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Studies concerning the response of potatoes to impact

Zbigniew Stropek and Krzysztof Gołacki*

Department of Mechanical Engineering and Automation, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland

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A b s t r a c t. The paper presents the research results of the response of "Ramos" potatoes under impact loading conditions. The parameters characterizing the impact such as: maximum stress, maximum force, impact time, maximum deformation, permanent deformation and restitution coefficient were determined. The extent of the damage was also assessed on the basis of the parameters describing the particular bruise such as: bruise depth and width. The impact parameters were related to the bruise size in order to determine the damage threshold for the potatoes under impact loading conditions and to show which parameters describe the bruise beginning to manifest itself. For the tested potato cultivar with a weight of 160-190 g the initiation of the bruise was found to occur at an impact velocity of 1 m s^{-1}. This corresponded to a bruise threshold (drop height) of 50 mm. The restitution coefficient changed to an insignificant extent which amounted to 0.44-0.49 in the tested range of the impact velocity which proves that the energy losses during the potato impact are constant and independent of the impact velocity. The maximum stress increased with increasing impact velocity, reaching a constant value of 0.9 MPa for the highest impact velocities. The stabilization of the maximum stress indicates that the damage to the potato tissue was determined by exceeding the specified stress value.

K e y w o r d s: potato, impact, maximum stress, restitution coefficient, bruise threshold

INTRODUCTION

Damage to potato tubers resulting from external forces is one of the most common reasons for quantitative losses and a reduction in their quality and market value. The causes of this damage are mainly bruises, which most frequently occur during harvest and grading. Based on American research results, Peters (1996) reported that 42% of the potatoes considered were damaged after harvesting. This share increased to 54% after grading. In addition, transport caused a further increase in damage by a margin of 10%. In Switzerland, 15 to 24% of total fresh potato production is lost in agricultural production and a further 14 to 15% in processing (Willersinn *et al*., 2015). Brook (1996) estimated that a 1% reduction in potato impact damage is worth approximately 7.5 million dollars a year in the US. Two potato growers in Washington State, whose production accounted for 20% of the entire potato output in the US, estimated their losses from bruising at 20-60 million dollars in 1993 (Mathew and Hyde, 1997). Studies concerning quantitative food losses in Austria and Germany have shown that 1-9% of field losses can occur during potato harvesting (Schneider *et al*., 2019). Due to potato bruising, the economic losses in Germany are estimated to amount to over 40 million euros (Geyer *et al.*, 2009). The average harvesting and transport losses of potatoes were estimated at 12.5 and 11.7% for the two regions in southwest Ethiopia, respectively (Kuyu *et al*., 2019).

Within this context, attempts have been made to determine the type of damage, the place of occurrence and the way of minimizing it. The first classification system of potato bruising was presented by Hughes (1980). He divided the damage to potato tubers into those with skin

*Corresponding author e-mail: zbigniew.stropek@up.lublin.pl

damage and without skin damage. Skin damage in potato tubers was caused by splitting, cracking and scuffing and in those without skin damage by internal fissures, crushing and blackspot. Noble (1985) improved the Hughes classification by introducing two additional types of damage (star shatter and ring shatter). He found that the type of internal damage depends on the impact conditions. Long impact times and low load speeds usually cause blackspot and internal crushing. On the other hand, short impact times and high load speeds mainly cause internal shattering. Baritelle *et al*. (2000) proposed a new classification of the damage recording system to assess the impact related to potato tubers. They found that tuber damage is generally divided into two categories: internal and external. They also distinguished new types of damage such as white knot, white spot and external cracking.

Potatoes damage may result from the characteristics of the machines used for harvesting, transport and handling and also from the physical, mechanical and biological properties of the tubers (Gancarz, 2016). Both of these factors influence the mechanical response of the potatoes to impacts. An impact is defined as a collision between bodies, as a result of which the released forces arise and disappear in a very short time and the stress occurring in the bodies propagates from the contact area in the form of a wave (Bajema *et al*., 1998; Stropek and Gołacki, 2016a). There are many measurement methods that test the effects of impacts on agricultural products. The most common are drop tests (Gancarz, 2018; Hussein *et al*., 2020; Pathare and Al-Dairi, 2021) and pendulum methods (Fu *et al*., 2017; Kołodziej *et al*., 2019; Stropek and Gołacki, 2018, 2019b; Xie *et al*., 2020). Another way to record load is to analyse impacts with an instrumented sphere (Desmet *et al*., 2004; Bentini *et al*., 2006) or with a potato-shaped instrumented device (Van Canneyt *et al*., 2003, 2004). A different research area is the simulation of impacts using the finite element method or the discrete element method (Gao *et al*., 2018; Zulkifli *et al*., 2020; El-Emam *et al*., 2021).

A significant field of research is the use of different testing methods to reduce losses in potatoes or to analyse changes in their properties. It may include studies which involve the use of ultraviolet radiation (Jakubowski, 2018) or acoustic emissions (Zdunek *et al*., 2008). The damage observed at the macro scale is the result of failure at the micro scale. Therefore, studies related to the cellular structure of fruit and vegetables which determine such parameters as: cell wall thickness, shape and size of cells and cell arrangement are very important for understanding the damage mechanism and response of agricultural products to loads (Liu *et al*., 2020).

The aim of the research was to record force-time and displacement-time courses during potato tubers impact. This allowed for the determination of parameters which characterize impacts such as: maximum stress, maximum force, impact time, maximum deformation, permanent deformation and restitution coefficient. Then the extent of the damage was assessed based on the parameters describing the bruise such as: bruise depth and width. In the next stage the impact parameters were related to the bruise size in order to determine the damage threshold for the potatoes under impact loading conditions and to show which parameters best describe the initiation of the bruising process.

MATERIALS AND METHODS

The research was carried using potatoes of the “Ramos” cultivar. In order to minimize the effect of weight, the 160-190 g potatoes were used for testing. Tubers were impacted at velocities of 0.5, 0.75, 1, 1.25, 1.5, 1.75 m s^{-1} which corresponded to drop heights of 1.3, 2.9, 5, 8, 11.5, 15.6 cm. At each drop height 10 repetitions were made. The moisture content was determined by drying in a KBC-65W oven (Wamed, Warsaw, Poland) for 18 h at a temperature of 80°C of 10 mm thick slices to a constant weight. Thirty potatoes were used for the measurements. The sample weight was measured before and after drying within an accuracy of 0.1 g. The mean value and standard deviation of the moisture content of the potato flesh was 80.5 ± 1.6%.

A pendulum measuring stand was used in the impact tests, in this case a potato was the impacting element. The pendulum was composed of a pair of 1 m long fishing lines and a fastening element in the form of a plastic plate and two tangs, which were stuck into the vegetable. The potato impacted into a flat plate screwed into a force sensor. In turn, the force sensor was attached to a sliding case which could be moved using a clamp. The clamp was welded to a steel plate fixed to a concrete wall. The sliding sleeve with the sensor could move in a horizontal plane, which allowed the potato to be positioned in such a way that at the time of impact the pendulum was vertical. Thus, the impact direction was perpendicular to the vertical surface of the plate. The measuring stand was equipped with adjusting screws, which made it possible to set the pendulum in such a way that the direction of impact would pass through the centre of the vegetable mass and the centre of the sensor simultaneously. This ensured that the conditions for a central collision were met. The drop height was determined using a scale placed on a board. The force during the impact was measured using a piezoelectric force sensor, (model 2311-10, Endevco, USA) with a sensitivity of 2.29 mV N^{-1} and a measuring range of ± 2200 N.

The force response course over time was determined using an LMS SCADAS recorder (Siemens, Munich, Germany) which was operated using LMS Test.Xpress software. The force response was measured at 10.24 kHz and the measurement was triggered when 0.5 N was exceeded. A digital high-speed camera Phanton Miro M320S (Vision Research, Wayne, USA) and a lens with a fixed focal length of 50 mm were used to record the impact course.

The impact course was analysed by means of Phantom Camera Control software (PCC-2) at 1024x768 pixel resolution and 3413 frames per second. The choice of such an image recording speed resulted from the applied force response registration frequency and was aimed at obtaining the total multiplication. In these tests, the frequency of the force response recording was 3 times higher than that of the displacement recording. Then the Tema Motion Version 3.8 software (Image Systems, Linköping, Sweden) was used to process the data, which facilitated the analysis of the potato movement in the recorded image. As a result, the displacement and velocity courses over time were determined.

The use of a camera for impact tests is associated with measurement errors. They result from the inaccuracy of the camera positioning with respect to the impact plane. The optical axis of the camera should be perpendicular to the plane in which the impact is recorded. Another cause of errors is the inadequate focus of the object image. The outline of the object should contrast well with the surrounding background. Errors can also arise as a result of the erroneous calculation of the object image dimensions and its deflection from pixels to millimetres. For the potato impact tests, the scale factor was 0.152 mm per pixel. The errors were minimized by placing the camera on a special mounting head equipped with three levels. This made it possible to position the camera in three mutually perpendicular planes with an accuracy of 1°. The large contrast of the image with the background was ensured by means of LED lighting.

Before each drop, the weight was measured with an accuracy of 0.2 g and the length, width and thickness of the potato tuber was measured with an accuracy of 0.1 mm. The mean values of length, width and thickness were 87.6, 64.5, and 52 mm, respectively. Then the potato was attached to a pendulum in the horizontal position so that it impacted the curve with the smallest radius. This position produced the smallest bruise area. Therefore, these were the most unfavourable impact conditions due to the strength of the potato tissue. Using adjustment screws, the potato was placed in a position where the sensor axis coincided with the impact direction passing through the potato mass centre. Thus, the conditions for a central collision were met (Fig. 1). Then a powder mixed with oil was applied to the potato surface in the position of the expected impact in order to determine the contact surface.

After the potato was dropped and the impact was recorded, it was left for 48 h at room temperature to discolour the bruised tissue. After that time the bruise depth d and width w were determined by cutting the potato tuber in a vertical plane passing through the impact centre. The bruise width and depth were measured by means of calliper. The impact tests allowed for the determination of the courses of force response, displacement and velocity over time (Fig. 2).

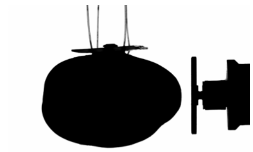

Fig. 1. Impact of potato onto a rigid, flat plate. On the right a plate, a force sensor and a sliding cave may be observed.

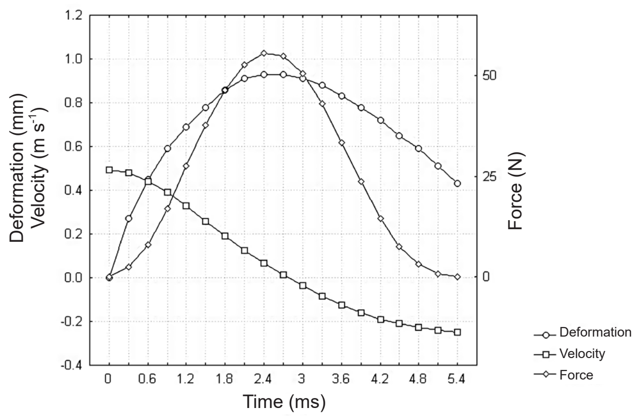

Fig. 2. Typical force response-time, velocity-time and deformation-time curves at the impact velocity of 0.5 m s^{-1}.

The parameters characterising the impact have been calculated using the following formulae:

The restitution coefficient e is a measure of energy dissipation during impact and is defined as the quotient of rebound velocity v_{reb} and impact velocity v_{imp}:

$$e = \frac{v_{reb}}{v_{imp}} . \qquad (1)$$

The maximum stress was determined from the formula:

$$\sigma_{\max} = \frac{F_{\max}}{A}, \qquad (2)$$

where: $F_{\max}$ – the maximum force (N), A – the contact area of potato with a flat plate during impact (mm^2).

For all impacts, the contact area of the potato with the flat plate was found to be elliptical. Therefore, the contact area was determined from the formula:

$$A = \pi\, ab, \qquad (3)$$

where: a, b – are the radii of the large and small axes of the ellipse.

The results were statistically analysed using Statistica 13 software. The statistical significance of the differences between the mean values of the studied quantities was determined on the basis of a one-way analysis (ANOVA) using the NIR test at a significance level of 0.05.

RESULTS

The restitution coefficient was close to the constant (p-value = 0.86) and amounted to 0.44-0.49 within the tested range of the impact velocity (Fig. 3a). This means that the energy losses during the impact of the potato are constant and independent of the impact velocity. The constant value of the restitution coefficient may be the result of the large water content in the potato tissue.

The maximum stress value increased with the increase in the impact velocity, reaching a constant value of 0.9 MPa for the highest impact velocities (p-value = 0.83) (Fig. 3b). Statistically significant differences were found between the mean maximum stress values for the four highest impact velocities and the mean maximum stress values corresponding to the two lowest impact velocities (p-value = 0.0001). This is important because at a velocity of 1 m s^{-1} the occurrence of bruising was observed. It follows that stress is an appropriate parameter with which to determine the initiation of the bruising process.

The maximum force response increased with increasing impact velocity (p-value = 0.00001) (Fig. 3c). The impact time decreased asymptotically to a value of 4.7-4.8 ms with increasing impact velocity (Fig. 3d). A statistically significant difference was only found between the mean value of the impact time for the lowest impact velocity of 0.5 m s^{-1} and the mean values of the impact time corresponding to the other impact velocities (p-value = 0.0002). Within the range of the impact velocity 0.75-1.75 m s^{-1} the mean values of the impact time did not differ significantly (p-value = 0.78).

The parameters characterizing the bruise size were: bruise width w and bruise depth d. Both values were measured by cutting the potato flesh in a vertical plane and passing it through the impact centre. Figure 3e and 3f show that from the value of 1 m s^{-1} the bruise width and depth increased with increasing impact velocity (p-value = 0.00001). Zero values for both parameters mean that no tuber damage occurs at the two lowest impact velocities. At an impact velocity of 1 m s^{-1} the initiation of the bruising process of the potatoes was observed. This corresponds to a drop height of 50 mm. At this velocity, some of the potatoes were bruised and some remained undamaged. This resulted in large values of the standard deviation of the bruise width and depth at an impact velocity of 1 m s^{-1}. It follows that for 160-190 g potatoes, the impact velocity of 1 m s^{-1} is a critical velocity and the corresponding drop height of 50 mm may be treated as a damage threshold.

Maximum and permanent deformation increased with increasing impact velocity (Fig. 3g and 3h) (p-value = 0.00001, p-value = 0.0005). For the velocity of 1 m s^{-1}, at which the initiation of the bruising process was found, the maximum and permanent deformation values were 1.5 and 0.7 mm, respectively. Therefore, it may be concluded that maximum deformation which occurs below 1.5 mm and permanent deformation which occurs below 0.7 mm do not cause potatoes to bruise. Both for the maximum and permanent deformation there is a sudden increase in these values between the impact velocities of 1 and 1.25 m s^{-1}. This shows that the values above can be used to properly describe the initiation of the bruising process in potatoes.

DISCUSSION

In this study, a measuring stand using the pendulum principle is employed. Apart from the choice of the load application method, it is important to obtain reliable results with the smallest possible measurement errors. In the proposed measurement system, a high-speed camera was used which had a separate fixture from the impact stand. Hence, the vibrations coming from the stand did not disrupt the recording of the movement of the potato by the camera. In previous measuring stands, where the angular sensor was permanently fixed in the rotation axis of the pendulum, the vibrations were reduced by increasing the rigidity of the stand which resulted in a larger moment of inertia of the pendulum. In the measuring circuit, Tema Motion software was used, this allowed for the direct determination of displacement-time courses based on image analysis, which is a novelty in this type of solution. Until the present time, obtaining the deformation-time course required either the double integration of the acceleration-time course or an FEM simulation based on the characteristics of the plant material under quasi-static loading conditions (there is no testing machine that can perform compression tests at velocities with the order of 1 m s^{-1}). An additional advantage of the presented stand is that the potato is suspended on inextensible, weightless lines. In previous measuring stands the fruit or vegetable was attached to a rigid pendulum, which meant that the shape and weight of the pendulum affected the dynamics of the impact process. It is commonly known that the moment of inertia of the stand should be as low as possible, compared to the moment of inertia of the potato attached to it. While discussing the dependence of individual parameters on impact velocity, it should be noted that the cellular structure of the potato tissue influences the constant course of the restitution coefficient in relation to the impact velocity. In the case of a potato, the air intercellular spaces in the total tissue volume account for nearly 0% (Pitt, 1992). In fruits with a lot of air spaces, especially in apples, where this share is estimated to be up to 20-28% (Roudot *et al*., 1991), a decreasing restitution coefficient was obtained with the increasing impact velocity (Pang *et al*., 1992; Dintwa *et al*., 2008; Stropek and Gołacki, 2016b). A similar result was observed in the case of pears (Stropek and Gołacki, 2019a) where the air spaces in the cellular structure take up 12% of the total volume (Baritelle and Hyde, 2001). Decreases in the restitution coefficient with increases in the impact velocity were also recorded for peas, soybeans and rapeseed (Horabik *et al*., 2017).

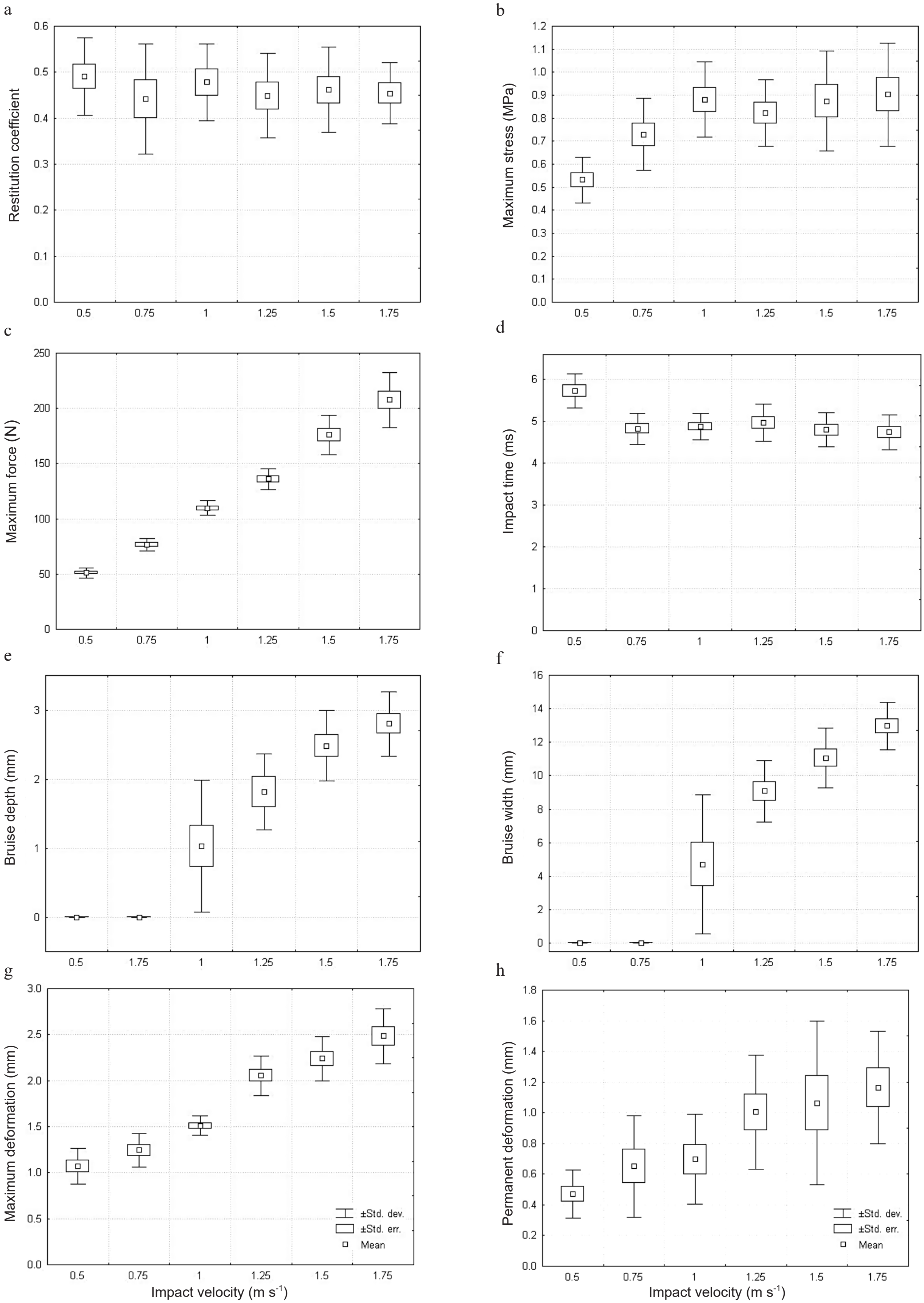

Fig. 3. Relationship between: a – restitution coefficient, b – maximum stress, c – maximum force, d – impact time, e – bruise depth, f – bruise width, g – maximum deformation, h – permanent deformation; and the impact velocity.

The constant value of the maximum stress σ_{max} for impact velocities larger than 1 m s^{-1} shows that the potato tissue damage was caused by exceeding the specified stress value. This confirms that stress is the critical parameter causing damage, as a result of stress concentration at the point of potato tissue damage. Therefore, the resulting mean stress value may be treated as the limiting value that the potato tissue is able to sustain.

Similar stress values for the potato tissue were obtained in other studies. Bajema *et al*. (1998) hit the cylindrical potato samples obtaining a failure stress of 1.1-1.15 MPa for the "Russet Burbank" and 0.75-0.8 MPa for the "Atlantic" cultivar, respectively. Celik *et al*. (2019) simulated the mechanical impact of two potatoes. The maximum stress on the impacting and impacted tuber was 1.4 and 3.13 MPa, respectively. In the other simulations, the "Sante" potatoes were tested (Nikara *et al*., 2020). The results showed that the maximum stresses for the two impact levels were 1.111 and 1.452 MPa respectively, these results being higher than the biological yield stress of potato tissue determined in the quasi-static compression test (0.978 MPa).

The increase in the maximum impact force or maximum acceleration with increasing impact velocity or drop height is widely known and was observed in many other impact tests. This is a natural phenomenon which assumes that the contact area increases with the increases in the impact force. The increase in maximum force with increasing impact velocity supports the hypothesis that the maximum force and the internal stress resulting from it, are critical elements in the occurrence of impact failure (Fluck and Ahmed, 1973).

There are two methods of determining the initiation of the damage. The first one is more common, it involves dropping the product from specified heights. Then the product is left at room temperature for 2-72 h in order to discolour the tissue at the impact point. After this period, the extent of the damage is examined (Opara and Pathare, 2014). The second method is IHMI (Increasing Height Multiple Impact) described by Bajema and Hyde (1998). This method is independent of the physiological response of the tissue to the damage inflicted on it and consists of dropping the product twice from an increased height. The occurrence of differences in the force curves at the same drop height means that the damage has been initiated and is defined as the bruise threshold.

Extensive literature exists concerning the determination of bruise sizes and the resulting bruise threshold. Mathew and Hyde (1997) obtained very similar results while investigating the initiation of damage to the potato. For the 250 g "Russet Burbank" potato tubers, which were dropped onto a steel plate at 21°C, the drop height without damage was 50 mm. Studman *et al.* (1997) investigated the changes in damage to the "McIntosh" apples between the green and red sides of the fruit during apple-to-apple impact. The results showed that the bruise threshold was 11 mm for the apples without removing the skin and 7 mm with the skin removed. By using the IHMI method, Bajma and Hyde (1998) determined the bruising threshold for apples and noted that below the drop height (16 mm), the force courses were identical for two consecutive impacts from the same height. However, the deviations from this trend were above this threshold. The impact tests of the three apple cultivars showed that the impact velocity at which the initiation of the damage occurred was 0.5 m s^{-1}, which corresponded to a drop height of 13 mm (Stropek and Gołacki, 2015). On the basis of images and photographic analysis Stopa *et al.* (2018) showed that bruising in apples occurred after they had been dropped from a height of 10 mm on the concrete and wooden substrates. In other studies using the same method of image analysis, the drop height at which apple bruising occurred was 20 mm for collision with the concrete and wooden surfaces (Komarnicki *et al.*, 2017). In research concerning pears, the initiation of bruising was found to occur at velocities of 0.5 and 0.75 m s^{-1} depending on the cultivar firmness. This corresponded to a bruise threshold of 13 and 29 mm, respectively (Stropek and Gołacki, 2020). According to Komarnicki *et al.* (2016) a drop height for the tested pears in the range of 30-46 mm is an acceptable drop value as it does not cause inelastic deformations.

CONCLUSIONS

1. In contrast to the standard solutions used for measuring displacement under impact loading conditions, the high-speed camera was not permanently attached to the measuring stand. Thus, it did not record vibrations during the impact. The elimination of mechanical vibrations from the stand contributed to a more accurate recording of the impact parameters over time. Additionally, the Tema Motion software allowed for the determination of the displacement-time courses directly without the need to integrate the acceleration-time courses twice. In this way, large calculation errors were avoided.

2. The research showed that for "Ramos" variety potatoes which had a weight of 160-190 g, the impact velocity of 1 m s^{-1} was the critical velocity at which the initiation of the bruising process occurred. This corresponded to a drop height of 50 mm.

3. The restitution coefficient obtained values close to the constant in the range of 0.44-0.49 within the tested range of impact velocity. This means that the energy losses during the impact of the potato were constant and independent of the impact velocity.

4. The maximum stress value increased with the increasing impact velocity, reaching a constant value of 0.9 MPa for the highest impact velocities. The fixed value of the maximum stress for the impact velocity larger than 1 m s^{-1} shows that the damage to the potato tissue occurred when

the specified stress value was exceeded. This confirms the validity of the critical stress criterion for the whole potatoes under the impact loading conditions.

5. The parameters that properly described the damage initiated under the impact loading conditions were: maximum deformation, permanent deformation and maximum stress. For the impact velocity of 1 m s^{-1} at which the initiation of bruising was found, the maximum and permanent deformations were 1.5 and 0.7 mm, respectively.

6. Despite the initial potato selection by weight testing, potatoes pose a great difficulty due to the large values of geometric parameter distribution which were determined during the tests. Potatoes are characterized by great differences in shape, or more precisely the different radii of curvature in tubers of similar weight. This is the main source of large values of the standard deviations of the determined parameters which can be eliminated by a careful selection of potatoes in terms of both weight and shape. However, in these conditions the impact responses of randomly selected potatoes cannot be fully depicted, because they are related to the specificity and nature of these vegetables.

Conflict of interest: The Authors declare they have no conflict of interest.

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