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Impact velocity and bruising analysis of potato tubers under pendulum impact test[1]

Velocidade de impacto e análise de danos de tubérculos de batata sob teste de impacto pendular

Shengshi Xie[2*], Weigang Deng[2] & Fei Liu[2]

[1] Research developed at College of Mechanical and Electrical Engineering, Inner Mongolia Agricultural University, Hohhot, China
[2] Inner Mongolia Agricultural University, Hohhot, China

HIGHLIGHTS:
Initial height and tuber mass significantly affect bruise volume and velocity characteristics.
Suitable temperature (above 20 °C) and impact material (especially rubber) can reduce bruise of potato.
Maximum and minimum velocities can predict bruise volume of potato.

ABSTRACT: A study was undertaken to investigate the relationship between the factors (initial height, tuber mass, tuber temperature and impact material) and the impact characteristic variables (impact velocity and bruise volume) as determined by pendulum impact test-rig. It was verified that bruise volume and maximum velocity significantly increased with increasing initial height, while its minimum velocity and time of reaching the maximum velocity decreased during the same impact process. With increment of tuber mass, its impact velocities and time of reaching the maximum velocity presented linear change, but the bruise volume nonlinearly changed. The relationships among tuber temperature and impact characteristic parameters were in accordance with linear relationships. The 65 Mn-rubber rod can notably reduce potato impact damage because of its cushioning effect. Potato bruise volume can be predicted based on the maximum and minimum velocity.

Key words: *Solanum tuberosum*, impact experiment, velocity characteristic, bruise volume

RESUMO: Um estudo foi realizado para investigar a relação entre os fatores (altura inicial, massa de tubérculo, temperatura de tubérculo e impacto material) e as variáveis características do impacto (velocidade e volume da lesão), determinado através do equipamento de teste de impacto de pêndulo. Verificou-se que o volume de contusão e a velocidade máxima aumentaram significativamente com o aumento da altura inicial, enquanto a velocidade mínima e o tempo de atingir a velocidade máxima diminuíram durante o mesmo processo de impacto. Com o incremento da massa do tubérculo, suas velocidades de impacto e tempo de atingir a velocidade máxima apresentaram alteração linear, mas o volume de contusão mudou não linearmente. Enquanto isso, as relações entre temperatura do tubérculo e parâmetros característicos de impacto foram de acordo com relações lineares. A haste de borracha de 65 Mn pode reduzir notavelmente os danos causados pelo impacto da batata devido ao seu efeito amortecedor. O volume de contusões de batata pode ser previsto com base na velocidade máxima e mínima.

Palavras-chave: *Solanum tuberosum*, experimento de impacto, característica de velocidade, volume de contusão

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Introduction

Potato (*Solanum tuberosum* L.) as the fourth largest food crop with abundant carbohydrates and minerals has been planted in China for more than 300 years (Wei et al., 2019). However, the emerged impact or compression between the potato tubers and rods greatly aggravated potato mechanical damage (Xie et al., 2019; Xie et al., 2020). Hence, investigations on reducing the impact damage of potato tubers, especially the damage caused by the collision between potatoes and rods, have an important significance for the development of commercial harvesting and post-harvesting equipment and the prolonging shelf life of potato.

Up to now, to investigate the formation of potato bruising, considerable studies on the potato impacted with plates using various software (ANSYS, FEA) and devices have already been widely reported (Celik et al., 2019; Deng et al., 2020; Deng et al., 2022). In terms of experiments, most researchers examined not only the influence of tuber properties and impact condition on the bruise volume, area and depth but also the influence of these factors on energy consumption, impact force and acceleration (Mathew et al., 1997; Baritelle & Hyde, 2003; Xie et al., 2018; Huang et al., 2022). However, the characteristics of potato impact velocity have not yet been reported, especially the relationship between potato impact velocity and bruise volume.

Based on the abovementioned factors, a study was undertaken to investigate the relationship between the factors (initial height, tuber mass, tuber temperature and impact material) and the impact characteristic parameters (impact velocity and bruise volume) as determined by pendulum impact test-rig. Meanwhile, the relationship between bruise volume and impact velocity characteristics was also investigated.

Material and Methods

The experiments were carried out in Inner Mongolia Agricultural University, Hohhot, China, located at 111°62'29.9" E and 40°80'77.2" N, 905m altitude. All the experiments were carried out from October 1 to 7, 2020. The selected potato tubers belonged to the Kexin No. 1 cultivar, which were manually collected from a crop planting base in Hohhot, China. After the harvest, ellipsoidal potatoes without any mechanical damage and diseases were chose and divided into four groups based on the mass according to the grades and specifications of potatoes in China (Ministry of Agriculture of the PRC, 2006), namely, 150 ± 5, 250 ± 5, 350 ± 5 and 450 ± 5 g. Subsequently, the potatoes were stored in three refrigerators at temperatures of 5, 15 and 23 °C (Xie et al., 2018).

The test equipment and data acquisition system were used to perform the experiment. The potato impact test rig mainly included bracket, ruler, light swing rod, clamp and rod. The data acquisition system consisted of data acquisition and analyzer (AVANT-MI7016, Hangzhou Yiheng Technology Co., Hangzhou, China), a 6 g-mass acceleration sensor with dimensions of Φ10×22 mm (1A102E, Jiangsu Donghua Testing Technology Co. Jiangsu, China) and computer (Figure1).

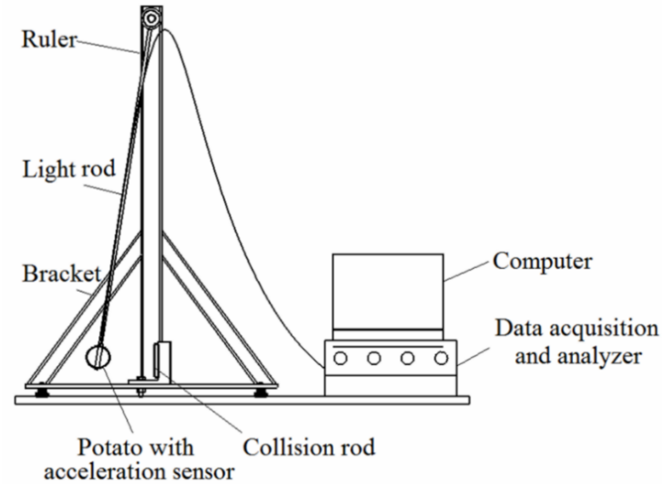


Figure 1. Test equipment and data acquisition system

The impact experiment was conducted on 160 tubers by the test equipment and data acquisition system. Every tuber was marked, holed and fixed in a clamp. Then they were separately lifted to the initial height and released at a zero initial velocity. After finished the impact, experiment was required to prevent the swing rod from exerting another hit to potato via manual intervention. Besides, the change in impact acceleration over time between the rod and potato tuber was measured with the acceleration sensor. This sensor was inserted in the potato along its lateral direction with an accuracy of ±10 mV g^{-1} and operated at a frequency up to 5 kHz (Xie et al., 2018). Acceleration data were then collected and recorded by a data acquisition and analyzer connected to a computer. After potato impact data was collected, the detected acceleration data were integrated once. Meanwhile, the obtained velocity data were calculated and sorted with the aid of a computer.

Overall, this experiment mainly covers four parts. And the designed testing conditions of every part are listed in Table 1 (Xie et al., 2018). For each impact test, the test data of 10 potatoes were carried out.

Potato bruise volume was assessed after storing the bruised potatoes for 48 hours at ambient temperature (20~22 °C). Likewise, the bruises were evaluated by preparing 5 mm-

Table 1. Program of potato impact tests

Test	Initial height (mm)	Tuber mass (g)	Tuber temperature (°C)	Impact material
Initial height	100 200 300 400 500 600	250 ± 5	15	65 Mn
Tuber mass	300	150 ± 5 250 ± 5 350 ± 5 450 ± 5	15	65 Mn
Tuber temperature	300	250 ± 5	05 15 23	65 Mn
Impact material	300	250 ± 5	15	65 Mn 65 Mn - Plastic 65 Mn - Rubber

65 Mn – 65 Mn steel rod with diameter of 10 mm; 65 Mn – Plastic- 10 mm diameter 65 Mn steel rod wrapped with PVC plastic; 65 Mn –Rubber- 10 mm diameter 65 Mn steel rod wrapped with rubber

thick slices parallel to the impact surface of potato. Note that the slices were successively cut through the entire potato bruise (Baritelle et al., 2000). The thickness of each slice was accumulated to regard as the bruise depth of potato. Afterwards, the largest bruise area of the potato slice was selected, and its radiuses along the long axis and the short axis respectively were measured. Finally, the bruise volume of the bruised potato was calculated according to the following equation (Stropek & Gołacki, 2013).

$$V = \frac{\pi abh}{6} \quad (1)$$

where:

V - the bruise volume of the bruised potato, mm^3;
a - the radius along the long axis of the bruise area, mm;
b - the radius along the short axis of the bruise area, mm; and,
h - the damage depth of the bruised potato, mm.

A typical velocity-time curve of potato impact is shown in Figure 2. The corresponding data were measured from a 250 g potato exposed to a temperature of 15 °C under the conditions of a 300 mm initial height and the impact material of 65 Mn during the experiment. Figure 2 reveals that potato impact mainly contained two stages:

(1) Impact stage. The first impact stage started from tuber contacting with the rod, then made potato velocity maximum and finally ended until the velocity of potato reached zero. Both elastic and plastic deformation and gas and liquid flow through the intercellular spaces (viscous deformation) were generated in this stage.

(2) Rebound stage. Since potato rebound energy stemmed from its elastic deformation and flow of gases and liquids through intercellular spaces, the measured potato velocity decreased from zero to the minimum value and then increased to zero again (Stropek & Gołacki, 2020).

The maximum velocity, minimum velocity and time of reaching the maximum velocity were selected as the impact velocity characteristics of potato in this study. Since the potato was released without an initial velocity, the impact velocity corresponding to the different initial heights was calculated based on the following equation, which was denoted as the theoretical value. Correspondingly, the maximum velocity measured by the sensor was recorded as the test value.

$$v = \sqrt{2gh} \quad (2)$$

where:

v - the theoretical value of the maximum velocity, m s^{-1};
h - the initial height, mm; and,
g - the gravitational acceleration, 9.8 m s^{-2}.

The data were submitted to correlation analysis between the impact velocity variables and bruise and regression analysis using SPSS 19.0 software.

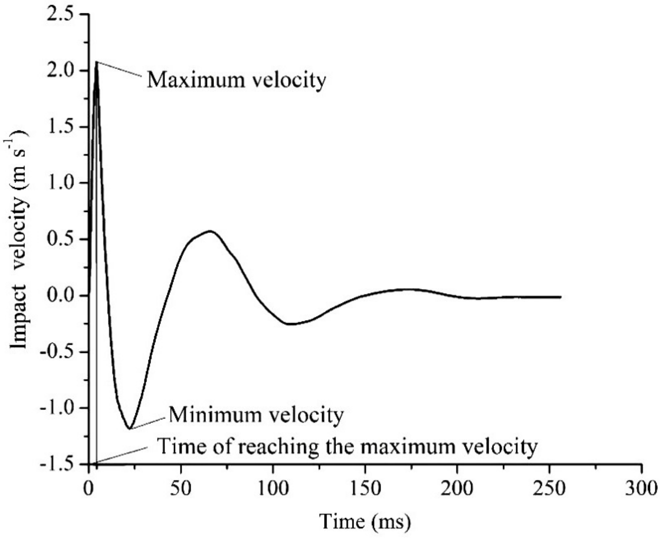
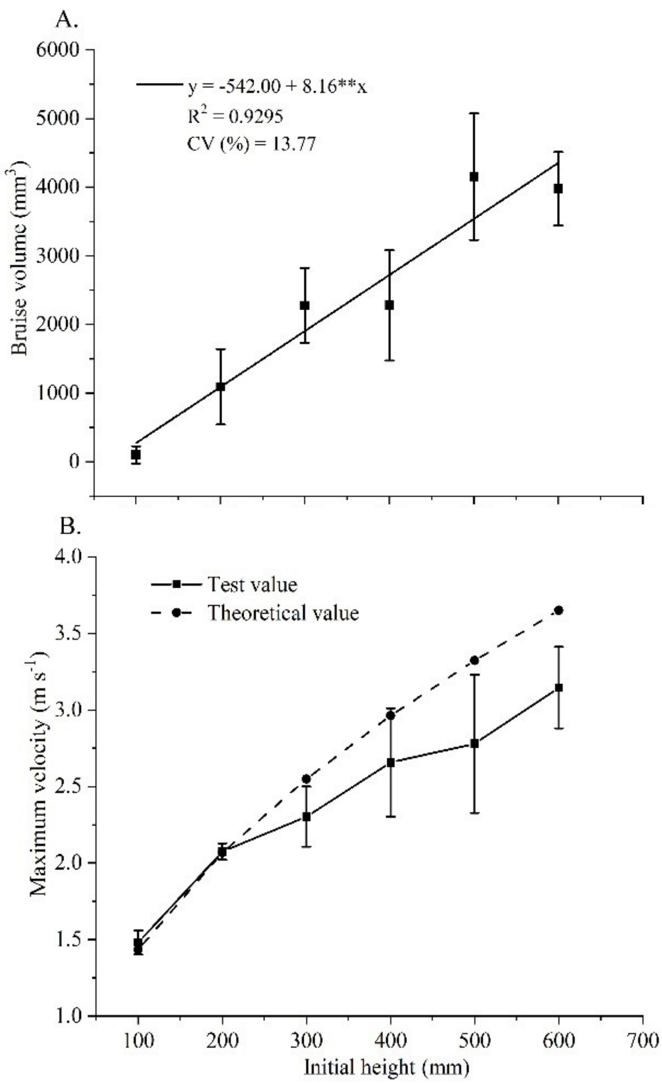


Figure 2. Velocity curve of the potato during impact

Results and Discussion

As depicted in Figure 3A, the bruise volume of potato progressively increased with increasing initial height. When



Vertical bars represent the standard deviation of the mean of the ten values. ** - Significant at p ≤ 0.01 based on the t test; CV - Coefficient of variation

Figure 3. Relationship between the bruise volume (A), maximum velocity (B) and the initial height after potato impacted with rod

an initial height became 100 mm, potato minor bruising occurred. The reason was that bruising threshold was 80 mm (Xie et al., 2020). Conversely, potato large bruise volume corresponding to the initial height ranged from 200 to 600 mm obviously created. Besides, potato maximum bruise volume at the initial height of 500 mm was 3.7 times larger than the minimum value at the initial height of 100 mm. A possible reason could be that the higher initial height imposed a greater impact force and impulse on the potato tuber (Geyer et al., 2009; Xie et al., 2020). Potato bruising increased with increasing drop height, which was also confirmed by other studies. For example, Ito et al. (1994) found that potato damage index increased linearly with increasing initial height (Ito et al., 1994). Xie et al. (2018) proved that the potato damage depth was positively correlated with the initial height (Xie et al., 2018). A similar change tendency was also found in fruits, such as pears (Stropek & Gołacki, 2020), pomegranates (Hussein et al., 2019), kiwifruit (Du et al., 2019) and apples (Stropek & Gołacki, 2013). These findings demonstrate that the initial height is critical for the parameters design of potato harvesting, handling, transportation, and sorting equipment. Therefore, to reduce the extrusion and impact effects of the rod on the potato, the parameters of the harvest and post-harvesting equipment, especially the initial height of the potato tuber, should be mainly considered in the design process.

The relationship between the maximum velocity and the initial height during potato impacted with rod is shown in Figure 3B.

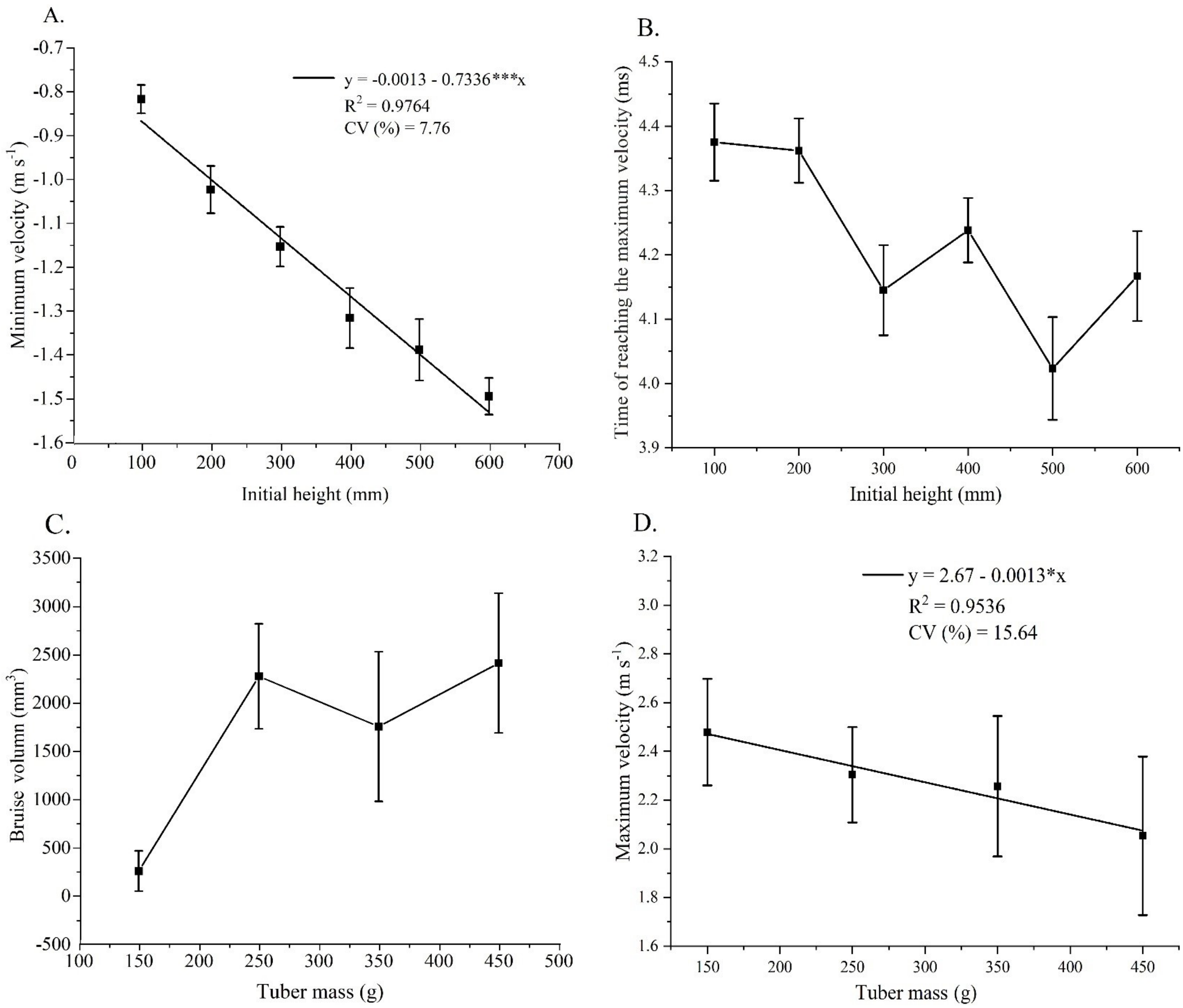
The test value of potato maximum velocity gradually increased with increasing initial height (Figure 3B). It was evident that the average test value of potato maximum velocity increased more than twice at the initial height of 600 mm than that at the initial height of 100 mm. When the initial height of potato was 100 and 200 mm, the obtained average test value of the maximum velocity remained basically consistent with the theoretical value, and its standard deviation was small(±0.11). This may be due to the elastic deformation and viscoelastic flow generated at the moment of impact between potato and rod when the initial height is small. Thus, velocity consumption did not occur at the moment of potato impact. Conversely, when the initial height of potato changed from 300 to 600 mm, the test value of the maximum velocity was relatively discrete, resulting in a large standard deviation (±0.49). In addition, the average test value of the maximum velocity was clearly lower than the corresponding theoretical value. This phenomenon is interesting for the mechanism investigation of potato bruising. Apparently, with increasing initial height, a larger percentage of the velocity was dissipated. This could resulted from the increased plastic deformation, which consumed much of the maximum impact velocity.

On the basis of the velocity curve in Figure 2, it was also possible to determine the minimum velocity (Figure 4A) and time of reaching the maximum velocity (Figure 4B). After potato impact, a very strong relation was fitted between the minimum velocity and the initial height with R^2 of 0.9764. Usually, a high initial height would lead to a more notable a higher flow of gases and liquids occurred in potato at the moment of impact. Note that the increased flow visibly accompanied an enhanced rebound energy (Stropek & Gołacki, 2020). This promoted a decrease in minimum velocity of potato because of increasing initial height.

As shown in Figure 4B, the linear correlation between the time of reaching the maximum velocity and the initial height during potato impacted with rod was poor. And the value of R^2 was merely 0.6409. When the initial height was lower than 400 mm, there was a decrease tendency for the impact time of reaching the maximum velocity with increasing initial height. Beginning at an initial height of 400 mm, this time fluctuated between 3.93 and 4.28 ms. Similar results have not been reported in other potato studies, but analogous conclusions have already been drawn from apples (Stropek & Gołacki, 2013). Based on this, the potato can be considered an elastomer at the stage of impact velocity increases from zero to the maximum value. In terms of the elastic impact process of potato, the time of the deformation phase is inversely proportional to the power of 1/5 of the impact velocity (in accordance with initial height) according to the Hertz theory (Valentin, 2019). A high initial drop height induces a higher impact velocity of potato and thus shortens the corresponding time of reaching the maximum velocity.

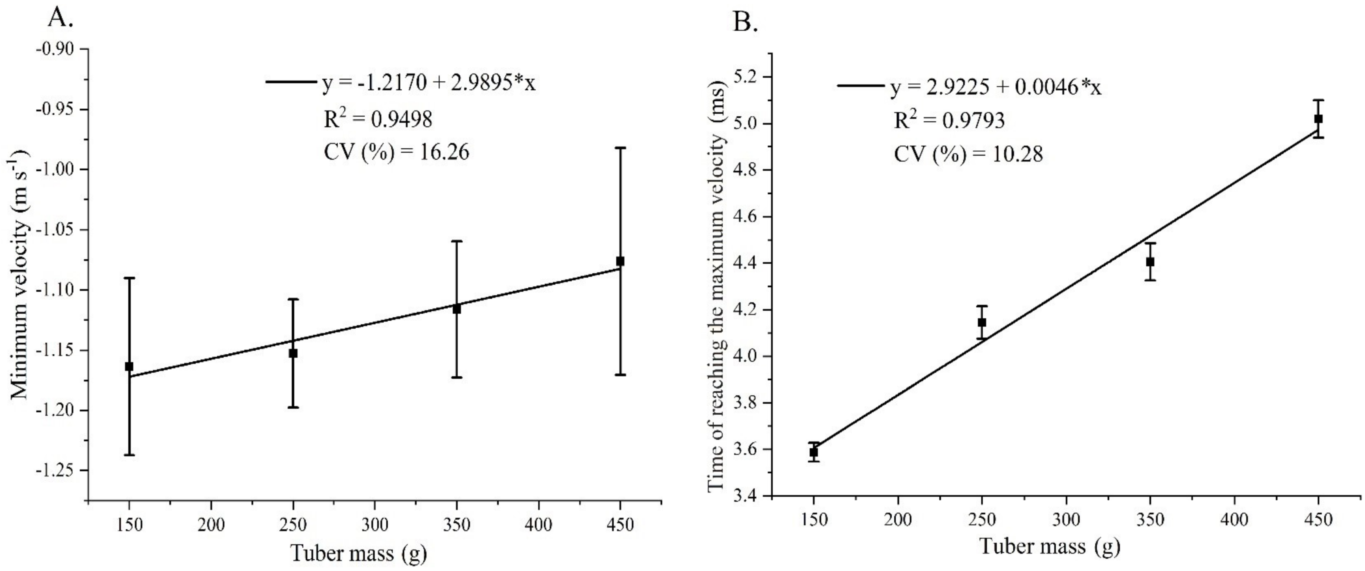
When potato tubers exposed at a temperature of 15 °C were dropped from a height of 300 mm onto a 65 Mn steel rod, their average bruise volume increased from approximately 262.76 to 2416.35 mm^3 with tuber mass varied from 150 to 450 g (Figure 4C). The larger bruise volume caused by the larger potato mass was mainly related to many factors such as a high impact impulse, high impact energy (Mathew & Hyde, 1997) or high impact force (Cerruto et al., 2015), when the potato tuber collided with the rod. This result agrees with those of studies on other potato varieties. Graeme et al. (2018) noted that larger potatoes (262±15 g) were usually more susceptible to bruise than small potatoes (120±5 g) (Graeme & John, 2018). In contrast, the bruise volume of the 350 g potato was smaller than that of the 250 and 450 g potatoes. This information can potentially imply that potato varieties of a moderate tuber size can effectively minimize the tuber damage during harvesting, transportation and packing.

The average maximum velocity of potato decreased from approximately 2.48 to 2.05 m s^{-1} as the tuber mass increased from 150 to 450 g (Figure 4D). In contrast, the average minimum velocity increased from approximately -1.16 to -1.08 m s^{-1} at the same conditions (Figure 5A). The reason for the velocity change could be that the larger potatoes exhibited a larger thickness of the tuber tissue between the acceleration sensor and impact rod, resulting in an increased cushioning effect. A similar change in impact acceleration with the increment of tuber mass was observed by Geyer et al. (2009) and Xie et al. (2020).



Vertical bars represent the standard deviation of the mean of the ten values. * - Significant at p ≤ 0.05; *** - Significant at p ≤ 0.001 based on the t test; CV - Coefficient of variation

Figure 4. Relationship between minimum velocity and potato initial height (A), time of reaching the maximum velocity and potato initial height (B), bruise volume and tuber mass (C), and maximum velocity and tuber mass (D)



Vertical bars represent the standard deviation of the mean of the ten values. * - Significant at p ≤ 0.05 based on the t test; CV - Coefficient of variation

Figure 5. Relationship between the minimum velocity and tuber mass (A), and time of reaching the maximum velocity and the tuber mass (B) after potato impacted with rod

Table 2. Effect of various factors on the impact velocity variables and bruise volume of the potato

Factors and values		Impact velocity variables			V (mm^3)
		v_{max} (m s^{-1})	v_{min} (m s^{-1})	T (ms)	
Tuber temperature (°C)	5	2.03 ± 0.24	-1.05 ± 0.06	4.45 ± 0.06	3652.93 ± 969.55
	15	2.30 ± 0.19	-1.15 ± 0.04	4.15 ± 0.07	2278.11 ± 545.12
	23	2.52 ± 0.16	-1.17 ± 0.07	3.76 ± 0.04	0391.02 ± 047.45
Impact material	65Mn	2.30 ± 0.19	-1.15 ± 0.04	4.15 ± 0.07	2278.11 ± 545.12
	65Mn - Plastic	2.40 ± 0.24	-1.18 ± 0.05	4.12 ± 0.05	1057.31 ± 359.60
	65Mn - Rubber	2.52 ± 0.16	-1.21 ± 0.04	3.71 ± 0.05	0808.67 ± 214.74

Values are mean±standard deviation; v_{max} - Maximum velocity; v_{min} - Minimum velocity; t - Time of reaching the maximum velocity; V - Bruise volume

According to Figure 5B, there existed a strong linear relationship between the average time of reaching the maximum velocity and tuber mass. Simultaneously, the linear correlation coefficient was high, reaching 0.98. The Hertz theory illustrates that the impact time is directly proportional to the power of 2/5 of mass (Valentin, 2019). Based on this theory, it is reasonable that the time of reaching the maximum velocity became prolonged because of increasing tuber mass.

As can be seen in Table 2, the effects of the tuber temperature and impact material on potato impact characteristics are given in detail.

According to Table 2, the mean bruise volume of potato decreased from 3652.93 to 391.02 mm^3 with rising tuber temperature. Mathew & Hyde (1997) also confirmed that potatoes were more susceptible to impact damage at lower temperatures. In addition to this finding, Mathew & Hyde (1997) reported that a 200 mm drop height onto steel caused damage in almost 50% of the potato tubers at 10 °C, whereas this level was reduced to 28% at a tuber temperature of 21 °C (Mathew et al., 1997). With respect to the impact velocity characteristics of potato, the mean maximum and minimum velocities and mean time of reaching the maximum velocity respectively ranged from 2.03 to 2.52 m s^{-1}, -1.05 to -1.17 m s^{-1} and 4.45 to 3.76 ms (Table 2). Van Canneyt et al. (2006) considered that a lower temperature imposed a major effect on the potato cell walls and membranes, making them glassy and vulnerable to impact damage (Van Canneyt et al., 2006). Moreover, flimsy cell walls and membranes lessened the cushioning effect of the tuber tissue between the acceleration sensor and impact rod. Thus, all of these factors resulted in a lower maximum velocity, a higher minimum velocity and a longer time of reaching the maximum velocity in cold environment. Combined the above analysis results with actual conditions, potato harvesting and processing temperatures above 20 °C are more conducive to potato damage reduction.

Cushioning materials are widely used to reduce the susceptibility of easily damaged fruits such as apples, pomegranates, pears and kiwifruit (Stropek & Gołacki, 2013; Du et al., 2019; Hussein et al., 2019; Stropek & Gołacki, 2020). Likewise, they are also available to lighten potato bruise. The experimental data showed that the bruise volume of a potato impacted with a 65 Mn-rubber rod was only one third of that of a potato colliding with the 65 Mn steel rod (Table 2). Additionally, there were apparent differences in the velocity characteristic parameters during potato impact between the different impact materials. It is clear from Table 2 that the highest impact maximum velocity, the lowest minimum velocity and the shortest time of reaching the maximum velocity of potato were determinated during potato collision with the 65 Mn-rubber rod in comparison with other impact materials. This phenomenon may be due to the high natural angular frequency during potato impact the 65Mn-rubber steel rod (Xie et al., 2018). Hence, cushioning materials, especially rubber, could reduce the impact damage occurring to potatoes (Mathew & Hyde, 1997).

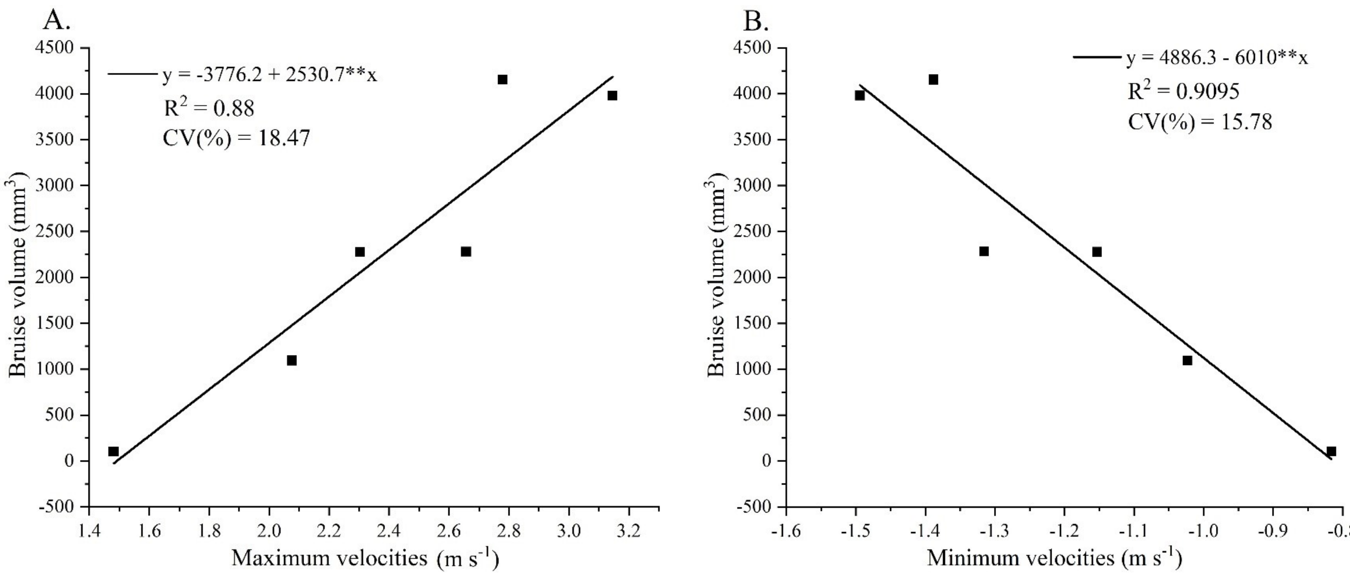
The correlation and significance results of potato maximum velocity, minimum velocity, time of reaching the maximum velocity and bruise volume were obtained as summarized in Table 3. When the test factor is the initial height, both the maximum and minimum velocities of potato are highly correlated with bruise volume, and their correlation coefficients separately reach 0.39 and -0.58. Therefore, to in-depth study the potato mechanical damage, the linear regression model determined among the maximum and minimum velocities and the bruise volume can accurately evaluate and predict the degree of potato impact damage.

It is important to evaluate the relationships between potato bruise volume and the impact velocities. The resulting average velocities and bruise volume of potato are plotted in Figure 6. It is found that the linear regression equations between potato maximum velocity, minimum velocity and bruise volume are as follows (Figure 6A and 6B), respectively.

Table 3. Correlation between the impact velocity variables and bruise

Factors	Indexes	v_{max}	v_{min}	t	V
Initial height (mm)	v_{max}	1			
	v_{min}	-0.89**	1		
	t	-0.31*	0.19	1	
	V	0.39**	-0.58**	0.33*	1
Tuber mass (g)	v_{max}	1			
	v_{min}	-0.76**	1		
	t	-0.42**	0.25	1	
	V	-0.48**	0.33*	0.50**	1
Tuber temperature (°C)	v_{max}	1			
	v_{min}	-0.75**	1		
	t	-0.47*	0.28	1	
	V	-0.69**	0.56**	0.49**	1
Impact material	v_{max}	1			
	v_{min}	-0.58**	1		
	t	-0.34	0.08	1	
	V	-0.45*	0.44*	0.32	1

** - Significant at ($p \leq 0.01$); * - and ($p \leq 0.05$) by t test; v_{max} - Maximum velocity; v_{min} - Minimum velocity; t - Time of reaching the maximum velocity; V - Bruise volume



** - Significant at p ≤ 0.01 based on the t test; CV - Coefficient of variation

Figure 6. Relationship between the maximum velocities and bruise volume (A) and minimum velocities and bruise volume (B) after potato impacted with rod

Conclusions

1. As the initial height increased, bruise volume and maximum velocity increased, while potato minimum velocity and the time of reaching the maximum velocity decreased.

2. In terms of potato tuber mass, it imposed a significant effect on the maximum velocity, minimum velocity and time of reaching the maximum velocity.

3. The relationships between the tuber temperature and impact characteristic variables were linear.

4. The bruise volume increased linearly in function of potato maximum velocity and decreased linearly in function of minimum velocity.

Acknowledgments

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