies examining fruit quality, including bruises, using hyperspectral imaging (Lu et al., 1999; Kim et al., 2001; Lu, 2003; Mehl et al., 2004; ElMasry et al., 2009; Huang and Lu, 2010). The potential of a hyperspectral imaging system working in the spectral region from 400 nm to 1000 nm was studied for early detection (<12 h) of bruises in 'McIntosh' apples (ElMasry et al., 2008; Sun, 2010). This system allowed detection of apple bruises on different background colours (green, red, and green-reddish). High separation ability was reached for apples presenting recent (1 h) and old (more than 3 days) bruises. Hyperspectral imaging was useful for detecting bruising by applying the principal component (PC) transform and minimum noise fraction transform (MNF) methods (Lu, 2007). The multiplication of the first and third PC images, which were acquired by applying the PC transform to all pixels of the hyperspectral images along the spectral axis, gave images in which the bruised areas were repeatedly darker than normal tissue. The author noticed that the bruised regions were visible in the third MNF images and that the difference in reflectance between normal and bruised apples was greatest between 900 nm and 1400 nm.

The application of supervised classification methods becomes effective in distinguishing early and old damage of apple tissues. The backpropagation neural networks (BPNN), the decision tree, the *K*-nearest neighbour and a Bayesian classifier were used by Kavdir and Guyer (2004) to distinguish surface quality conditions of 'Empire' and 'Golden Delicious' apples. The classification accuracy using textural features ranged between 72.2% and 100% for 'Empire' apples and between 76.5% and 100% for 'Golden Delicious' apples. A systematic approach was developed using hyperspectral imaging in conjunction with partial least squares regression (PLS) as well as stepwise discrimination analysis to define several optimal wavelengths in hyperspectral analysis of apples (ElMasry et al., 2009). The artificial neural networks were also used by ElMasry et al. (2008) to select the optimal wavelengths, to classify the apples, and to detect firmness changes due to chilling injury. Baranowski et al. (2012) created a system that included hyperspectral cameras equipped with sensors working in the visible and near-infrared (400–1000 nm), short wavelength infrared (1000–2500 nm) and thermal imaging camera in mid-wavelength infrared (3500–5000 nm) ranges. The comparison of the results obtained using the supervised classification methods, including Soft Independent Modelling of Class Analogy (SIMCA), Linear Discriminant Analysis (LDA), and Support Vector Machines (SVM), confirmed that the broad spectrum range (400–5000 nm) of fruit surface imaging can improve the detection of early bruises with varying depths. From a practical point of view, a potential possibility to evaluate how long the bruise defect maintains would give a chance to sort and grade the apples more effectively. This information would enable better prediction of susceptibility of affected apples to infections. Therefore, the aim of this study was to examine the applicability of hyperspectral imaging in VNIR and SWIR wavelength ranges for classification of apple bruising with respect to the time after damage of five selected cultivars.

2. Materials and methods

2.1. Material and its preparation for measurements

Apples were collected from an orchard of the 'STRYJNO-SAD' Fruit Producers Association (15 km from Lublin, Poland), directly after hand harvesting in autumn 2011 and 2012. Five apple (*Malus domestica* Borkh) cultivars, 'Champion', 'Gloster', 'Golden Delicious', 'Idared' and 'Topaz', were selected for the study to create diverse material according to colour and physico-chemical properties. During hyperspectral measurements, which lasted for two weeks, the apples were stored in a climate chamber at 3 °C and 80% RH, and removed to the laboratory conditions (21 °C) only for measurements. Apples with a diameter of 7–8 cm of each cultivar were selected for analytical analysis and hyperspectral measurements.

Bruised and unbruised regions were studied with an hyperspectral system using a total of 580 apples (480 of which were used as a training set for supervised classification and 100 as a testing set). Each apple was bruised along the equatorial line of its surface. A plastic cylinder with a diameter of 10 mm and a thickness of 1 mm was used for bruising. It was applied vertically on the apple surface (the apple was lying with its equatorial area touching the table surface) and a cylindrical weight of 0.2 kg was dropped (the contact surface was the base of the cylinder) from a height of 400 mm (Baranowski et al., 2012).

2.2. Analytical measurements

At the beginning and end of the experiment, measurements of basic physical properties of the apples were done. Fruit firmness was measured using a Lloyd LRX Universal Testing Machine, produced by Lloyd Instruments Ltd., Hampshire, UK, equipped with a cylindrical tip of 11.3 mm in diameter made of steel. A tip was moving at a constant speed of 8 mm/s towards the fruit with skin slice removed. The firmness was taken as the maximum force needed for the tip to penetrate the fruit to a depth of 8 mm. Three measurements of firmness were made on each fruit, in the pedicle area, the middle part of the apple, and in the calyx area. The means of these three firmness readings were expressed in *N*.

Soluble solids contents (SSC) were determined using an Atago pocket refractometer produced by Atago Co., Ltd., Tokyo, Japan, at ambient temperature of 20 °C. For each apple, two measurements of SSC were made at the opposite sides of the fruit, with three replications for each side. The averaged values of these measurements were analyzed. The values obtained were expressed in %.

Apparent densities of apples of all studied cultivars were determined. Each apple was weighed with an electronic digital Mettler XS1003S balance, Mettler Inc., Switzerland (operating capacity of up to 1000 g with a readability of 0.001 g), and apple volumes were determined through the measurement of the water volume displaced by the fruit.

2.3. Hyperspectral imaging system

Hyperspectral imaging systems enable complex information on the studied objects to be obtained. A hyperspectral image consists of spatial (2-dimensional) and spectral (1-dimensional) data. They create a 3-dimensional spectral cube in which the spectral characteristics of selected pixels can be studied, while images obtained for various wavelengths can be analyzed with the use of available image processing methods.

In this study, two linear hyperspectral scanners were used as the hyperspectral system: a visible and near infrared (VNIR) camera with an ImSpector V10E imaging spectrograph (400–1000 nm) and a short wavelength infrared (SWIR) camera with a N25E 2/3″ imaging spectrometer (1000–2500 nm) manufactured by SPECIM, Finland. The set up of this system is presented in Fig. 1. The cameras were mounted 40 cm above a belt conveyor which had the speed regulated for each camera (to perform line scanning of the fruit). The illumination source in the system consisted of 12 halogen lamps of 20 W each placed in the inside bottom part of a hemispherical diffuser. The lamps were placed along the perimeter at the angular distance of 30°. The lamps illuminated the diffuser inner surface made of aluminium. The diameter of the diffuser's dome was 50 cm. The diffuser allowed homogeneous illumination of the scanned surface of the apple to be obtained. The lamps were powered by three 12 V DC power supplies. The measurements were