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Optical analysis using monochromatic imaging-based spatially-resolved technique capable of detecting mealiness in apple fruit

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ABSTRACT

Mealy apples are often rejected by consumers due to their soft and dry tissue. As mealiness is an internal disorder without any noticeable external symptoms, it is necessary to use methods capable of non-destructive description of the tissue. This study is intended to investigate the possibility of non-destructive apple mealiness classification using spatially-resolved light scattering imaging technique. To this aim, scattering images of 'Fuji' apples were acquired at 650 and 980 nm. The scattering profiles were analyzed by Farrell, modified Lorentzian, modified Gompertz, and Gaussian–Lorentzian models. Statistical results showed significant changes in most of the parameters of the models while apples became mealy. Poor apple mealiness classification accuracies were achieved for PCR, PLSR, and ANN classifiers of three outputs assigned to fresh, semi-mealy, and mealy apples. The results improved when the number of classifier outputs was reduced to two classes. In that case, the best results were obtained for ANN models developed based on a combination of all effective optical parameters acquired at both wavelengths. In that case, classification accuracy of 76% and 82% was resulted in for non-mealy and mealy apples, respectively. Afterwards, classification of the non-mealy apples into fresh and semi-mealy was carried out, which resulted in 88% of fresh and 59% of semi-mealy apples to be correctly classified. Results of this study showed the possibility of application of monochromatic imaging-based spatially-resolved technique for apple mealiness classification, however, better performances would be expected in the case of increasing the number of wavelengths.

1. Introduction

Mealiness is an internal disorder occurring in apple and some other fruits/vegetables due to pectin degradation in the middle lamellae. It brings about a soft and dry tissue unpleasant to consumers, which negatively affects on apple commercial value (Arefi et al., 2015). As an inevitable phenomenon, mealiness is influenced by different factors such as variety, date of harvest, fruit size, growth condition, storage condition, etc. The bigger fruit, the more susceptible to mealiness. Increasing room temperature can heavily accelerate mealiness intensity while the early harvest postpones its development (Barreiro et al., 2000; Barreiro et al., 1998; Harker and Hallett, 1992). The most traditional way of detection of mealiness in apple is based on sensory panels in which some expert people are asked to score mealiness according to different sensorial descriptors. Hardness and juiciness have already been reported as the best sensorial descriptors for mealiness detection (Barreiro et al., 1998). The sensory test is affected by some drawbacks, such as need of expert people, being destructive, time-consuming, and subjective, which limit its application to small number of samples and laboratory scales. To overcome these disadvantages, it has been tried to replace the sensory method by instrumental tests. Different instrumental tests such as compression, puncture, tensile, twist, and Kramer shear tests have been used to predict sensory attributes, especially hardness and juiciness (Harker et al., 2002; Mehinagic et al., 2004). According to the literature, compression test was more suitable for describing hardness and juiciness by which measurement of both hardness and juiciness was possible with high accuracy (Barreiro et al., 1998). Except for being objective, instrumental tests still suffer from destructive and time-consuming disadvantages, and therefore, they are more suitable for standard tests and not for online applications. During the past years, different non-destructive testes, such as ultrasonic (Bechar et al., 2005; Mizrach et al., 2003), nuclear magnetic resonance spectroscopy/imaging (Barreiro et al., 2002; Barreiro et al., 2000), florescence spectroscopy (Moshou et al., 2003), near-infrared spectroscopy (Mehinagic et al., 2003), time-resolved spectroscopy (Valero et al., 2005), hyperspectral imaging (Huang and Lu, 2010; Huang et al., 2012), and biospeckle imaging (Arefi et al., 2016), have been investigated with the aim of mealiness detection in apple. Despite

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of some good results achieved by the previous studies, there is still need of investigating less expensive, rapid, and reliable techniques for detection of mealiness.

As a low cost and easy to implement technique, laser light backscattering imaging (LLBI) is an imaging-based spatially-resolved technique that measures the spatial distribution of light intensity scattered from a sample. Lasers, as monochromatic illumination sources, provide possibility of deeper penetration of light into the biological tissue, and therefore, delivering more information of internal characteristics of sample. LLBI technique enables measuring both absorption and scattering properties, and therefore, it provides a direct link to chemical (related to absorption coefficient) and textural (related to scattering coefficient) attributes of the biological tissue. LLBI has been studied for quality evaluation of apple that resulted in correlation coefficient (r) range of 0.87-0.90 and 0.89 for the prediction of firmness and soluble solid content, respectively (Qing et al., 2007; Sun et al., 2016). Previous studies showed the potential use of LLBI technique for detection of chilling injury in banana (Hashim et al., 2014), and its capability of banana classification into 2–7 ripening groups with the highest classification accuracy of 97.53% (Adebayo et al., 2016). The backscattering images processed by texture-based analysis brought about correlation coefficients of 0.919 and 0.896 in the prediction of elastic module of tomato and mushroom, respectively (Mollazade et al., 2013). Application of LLBI technique in classification of sound and decaying citrus showed an overall classification accuracy up to of 96.1% (Lorente et al., 2015; Lorente et al., 2013). There are also reports in regards to the application of LLBI technique in quality evaluation of kiwifruit (Baranyai and Zude, 2009), pear (Adebayo et al., 2017), etc. To our knowledge, there is no report regarding detection of mealiness in fruits/vegetables, especially apple fruit, using monochromatic imaging-based spatially-resolved technique. Hence, the primary aim of this study is to investigate the feasibility of LLBI technique in apple mealiness classification for the first time. Accordingly the following sub-objectives are intended in this study:

- Analyzing the scattering profiles by Farrell, modified Lorentzian (ML), modified Gompertz (MG), and Gaussian–Lorentzian (GL) models.
- Development PCR, PLSR, and ANN classification models to separate apples into fresh, semi-mealy, and mealy groups.

2. Material and methods

2.1. Sample preparation

Approximately 496 ‘Foji’ apples were harvested in October 2016 from an orchard located in Sanandaj, Kurdistan province, Iran. The apples were selected in a wide range of size and without any external defects. They were immediately transferred to the laboratory and stored under FAIR standard (FAIR, 1998). According to this standard, apples were divided into three groups and stored under specific storage conditions as follows:

- Group I: 134 out of 496 apples were stored under temperature of 3 ± 1 °C and relative humidity (R.H.) of 95 ± 2% for 26 days.
- Group II: the number of 165 apples were first stored under storage condition of 3 ± 1 °C and 95 ± 2% R.H. for 16 days, and then, they were transferred to an incubator providing temperature of 20 ± 1 °C and R.H. of 95 ± 2% for 10 more days.
- Group III: the rest of apples (197 apples) were kept under storage condition of 20 ± 1 °C and 95 ± 2% R.H. for 26 days.

2.2. LLBI system and image acquisition

The system consisted of laser didoes, camera, imaging box, and a high performance computer (Fig. 1). Two laser diodes at wavelengths of 650 and 980 nm were used in this study. Selection of the wavelengths were based on the literature in which ranges of 650–680 nm and 960–980 nm were introduced as effective wavelengths in description of textural attributes such as crispness, juiciness, and mealiness (Huang and Lu, 2010; Mehinagic et al., 2003; Valero et al., 2005; Watada et al., 1985). A high-performance CCD camera (N.B-CCTV, IR Digital Camera, China) equipped with a 18–120 cm zoom lens (Avenir CCTV lens-Japan), which provided suitable zoom of scattering area, was used to acquire scattering images. Optical components were all placed in imaging box in order to avoid the ambient light. A high performance computer (CPU 2.53 GHz Core 2 Duo, RAM 4 GB, 32-bit Windows 7 Operating System) was also used to run the camera and also to save the acquired images.

Samples were illuminated by lasers located at the angle of ca. 20° with respective to the vertical line, and at vertical distance of 30 cm from the sample. Scattering photons from the sample were registered by camera located at the top, 35 cm away from the sample and perpendicular to it. At first, samples were placed in the imaging box in a successive way to acquire their images at 650 nm, and then, image acquisition process was followed by 980 nm laser. It is worth noticing that image acquisition was carried out using *imaq* toolbox of Matlab software.

2.3. Physical and chemical measurements

2.3.1. Mass, size, and color

Samples were weighed using a digital scale with resolution of 0.01 g. In addition, three main diameters of apples were measured using a digital caliper in order to compute their arithmetic mean diameter (Eq. (1)). Furthermore, L^*, a^*, and b^* parameters in three replications were measured for skin and flesh of apples using a color meter device (TEA, 135A, Taiwan). L^* stands for the intensity, which varies from zero (black) to 100 (white), a^* represents redness varying from mines (green color) to positive values (red color), and b^* indicates yellowness ranging from minus (blue color) to positive values (yellow color).

$$AMD = \frac{D_1 + D_2 + D_3}{3} \tag{1}$$

where, *AMD* represents arithmetic mean diameter, and D_1, D_2, and D_3 represent major, medium, and minor diameters, respectively.

2.3.2. Stiffness and juiciness

A cylindrical sample with 17 mm in diameter and height was extracted from each apple on its equatorial line using a cork borer. The cylindrical sample was confined into a steeliness disk with a hole of the same diameter in. The confined sample was exposed to a texture analyzer (Santam, STM1, Iran) equipped with a 50 kg load cell and a 15.3 mm in diameter cylindrical probe (Fig. 2-a). The sample was compressed at the speed of 20 mm/min for the max displacement of 2.5 mm. Finally, stiffness was computed as the slope of force-displacement curve between one-third and two-thirds of the maximum force and it was expressed in N/mm. A filter paper (Whatman Grade No.5) was used beneath the disk to collect the juice released during the compression test for each sample. The border of soaked area was highlighted by a pen and then it was scanned and saved in the computer (Fig. 2-b). Afterwards, the soaked area was extracted by a simple image processing algorithm coded in Matlab and it was considered as juiciness expressed in cm^2 (Fig. 2-c). After measuring the stiffness and juiciness, apples were classified into fresh, semi-mealy, and mealy groups as follows:

- Apples with firm and juicy tissues (stiffness ≥ S and juiciness ≥ J) were labeled as fresh group.
- The soft and juicy (stiffness < S and juiciness > J) or firm and dry (stiffness > S and juiciness < J) apples were assigned to semi-mealy

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