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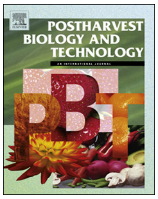

Determining the resistance to mechanical damage of apples under impact loads

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ABSTRACT

The most destructive impacts on biological materials are impact loads, which cause tissue damage under surface peel. For apples, tissue damage increases due to the contact stresses resulting from the round shape of the fruit. Measurements of surface and volume of bruised apples expressed as a function of drop height have been measured, and a method has been developed to determine the resistance and the threshold to bruising for 'Idared', 'Golden Delicious' and 'Jonagold' apples. This method determines the resistance to bruises based on average surface pressures used as a load parameter in relation to the volume of damaged tissue. The relationship between the bruise surface and the volume was determined and confirmed as a power curve with a R^2 determination factor of 0.97. A Bruise Resistance Index (*BRI*), defined as ratio of the average pressures to the bruised surface, was calculated as the ratio of surface pressure to measured bruise volume depending on the drop height. Comparison of both indicators showed that proposed BRI_b power models precisely represent real *BRI* power curves. The bruise threshold as well as the bruise resistance for apples is an effective and rapid tool for assessment of damage degree.

1. Introduction

Apples are often exposed to mechanical damage after harvest as a result of transport, reloading or storage, being subjected to various quasi-static, dynamic, or impact loads. Previous studies indicated that these processes generate 50% all damages of the apples, especially among delicatessen cultivars (Li et al., 2017; Sablani et al., 2006; Opara, 2007; Hussein et al., 2018). Commonly, bruises form when a fruit impacts a rigid surface or another fruit. These include dynamic collisions between fruit and the packaging or container during transport. Additional source of damage are vibrations such as in during transport in vehicles and containers, and conveyor belts (Li and Colin, 2014). The damage is mainly influenced by the type of surface onto which the fruit drops and drop height, as well as the velocity at the moment of collision. Another type of damage is compression bruising, which results from the pressure of fruit layers stored in a large container. To limit compression bruising, a vibration damping system can be applied to absorb some of the crash energy (Jarimopas et al., 2007). The crash force is distributed on the higher surface of the fruit. Hence, there is a lower pressure on the tissues (force per surface unit) as well as lower probability of bruise occurrence. Consequence redemption reduces damage caused by collision in two ways: by absorbing energy and distributing the load (Li et al., 2016). Currently, there are different methods used to protect biological material during transport, including the use of a special vehicle equipped with a vibration damping system or containers that include special soft material that contacts the biological material (Sadrnia et al., 2008; Fadiji et al., 2016a, 2016b; Pathare et al., 2012).

Bruising of fruit is described as a browning tissue under the fruit peel that results from excessive variable impact loads (Ahmadi et al., 2016, 2012; Blahovec and Paprštein, 2005; Fu et al., 2016). Due to excessive surface pressure, the cell walls of the parenchymal tissue are broken, so oxidation reactions occur when fluid escapes. The size of generated force at the moment of impact influences the colour and place of bruise.

In recent years, studies have focused on bruise assessment using thermographic methods (Baranowski et al., 2009; Kheiralipour et al., 2013). Doosti-Irani et al. (2016) suggested that thermal imaging allows the relationship between the temperature at a certain depth and that at the external surface of the bruised tissue to be evaluated. Zhang et al. (2017) confirmed that a small bruise area on an apple could be detected on the basis of a non-destructive optical technique. To evaluate

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mechanical damage on the surface of the apple, x-ray image magnetic resonance or infrared radiation methods were used (Clark and Macfall, 2003; Qin and Lu, 2009).

Bruises are variable due to the different shapes and sizes of fruit. Mature apples may be round, conical, flattened, oblique, and longitudinal, as well as oval. Hence, the significant impact on the type and size of damage generates a contact load that is characterized by the force that occurs on a small contact zone (Shirvani et al., 2014; Van Zeebroeck et al., 2004). Contact stress is one of the most complicated elastic theories when applied to biological material, issues including the impact of the contact zone shape, friction force in the contact zone, irregular shape of contacting objects, or adhesive force on the surface pressure distribution (Stopa et al., 2014, 2017). A small force was shown in these studies to cause a local excessive surface pressure, which resulted in the destruction of the internal structure of the fruit (Komarnicki et al., 2016). The most effective method for assessing the susceptibility of a fruit to bruising uses the stress properties; common parameters include the maximum surface pressure transferred by the tissue of the fruit that does not influence subsequent damage, bruise threshold and bruise resistance. The bruise threshold as well as the bruise resistance is related to the energy in the moment of rebound and the bruise volume (Opara et al., 2007; Opara and Pathare, 2014). Evaluation of the bruise volume is difficult (Bollen et al., 1999). The bruise threshold is defined as the height at which a bruise is characterized by a specific shape, mass and impact surface. The bruise threshold and bruise resistance under similar natural load conditions have been determined, especially in relation to the velocity and energy at the moment of collision. Hence, many studies have been conducted based on the impact load (Celik et al., 2011; Shafie et al., 2015; Studman et al., 1997; Van Zeebroeck et al., 2003). Pang et al. (1996) showed that the bruise surface was a better parameter for assessing damage than the bruise volume. They suggested that bruises should be evaluated according to the initial moment of a visible bruise, and that from a practical point of view better indicators for bruise measurement were based on a smaller bruise area such as commercial thresholds of approximately 1 cm^2. Komarnicki et al. (2017b) compared changes in the contact surface values that occurred at the moment of rebound with the surface of fruit for four tested surfaces and confirmed the usefulness of this information for determination of the bruise threshold. The literature describes a technique of performing energy evaluation by dropping fruit from a specified height and recording the energy values absorbed during subsequent rebounds (Barikloo and Ahmadi, 2013; Gołacki et al., 2009; Stropek and Gołacki, 2010).

The objective of this study was to determine the bruise resistance and the bruise threshold for different surfaces using apple cultivars subjected to impact loads during free drop. A relationship between the bruise surface and the bruise volume as well as comparison of two bruise resistance indicators was identified. The first one was calculated on basis of the surface pressures and measured bruise volume, while the second was obtained using pressure and volume expressed as function of the bruise surface.

2. Materials and methods

2.1. Research material

'Idared', 'Golden Delicious' and 'Jonagold' apples from a Polish orchard were purchased directly from a producer in October 2017. Fruit were stored for one month in 2% O_2 and 0.7% CO_2 at 2 °C 95%, relative humidity (RH). The characteristics of the cultivars are presented in Table 1.

Tested material were selected based on geometry and weight. Flesh firmness of twenty apples were conducted by means of the hand-held penetrometer fitted with an 11.1 mm probe (Facchini FT 327, Alfonsine, Italy). The measurement of firmness was made for apple flesh after earlier skin removal by means of special knife, generally two measurements for each fruit were carried out. A uniaxial compression test was then performed using an Instron 5566 (Norwood, Massachusetts, USA) for 50 samples of flesh cut radially from 10 fruit for each cultivar. After cutting each sample, the juice was drained using paper towels. The last phase this experiment was application of contrast markers, which was the basis for measuring deformations in two different ways. Synchronically, with a sampling accuracy of 0.1 ms, the non-contact deformation by means of fully image camera with a matrix CCD (charge-coupled device) (Videoekstensometr ME–46, Messphysik, Fürstenfeld, Austria) was measured. Cuboidal samples with a base area of $10 \times 10\ mm^2$ and a height of 15 mm were tested. The measurements were carried out to total sample destruction while the velocity of working head, $3 \times 10^{-5}\ ms^{-1}$. Findings of the loads as well as deformations allowed determination of the longitudinal E modulus of elasticity and Poisson's ratio v. The soluble solids concentration (SSC) was measured using a refractometer (model RMR 200, Hanna Instruments, Woonsocket, Rhode Island, USA) on juice squeezed from the apples used in firmness measurement by means of manual fruit press.

2.2. Impact-tests

The tests were conducted at 25 °C 50% RH. Fruits were dropped a specified height against four surfaces: concrete, 5 mm in thickness; spruce; five-layer corrugated cardboard, 5 mm in thickness; and polyethylene foam, 3 mm in thickness. The total number of tested apples was 900. The studies included three cultivars, four different substrates, fifteen heights and five repetitions. More information on the these tests are described in Komarnicki et al. (2017a). The instrument was connected to a Tekscan® (South Boston, MA 02127, USA) which calculated the average values of the surface pressure on the basis of the force that affected the whole contact surface A_c between the fruit and pressure sensor. The phase of maximum surface pressure values was analysed. Hence, the force as well as contact surface values depended on the maximum surface pressure at the moment of contact. Surface pressure was determined by a distribution in relation to the different drop heights. Measurement errors mainly resulted from the apple geometry, pressure force and apple contact surface (the contact surface variation of the curvature radius did not exceed 4%). Due to the precisely conducted selection of tested samples, general differentiations were omitted. Measurements at specified drop height were conducted with five replicates. The results were assessed using Statistica 13.2. and Excel.

2.3. Computer analysis of bruised images

After the impact-tests, fruit were marked and stored at 25 °C for 4 d until the full colour of the bruised area developed. The method for recording the bruise area described in Komarnicki et al. (2017a) was used. Computer analysis of the bruise surface divided into phases was performed (Fig. 1):

The procedure for image analysis by means of the ImageJ program was as follows:

1) import of non-processed images and calibrate them to real dimensions;
2) transformation of colour RGB images to the 8 bit grey scale;
3) adjustment of brightness and contrast;
4) threshold segmentation using several methods that depend on the contrast and brightness of the image types. In many cases, automatic thresholding methods (Shanbhag, Otsu, Mean) are used, which differ in regard to the brightness thresholds or are manually corrected to obtain the expected results;
5) edge segmentation (detection of indicated area) is used to determine the bruised area;
6) dimensioning in AutoCAD 2017.