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Determination of apple bruise resistance based on the surface pressure and contact area measurements under impact loads

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ABSTRACT

The bruises as well as other affects in fruit quality cause lower selling prices and generate loss for fruit growers. For proper identification of damages in biological material, the impact load, contact pressure as well as force affecting on apple skin should be examined. In this paper, the authors present an experimental method in assessing of the bruise resistance as well as the bruise threshold for the 'Gala' apple cultivar consisting a relationship between the impact loads during free drop against four rigid surfaces. The authors measured the contact surface between tested fruit and fixed material to determine the bruise resistance. The Tekscan® measuring system was applied to determine the contact surface and the surface pressures at the moment of collision during impact test. Damaged tissue was photographed and subjected to the computer image analysis in order to determine the bruise volume. In this study, the bruise resistance index (BRI) as relationship between determined bruise volume and surface pressure at varying drop heights was presented. Due to the difficulty and time–consuming process of the bruise volume evaluation, the authors decided to replace commonly used method with functional relation of the contact surface. It allowed for assessing the alternative BRI_c indicator which was based on the relationship between the surface pressure and the contact surface. Both the indicators as well as verifying linear regression analysis showed, that proposed BRI_c power model with high precision describes power curves of the *BRI* indicator. From conducted analysis results that the BRI_c indicator allows for the determination of the bruise resistance for the 'Gala' apple cultivar and precisely describes the *BRI* indicator. Based on the BRI_c curves and changes in the bruise area–drop height relationship, a graphical method in assessment of the bruise resistance and the bruise threshold was proposed. The presented method can be used as effective tool in mechanical damage assessing.

1. Introduction

1.1. The importance of scientific problem

Currently, consumers prefer highly qualitative fruits, assessing mainly their appearance and taste. Hence, the fruit supplied to stores should meet the following international quality standards of fresh, firmness and certain quality parameters (Lubes and Goodarzi, 2017; Commission Implementing Regulation (EU) No 543/2011; Bollen et al., 2001). Usually, apples are characterized by high water content, soft flesh, unstable as well as complex internal structure. During postharvest processes, apples are exposed to mechanical damage caused by various quasi–static, dynamic or impact type loads. Other reasons of loss in the postharvest process are inappropriate conditions during transport, reloading and storage (Mohsenin, 1986; Opara, 2007).

Mechanical damages, such as bruises or collapses are difficult to limit. However, proper understanding the mechanism of bruises occurrence allows to reduce this undesirable phenomenon. For instance, to minimize these negative consequences during transport, a special vehicle equipped with vibration damping system can be applied. Moreover, larger containers with soft materials (foil, foam) in internal side can be used (Fadiji et al., 2016a, 2016b; Pathare et al., 2012; Qin and Lu, 2009). Commonly known bruises are characterized by browning tissue area under the fruit skin caused by variable and excessive impact loads (Ahmadi et al., 2010, 2012; Blahovec and Paprštein, 2005).

1.2. Research state

Depending on the impact force, bruised place receives different colour. In recent years, experiments focused on practical studies,

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Nomenclature

BRI	bruise resistance index, MPa m^{-3}	*x*	depth of the bruised apple above of contact plane, m
BRI_c	optional bruise resistance indicator, MPa m^{-3}	*y*	depth of the bruised apple below of contact plane, m
h	drop height, mm	SD	standard deviation
V	bruise volume, mm^3	R^2	coefficient of determination
p	surface pressure, MPa	R	correlation coefficient
A_c	contact area, mm^2	P	statistical significance
A_b	bruise area, mm^2	*v*	Poisson's ratio
w_1, w_2	larger and smaller axis of the ellipse, m	*E*	conventional elastic modulus, MPa

concerning the bruise assessment by means of i.a. the thermography method performed in order to determine the quality of harvested fruits. Another technique was an analysis of destructed fruits in the non–destructive way on the basis of thermographic device (Kheiralipour et al., 2013; Baranowski et al., 2009). Doosti-Irani et al. (2016) applied the thermal imaging system to evaluate a relationship between the temperature in depth of tested fruit in comparison with temperature on external surface where bruised place appeared. To assess a mechanical damage during apples harvest (Clark and Macfall, 2003; Cubeddu et al., 2001; Keresztes et al., 2017; López-Maestresalas et al., 2016) the x–ray image magnetic resonance as well as the near–infrared radiation method used. By contrast, Zhang et al. (2017), López-García et al. (2010), Li et al. (2011) undertook research toward the bruise estimation using the non–destructive optical technique. Commonly used methods allow to determine the bruise area but they were not useful in contact surface and bruise volume assessment. In order to improve bruise assessment quality, Zapp et al. (1989) and Sober et al. (1990) used electronic fruit model which during tests dropped onto different surfaces from some specified heights.

Due to the round shape of agricultural products, a significant impact on bruise's size and type affecting force influenced (Van Zeebroeck et al., 2004; Komarnicki et al., 2016; Li and Thomas, 2014; Li et al., 2017). Stopa et al. (2012, 2014) in his study confirmed that occasionally lower force value caused a local exceeds in the surface pressure which resulted in destruction of the fruit's internal structure. The most common technique applied during surface pressure determining the Hertz formulas were, although they were formulated on the basis of assumption that should not be applied to biological materials because of its significant deformation, friction in the contact zone and irregular shape (Shirvani et al., 2014). Rabelo et al. (2001) for instance, studied the Hertz method in analysis of the contact area among oranges, but obtained results clearly indicated limitations of applying this method to such complex fruit flesh. Fu et al. (2016) conducted a study consisting of fruit behavior analysis under impacting force. In most cases, experimental studies included a measurement of changes in the contact surface area between tested apple and fixed flat surface by means of the strength machine (Herold et al., 2001). Lewis et al. (2008) applied the ultrasonic technique to determine contact areas as well as stress values under loads that may occur in containers especially during harvest. These results were used in determining the allowable limit load and based on this the bruise threshold was determined.

The literature reports and previous studies found that the best technique in assessing of the susceptibility to bruising of apple, the strength properties of tested fruit provide. This approach ensures accurate and real results. The most common parameters used in this analysis were: bruise threshold, bruise resistance, and the maximal surface pressure values transferred by apple's tissue which does not cause damages. The bruise threshold can be assessed consisting the maximal drop height at which bruise on apple's peel occurs. Additionally, it should be taken into account object mass as well as its shape and contact area. Resistance as well as threshold to bruise were determined in terms of quasi–natural loads, particularly with respect to impact velocity and impact energy. Therefore, many conducted studies included impact load (Studman et al., 1997; Celik et al., 2011; Van Zeebroeck et al., 2003; Shafie et al., 2015). Pang et al. (1996) indicated bruise area analysis as better parameter than the bruise volume in fruit quality assessment. They also suggest, that basis for evaluation of bruised surface should be the moment when first bruised place appears.

From a practical point of view, they confirmed that accurate indicator in bruising measurement is based on smaller bruise area observation – up to 1 cm^2 similar to commercial standards required in bruise threshold determination. Frequently, the susceptibility to bruise or resistance to bruise were expressed as the bruise energy or the bruise volume (Opara et al., 2007; Opara and Pathare, 2014; Holt and Schoorl, 1977; Blahovec, 1999). Hence, the bruise volume should be determined precisely Bollen et al. (1999). Another method in assessing the bruise area consists in repeated dropping of tested apple from different heights and recording of absorbed energy during the subsequent rebound (Bajema and Hyde, 1998; Barikloo and Ahmadi, 2013; Gołacki et al., 2009).

1.3. Scientific purpose

Currently, there is a lack of satisfying theory describing behavior of the plant tissue exposed to impact loads. Literature reports presents a small number of studies in which universal method or technique describing the bruise resistance to impact loads applied. From the view point of reduce the loss in biological material, it's essential to determine the stress course line, impact load, and consequences of contact stress expressed as influence of force focused on small contact area (fruit–rigid plate, fruit–fruit). Evaluation of the mechanisms and conditions in which damages appear, can improve product quality and, moreover reduce production costs resulted finally in fruits price.

Proposed technique allows for analysis of surface pressure distribution at the moment of rebound. According to the authors, a given method for rapid and accurate determination of the fruit resistance to mechanical damage can be used because provides useful information such as bruise surface, and comparison of the surface pressure distributions at the moment of impact with images showing a deformed tissue. Important aspect of this work is also an approach for determining of the fruit bruised volume on the basis of measured contact surface. In fact, a measurement of the bruise volume is difficult and time-consuming whereas obtained results depend mainly on following factors i. a. temperature of the fruit in storeroom, a technique of apple peel removal as well as radius of curvature. During these studies, authors observed close relationship between bruise volume and contact surface area.