CONSTRUCTION OF IMPACT MECHANICS MODEL AND EXPERIMENTAL STUDY ON IMPACT DAMAGE OF POTATO TUBER
/
马铃薯块茎碰撞物理模型构建和碰撞损伤试验研究

Tianci HUANG [1)], Bei WU [*1,2)], Lucen LI [1)], Tianlin ZUO [1)], Fangping XIE [1,2)] [1]

[1)] Hunan Agricultural University, College of Mechanical and Electrical Engineering, Changsha/China;
[2)] Hunan Key Laboratory of Intelligent Agricultural Machinery and Equipment, Changsha/China·
Tel: +86 15802521582; E-mail: wubei@hunau.edu.cn
Corresponding author: Bei Wu
DOI: https://doi.org/10.35633/inmateh-66-14

Keywords: *potato tuber, impact mechanics model, impact damage, orthogonal test, comprehensive damage index*

ABSTRACT
Reducing potato tuber injury rate is responsible for the optimal design of potato harvester, one of the most important goals. To assess the influence of various factors on potato tubers' impact damage, the impact mechanics model of potato tuber was constructed in terms of the deformation and deformation energy analysis during the collision. Secondly, the orthogonal test was conducted. The impact material, potato varieties, potential energy, impact angle were selected as factors. The comprehensive damage index (DI) was taken as the evaluation index. The results showed that the damage degree of potato tuber was decreased with the increasing of coefficient of restitution of impact material, potato yield strength and collision angle, but increased with increasing potato potential energy. When the impact material is a plank, the potential energy is 1.2 J, the type of potato is Lishu No.6, and the collision angle is 15°, the comprehensive damage index is the lowest, 0.0055. According to the result of the orthogonal test, the mathematical regression model was obtained. At the same time, the verification tests were performed. The verification tests showed that the average error between the predicted data of the comprehensive damage index calculated by the mathematical regression model and the experimental data was 5.22%.

摘要
降低马铃薯块茎损伤率是马铃薯收获机优化设计过程中的主要目标之一，为了评估各因素对马铃薯块茎碰撞损伤的影响，本文从马铃薯碰撞变形量和变形能两方面进行分析，构建了马铃薯块茎碰撞物理模型，选取碰撞材料、马铃薯品种、马铃薯重力势能和碰撞角度作为试验因素，以马铃薯损伤综合指数（DI）作为评价指标开展了正交试验，结果表明：随着碰撞恢复系数、马铃薯屈服应力和碰撞角度增大，马铃薯损伤减小，而马铃薯势能越大，马铃薯损伤越大。当碰撞材料为木板、马铃薯种类为丽薯6号、马铃薯势能为1.2J、碰撞角度为15°时，马铃薯损伤综合指数最小为0.0055。根据正交试验结果得到了马铃薯损伤综合指数的回归模型并进行了验证试验，试验结果显示：回归模型对马铃薯损伤综合指数的预测值与实际测量值相比平均误差为5.22%。

INTRODUCTION
The potato is the fourth largest food crop globally after rice, wheat, and maize and has been awarded "underground apple" (*Shi et al., 2010*). The survey outcome showed that about 70% of tuber injury is derived from potato harvesting (*Jian, 2008*). The degree of mechanization in China increased year by year. Therefore, it is of great economic significance to reduce potato damage during the harvesting process to improve the internal quality of potatoes.

At present, the research on the mechanical damage of potato tubers mainly starts from the two aspects of agricultural materials science and damage factors based on harvester analysis. One of the effective strategies to study the damage of mechanized potato harvest is to conduct a collision damage experiment of potatoes under laboratory conditions. Part of the experiments method refers to the collision damage experiment of apples (*Li et al., 2005*) and pears (*Shan et al., 2003; Hui, 2014*). Some scholars analyzed the factors influencing the critical damage rate based on the Hertz model (*Han, 2019; Wei et al., 2020*).

---

[1] *Tianci Huang, Ms. Stud.; Bei Wu, Lect. Ph.D.; Lucen Li, Ms. Stud.; Tianlin Zuo, Ms. Stud.; Fangping Xie, Prof. Ph.D.*

There are also some scholars who analyzed dynamical systems theory (*Parks et al., 1990*). To study the damage degree of potato, a device of potato model was designed (*Ito et al., 1994*). Peters has an assessment of the degree of external damage of potato, based on the appearance of the epidermis (*Peters, 1996*). However, mechanized harvesting also damages the inner structure of potatoes; some investigators studied internal damage changes through mathematical models (*Stephen and McRae, 1998*), the MRI (*Thybo et al., 2004*) and computer-assisted analysis（Mayer et al., 2017）.

Researchers, in turn, carry out a comprehensive and systematic classification of the Internal and external forms of damage (*Baritelle et al., 2000；Arfa, 2007; Mayer et al., 2017*). From the previous research，respiration rate, damage area, damage volume, and damage ratio have all been proposed as indicators of injury assessment to analyze the impact of each factor on the damage degree of potato (*Han, 2019; Mathew and Hyde, 1997; Molema et al., 2000*). There is, however, little isolated information regarding the comprehensive damage index. So, the problem of potato collision damage cannot be comprehensively evaluated. Therefore, this paper aimed to build the mechanistic model of the deformation and deformation energy during the collision process to study the factors affecting the damage of the potato. Then we can analyze the relationship between each factor and the comprehensive damage index, and each factor aligned in order of increasing the comprehensive damage index.

MATERIALS AND METHODS

Deformation analysis

The collision of potato tubers involves two phases, elastic compression phase and elastic-plastic compression phase. Tubers damage begins to occur at critical points between two phases. The collision model of potato tuber and impact material was developed based on Herz-Mindlin contact theory, (*Zhi, 2017; Han, 2019*), which discussed the elastic compression phase up to the critical point during the collision. In the discussion of contact problems, it is generally assumed that:

The potato tuber was simplified to a uniform and isotropic ellipsoid.

The material of the contact body is in an elastic state.

The contact point of the potato tuber and impact material gradually becomes elliptical.

The friction of contact surface and potato falling are not considered.

The potato tuber occurs slight strain during collision. That is: the size of the contact surface is much smaller than the radius of curvature of the elastomers (i.e., potato tubers and impact material) surface.

According to Hertz theory, the relationship between the elastic phase loading and the amount of compressive deformation can be obtained as follows:

$$F = \frac{4}{3} E^* \sqrt{R^*} \delta^{\frac{3}{2}} \tag{1}$$

Where:

F denotes the contact loading, [N]; δ represents the amount of compressive deformation, [mm];

R^* expresses equivalent radius of contact between potato tuber and impact material, [mm]; Since the collision between the potato tuber and the impact material could be simplified as a collision between a sphere and a plane, the equivalent radius equals the curvature radius of potato tuber at collision point.

E^* represents the equivalent modulus of elasticity of potato tuber and impact material, [MPa], which can be obtained as follows:

$$\frac{1}{E^*} = \frac{1-\mu_1^{\ 2}}{E_1} + \frac{1-\mu_2^{\ 2}}{E_2} \tag{2}$$

Where:

E_1 denotes the modulus of elasticity of potato tuber, [MPa];

E_2 denotes the modulus of elasticity of impact material, [MPa];

μ_1 represents the Poisson's ratio of potato tuber;

μ_2 represents the Poisson's ratio of impact material.

As the contact loading increases, the stresses within the contact body also increase. These stresses eventually cause the material within the sphere to yield. The deformation at this initial point of yielding is known as the critical deformation. Jackson and Green (*Jackson and Green, 2005*) derive this critical deformation analytically using the von Mises yield criterion.

The relationship between material yield strength and critical deformation can be written as follows:

$$\begin{cases} \delta' = \left(C\sigma'\right)^2 \left(\dfrac{\pi\sqrt{R^*}}{2E^*}\right)^2 \\ C = \min\left(1.295\mathrm{e}^{0.736\mu_1}, 1.295^{0.736\mu_2}\right) \end{cases} \tag{3}$$

Where:

δ' denotes the critical deformation at the initial point of yielding, [mm];

σ' represents the yield strength of contact material, [MPa];

C is the coefficient.

Substituting equation (3) into equation (1), the critical contact loading was calculated. The resulting critical contact loading at initial yielding is:

$$F = \frac{R^{*2}\left(\pi C\sigma'\right)^3}{6E^{*2}} \tag{4}$$

And then, the maximum elastic energy before tubers damaged (i.e., on the verge of yielding, or plastic deformation) can be expressed as (*Green, 2005*):

$$W_1 = \frac{4}{3}E^*\sqrt{R^*}\int_0^{\delta'}(\delta^{3/2})d\delta = \frac{\left(\pi C\sigma'\right)^5 R^{*3}}{60E^{*4}} \tag{5}$$

Deformation energy analysis

During the collision between potato tuber and impact material, according to the kinetic energy theorem, the following relation is satisfied before the collision.

$$T_0 = mgh = \frac{1}{2}mv_0^{\ 2} \tag{6}$$

where:

T_0 is the kinetic energy before the collision, [J];

m denotes the potato tuber mass, [Kg];

g represents the acceleration of gravity, [m/s^2];

h expresses the drop height, [m];

v_0 is the initial impact speed, [m/s].

The velocity satisfies conservation in the tangent and normal direction during the collision, respectively.

$$v_1 \sin\lambda = v_0 \sin\varphi \tag{7}$$

$$v_1 \cos\lambda = e v_0 \cos\varphi \tag{8}$$

where:

v_1 denotes the critical velocity after collision, [m/s];

φ represents the angle between the velocity v_0 and the normal of the contact surface, [degree];

λ expresses the angle between the velocity v_1 and the normal of the contact surface, [degree];

e is the coefficient of restitution between potato and impact material.

Then, the kinetic energy after the collision can be expressed as:

$$T_1 = \frac{1}{2}mv_1^{\ 2} \tag{9}$$

where:

T_1 is the kinetic energy after the collision, [J];

During the actual collision, if heat generation of the friction between potato tuber and collision material was not considered, all the mechanical energy lost is used to cause tubers damage.

Therefore, the amount of loss with the mechanical energy can be expressed as:

$$E \approx T_0 - T_1 \approx mgh\left(1-e^2\right)\cos^2\varphi \tag{10}$$

Potato tuber drop impact test platform

The drop impact test platform is shown in Fig. 1. The testing device consists of a base, inclination-regulated unit, fixation, column, impact material, and height-adjustable stabilizing apparatus. During the experiment, the potato tuber free-drop onto the platform, which was employed to simulate the collision of potato and harvester. Firstly, the drop impact test platform was placed on the ground stably and away from other object to prevent secondary damage to the potato tuber by other factors. Then, the initial height of the potato tuber is controlled by adjusting the height of the height-adjustable stabilizing apparatus, and the angle between the horizontal plane and impact material could be controlled by adjusting the height of the inclination-regulated unit.

The collision angle can be adjusted precisely to 0°, 15° and 30° through the joint action of the fixing device and the tilting device. Finally, the centers of the height-adjustable stabilizing apparatus and potato tuber were guaranteed at the same height, and the vision is aligned such that potato tuber free-drop in the center of the impact material. The impact materials which were selected include steel Q235, aluminum alloy and plank. The thickness of impact material is no less than 10mm (*Jian et al., 2017*).

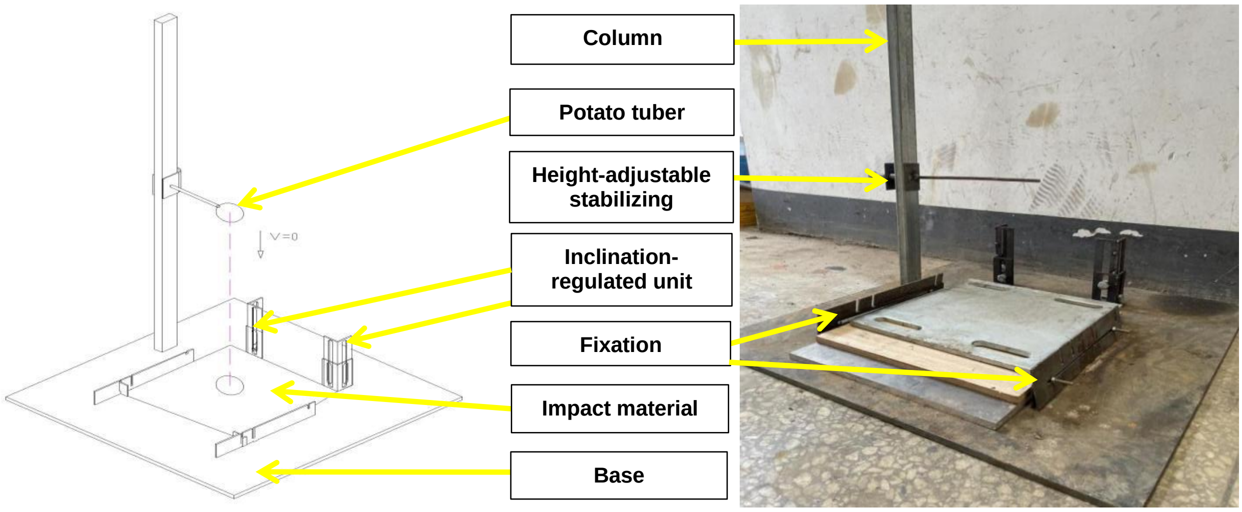


Fig. 1 - Potato tuber drop impact test platform

Orthogonal test scheme

The orthogonal test was conducted to analyze the influence of the various factors on potato tuber damage. According to impact mechanics model in equation (5) and (10): the coefficient of restitution of the impact material (e), the yield stress of the potato (σ'), the modulus of elasticity of potato and impact material (E_1 and E_2), the Poisson's ratio of potato and impact material (μ_1 and μ_2), the curvature radius of potato tuber at collision point (R^*), the potential energy of the potato tuber before collision (mgh) and the collision angle (φ) are all linked to potato damage. In these parameters, e, E_2 and μ_2 cannot be precisely controlled in the experiment, but they all depend on the material type, so the collision material type was selected as one of the test factors. Similarly, potato varieties were selected as another test factor considering the uncontrollable of σ', E_1, μ_1 and R^*. In addition, the potential energy (mgh) and the collision angle (φ) were selected as the third and fourth test factor, which can be precisely controlled during the test.

Steel Q235, aluminum alloy and plank were selected as impact materials. A uniformly steel ball was used to free fall onto the materials at the same height to obtain the coefficients of restitution e between the steel ball and the impact materials, and E_2 and μ_2 were obtain by consulting materials mechanics books. For potato varieties, three varieties (i.e., Atlantic, Longshu NO.7 and Lishu NO.6) commonly grown in China were selected as test material, and their mechanical parameters (i.e., σ', E_1 and μ_1) were measured by a universal testing machine (*Caglayan et al., 2018; Celik et al., 2019*). All of the parameters mentioned above are shown in Table 1 and Table 2.

Table 1

Mechanical parameters of different impact materials

Impact materials	E_2 [MPa]	μ_2	e
Q235 steel	2.14×10^5	0.27	0.55
Aluminum alloy	6.8×10^4	0.321	0.59
Plank	1.35×10^4	0.37	0.72

Table 2

Mechanical parameters of different potato varieties

Potato varieties	E_2 [MPa]	μ_2	σ' [MPa]
Atlantic	1.59	0.265	0.76
Lishu NO.6	1.74	0.19	1.10
Longshu NO.7	1.84	0.189	0.99

During the test, the potato tubers of similar shape and maturity were chosen for each variety. In order to set the potential energy to a certain value before collision, the drop height was calculated according to the tuber mass. In the test, the range of tuber mass was 0.10-0.50 kg and the range of drop height was 0.39-2.81 m. Before the test, the original damaged part was marked to avoid confusion with test damage. The test scheme was designed according to the Box–Behnken design method. The tests were performed with five potato tubers per group, and the results were averaged. The test factors and levels were shown in Table 3.

Table 3

Factors and levels

Level	Impact material A	Potato varieties B	Potential energy C [J]	Impact angle D [°]
-1	Q235 steel	Atlantic	1.2	0
0	Aluminum alloy	Lishu NO.6	2.4	15
1	Plank	Longshu NO.7	3.6	30

Evaluation metric

Potato tuber damage during the mechanical harvest is mainly caused by collision, extrusion and friction. The overall extent of damage to the potato can be determined as undamaged, scuffed, peel damage or severe damage (*Arfa, 2007*). According to different performance situations, the damage type can be divided into epidermal abrasions, tissue damage, and tuber fragmentation (*Jian, 2008*). In this experiment, these three types of potato damage were considered and measured separately, and finally a comprehensive damage index (*DI*) was defined. The measurement methods of the three types of damage were as follows.

(1) The measurement method of epidermal abrasions. The degree of epidermal abrasions was determined by calculating the area of the potato tuber damage part. For assessing the area of potato tuber damage part, the area was approximated with an ellipse. As shown in Fig. 2.

$$S = \pi ab \tag{11}$$

where:

S denotes the max epidermal damage area, [m^2];

a represents the long-axis of the ellipse, [m];

b expresses the short-axis of the ellipse, [m].

(2) The measurement method of tuber fragmentation. The crack length was measured with a vernier caliper (0.02 mm accuracy). When multiple cracks were noted, the longest crack was measured; when the longest crack had multiple small branches on both sides, the middle crack was selected; when the longest crack had multiple small branches at the end, the most obvious crack was measured. As shown in Fig. 3.

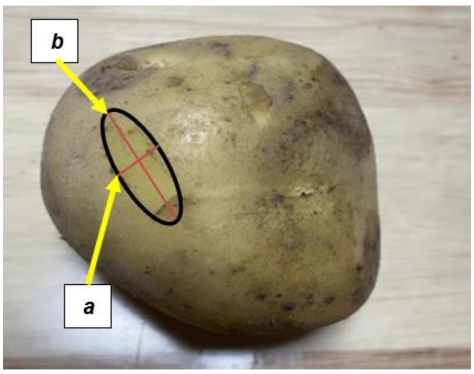


Fig. 2 - Epidermal abrasions

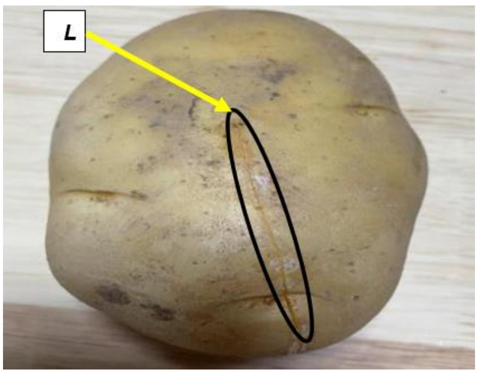


Fig. 3 - Tuber fragmentation

(3) The measurement method of tissue damage. Firstly, potato tubers after the collision were placed on dry ground for five days. Secondly, the potato tubers were cut into slices (1 mm in thickness) (*Jian, 2008*) and then photographed the slices, and the photos were imported to Photoshop software. The original images were converted to gray-scale images by adjusting the RGB mode.

The 3*3 pixels is used as a reference point to check the gray-scale value, and the added value of gray-scale of damaged part can be expressed as:

$$K = K_2 - K_1 \tag{12}$$

where:

K denotes the added value of gray-scale of damaged part;

K_1 represents the gray value of the undamaged part in the potato tuber;

K_2 expresses the gray value of the damaged site in the potato tuber.

Fig. 4 - Slices with a thickness of 1mm

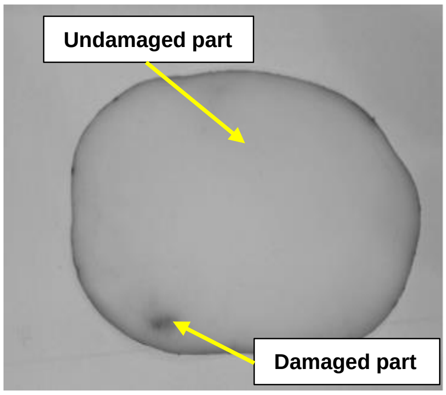


Fig. 5 - Gray-scale image

Before constructing comprehensive damage index (*DI*) by weight distribution of three types of damage, the measured data should be processed without dimensionality as follows:

$$X_{m'(k)} = \frac{\left| X_{m(k)} - \bar{X}_m \right|}{\sigma} \tag{13}$$

where:

$X_{m'(k)}$ represents the dimensionless data;

$X_{m(k)}$ represents the raw data of the k^{th} element derived from the evaluation metrics;

$\bar{X}$ denotes the average values of the same evaluation indices;

σ is the standard deviation of the same evaluation indices.

Then the comprehensive damage index (*DI*) was constructed using three factors, including the epidermal damaged area, the length of the fissure and the added value of gray-scale (*Bin, 2018*), which can be calculated by:

$$DI = 0.25 \cdot X_{S'} + 0.35 \cdot X_{K'} + 0.4 \cdot X_{L'} \tag{14}$$

where:

DI denotes the comprehensive damage index;

$X_{S'}$ is the dimensionless data of epidermal damage area;

$X_{K'}$ is the dimensionless data of added value of gray-scale;

$X_{L'}$ is the dimensionless data of length of the fissure.

RESULTS

Orthogonal test results

The range analysis results are shown in Table 4. The order of influencing factors for the comprehensive damage index is as follows: impact material>potential energy>potato varieties>impact angle. In addition, the results showed that the comprehensive damage index was the lowest when the impact material was a plank, the potential energy was 1.2J, the type of potato was Lishu NO.6, and the impact angle was 15°.

Table 4

Experimental results and range analysis

Test No.	Impact material *A*	Potato varieties *B*	Potential energy *C* [J]	Impact angle *D* [°]	*DI*
1	0	-1	1	0	0.5140
2	0	0	0	0	0.2526
3	-1	-1	0	0	0.4917
4	0	-1	0	-1	0.4566
5	-1	0	-1	0	0.3096
6	0	0	1	-1	0.4055
7	1	0	0	1	0.3054
8	0	1	0	1	0.2296
9	0	-1	0	1	0.2972
10	1	0	1	0	0.2576
11	1	1	0	0	0.3841
12	0	0	-1	1	0.2166
13	0	1	1	0	0.4247
14	1	-1	0	0	0.3388
15	1	0	0	-1	0.1412
16	0	0	0	0	0.2526
17	1	0	-1	0	0.0055
18	-1	0	0	1	0.5014
19	0	0	1	1	0.3076
20	0	0	-1	-1	0.1590
21	-1	0	1	0	0.5608
22	0	-1	-1	0	0.2015
23	0	1	-1	0	0.1742
24	-1	1	0	0	0.6598
25	-1	0	0	-1	0.4859
26	0	1	0	-1	0.3079
K_{-1}	0.5015	0.3833	0.1777	0.3260	
K_0	0.3000	0.2872	0.3646	0.3438	
K_1	0.2388	0.3634	0.4117	0.3696	
R	0.2627	0.0961	0.2340	0.0436	

Table 5

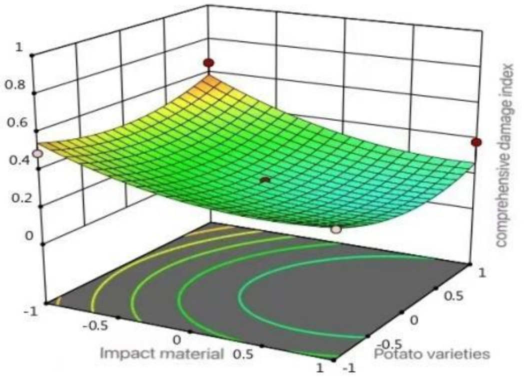
Variance analysis of test result of the comprehensive damage index

Source of variation	Sum of squares	Degree of freedom	Mean square	*F*-Value	*P*-Value
Mode	0.4872	14	0.0348	5.1	0.0054
A	0.2071	1	0.2071	29.84	0.0002
B	0.0012	1	0.0012	0.1715	0.6868
C	0.1642	1	0.1642	23.66	0.0005
D	0.0008	1	0.0008	0.1160	0.7398
AB	0.0038	1	0.0038	0.5432	0.4766
AC	2.025E-07	1	2.025E-07	0.0000	0.9958
AD	0.0055	1	0.0055	0.7964	0.3913
BC	0.0010	1	0.0010	0.1385	0.7169
BD	0.0016	1	0.0016	0.2369	0.6360
CD	0.0060	1	0.0060	0.8709	0.3707
A^2	0.0353	1	0.0353	5.08	0.0455
B^2	0.0391	1	0.0391	5.64	0.0369
C^2	0.0024	1	0.0024	0.3394	0.5719
D^2	0.0006	1	0.0006	0.0821	0.7798
Residua	0.0763	11	0.0069	—	—
Lack of Fit	0.0763	10	0.0076	—	—
Pure Error	0.0000	1	0.0000	—	—

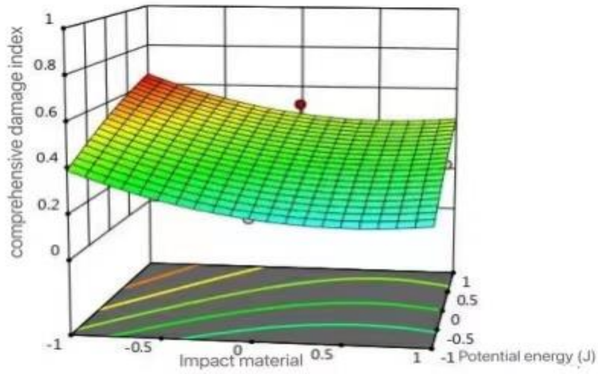
The variance analysis of test result was shown in Table 5 and the P-Value shows that the test factor B (potato varieties) and D (impact angle) have no significant effect on the comprehensive damage index. On the contrary, factor A (impact material) and C (potential energy) have significant effect on the comprehensive damage index.

Response surface analysis of the comprehensive damage index

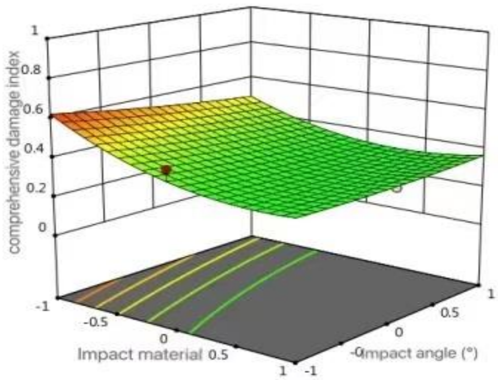
Design-Expert software was used to plot the response surface of the comprehensive damage index, the effect of various factors and the interaction between various factors on the comprehensive damage index is shown in Fig. 6.



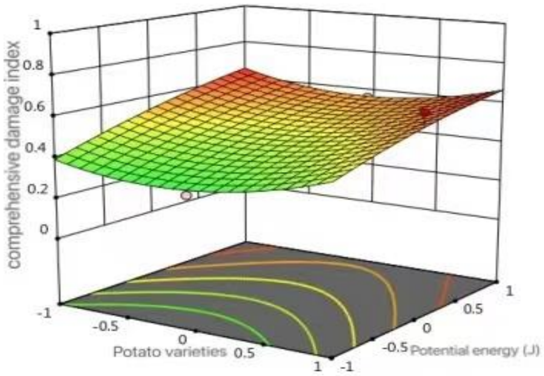
a) DI = (*A*, *B*, 0, 0)



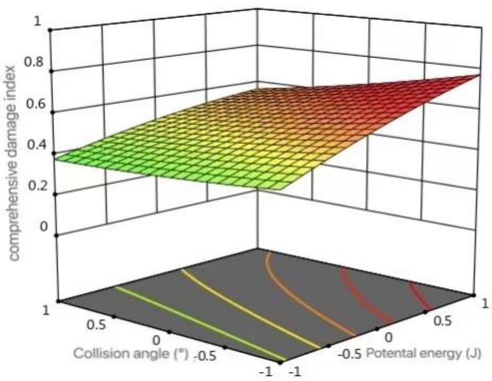
b) DI = (*A*, 0, *C*, 0)



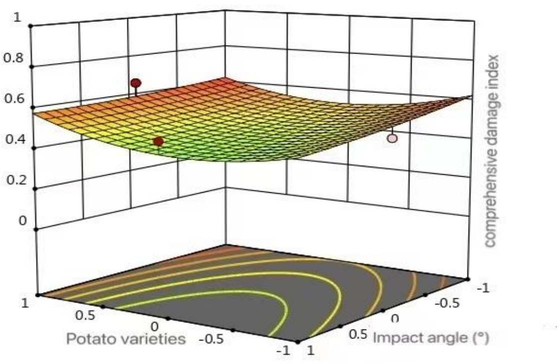
c) DI = (*A*, 0, 0, *D*)



d) DI = (0, *B*, *C*, 0)



e) DI = (0, 0, *C*, *D*)



f) DI = (0, *B*, 0, *D*)

Fig. 6 - Response surface of the impact material, potato species, potato potential energy and impact angle to the comprehensive damage

According to the results of Table 1, Table 2, Table 4, and Fig. 6, the comprehensive damage index (DI), which represents the damage degree of potato tuber in collision decreased with the increasing of coefficient of restitution of impact material (e), potato yield strength (σ') and collision angle (φ), but increased with the increasing of potato potential energy (mgh). The experimental results agreed well with the damage phenomenon explained by the mechanic impact model in equation (5) and (10).

The bigger the coefficient of restitution of the collision material, the less energy lost during the collision and the energy used to damage the potato was less too. Therefore, covering a layer of impact material with a higher coefficient of restitution on the parts of potato harvester to reduce the tuber damage degree should be a feasible method. The higher the potato yield strength, the greater the potato's ability to resist plastic deformation, which means the longer elastic compression phase, and under the premise of no damage, the greater the impact load could bear. These points indicated that potato varieties with high yield strength are more suitable for mechanical harvesting. The larger the potential energy, the greater the initial impact speed, the more mechanical energy lost after a collision, and the greater damage degree.

The larger the collision angle, the greater contact area between the potato tuber and the impact material, which leads to greater damage. Thus, the harvester's operating and structure parameters could be optimized from the perspective of reducing the potential energy of potato tuber being harvested and improving the potato tuber impact angle during harvesting.

Experimental verification

According to Table 3, the two-regression method was applied to analyze the comprehensive damage index and a mathematical regression model was established to explain the relationship between tuber damage degree and the four test factors.

$$\begin{aligned} DI = &0.2526 - 0.1314 \cdot A - 0.0100 \cdot B + 0.1140 \cdot C - 0.0082 \cdot D - 0.0307 \cdot AB + 0.0002 \cdot AC + 0.0372 \cdot AD \\ &- 0.0155 \cdot BC + 0.0203 \cdot BD - 0.0389 \cdot CD + 0.0899 \cdot A^2 + 0.0947 \cdot B^2 - 0.0232 \cdot C^2 + 0.0114 \cdot D^2 \end{aligned} \tag{15}$$

where:

A denotes the impact material; B expresses the potato varieties; C represents the potato energy; D is the impact angle.

The error value Δ was obtained by performing five randomized validation trials (five potato tubers per group, and Level factors were randomly selected) and comparing the actual measurement results (DI_1) with the regression model predicted results (DI_2). The predicted results of the comprehensive damage index *were calculated by the* formula (15). The results of validation trials are shown in Table 6.

Table 6

The results of validation trials

Test No.	*A*	*B*	*C* (J)	*D* (°)	DI_1	DI_2	Δ (%)
1	-1	0	0	-1	0.5559	0.5307	4.5
2	0	0	0	0	0.2423	0.2526	4.9
3	-1	-1	0	0	0.5182	0.5479	5.7
4	0	0	1	-1	0.4211	0.4049	3.8
5	0	1	1	0	0.3878	0.4156	7.2

Table 6 shows that the error values Δ in each group are less than 10%, so the quadratic regression model of the comprehensive damage index is hereby able to capture the test situation, the average error between the experimental and predicted data was 5.22%. This model can be used to estimate the damage degree of potato tuber collision.

CONCLUSIONS

(1) The physical model of potato tuber collision was constructed in terms of the deformation and deformation energy analysis during the collision. The model showed that potato damage degree correlates with impact material, potato varieties, potential energy, and impact angle.

(2) The range analysis suggest the order of influencing factors for the comprehensive damage index is as follows: impact material＞potential energy＞potato varieties＞impact angle. The results of the orthogonal test showed that the potato varieties and the impact angle have no significant effect on the comprehensive damage index. On the contrary, impact material and the potential energy have significant effect on the comprehensive damage index. Furthermore, when the impact material is plank, the potential energy is 1.2 J, the potato varieties is Lishu NO.6, and the collision angle is 15 °, the comprehensive damage index is the lowest, 0.0055.

(3) The comprehensive damage index (DI) was decreased with the increasing of the coefficient of restitution between impact material and steel (e), potato yield strength (σ') and collision angle (φ), but increased with the increasing of potato potential energy (mgh).

(4) The quadratic regression model of the comprehensive damage index is obtained by orthogonal test results. The average error between the predicted data of the comprehensive damage index calculated by the mathematical regression model and the experimental data was 5.22%.

ACKNOWLEDGEMENT

The study was supported by Hunan Provincial Natural Science Foundation (NO.2019JJ50275) and Hunan Dry Grain Industry Technology System.

REFERENCES

[1] Arfa, G.K. (2007). The effect of harvesting operation on potato crop handling. *Misr Journal of Agricultural Engineering*, Vol. 24, pp. 492-503, Egypt.

[2] Baritelle, A., Hyde, G., Thornton, R., Bajema, R. (2000). A classification system for impact-related defects in potato tubers. *American Journal of Potato Research*, Vol. 77, pp. 143-148, USA.

[3] Thybo, A.K., Jespersen, S.N., Lærke, P.E., Stødkilde-Jørgensen, H.J. (2004). Nondestructive detection of internal bruise and spraing disease symptoms in potatoes using magnetic resonance imaging. *Magnetic resonance imaging*, Vol. 22, pp. 1311-1317, USA.

[4] Bin, F., (2018). *Study on Physical Characteristics and Damage of Potato Tubers at Harvesting Stage* (收获期马铃薯块茎物理特性及损伤机理研究) [Doctoral dissertation, Gansu Agricultural University]. China National Knowledge Infrastructure. https://kns.cnki.net/kns8/defaultresult/index.

[5] Caglayan, N., Oral, O., Celik, H.K., Cinar, R., Rodrigues, L.C.D.A., Rennie, A.E., Akinci, I. (2018). Determination of time dependent stress distribution on a potato tuber during drop case. *Journal of Food Process Engineering*, Vol. 41, pp. e12869, USA.

[6] Celik, H. K., Cinar, R., Yilmaz, D., Ulmeanu, M. E., Rennie, A. E., Akinci, I. (2019). Mechanical collision simulation of potato tubers. *Journal of Food Process Engineering*, Vol. 42, pp. e13078, USA.

[7] Molema, G.J., Bouman, A., Verwijs, B. R., Van Den Berg, J. V., Klooster, J. J. (2000). Subcutaneous tissue discoloration in ware potatoes. 1. A chain analysis in the Netherlands. *Potato research*, Vol. 43, pp. 211-224, Netherlands.

[8] Green, I. (2005). Poisson ratio effects and critical values in spherical and cylindrical Hertzian contacts. *Applied Mechanics and Engineering*, Vol. 10, pp. 451, Netherlands.

[9] Hui S., (2014). *Contact Pressure Analysis of Drop Impact for Korea Pear and Bruising Predication Using Finite Element Analysis* (库尔勒香梨跌落碰撞接触应力分析及损伤预测的研究) [Master's dissertation, Shihezi University]. https://kns.cnki.net/kns8/defaultresult/index.

[10] Han D., (2019). *Mechanical Damage Analysis and Experimental Research on Potato Harvester Elevator* (马铃薯收获机升运过程机械损伤分析与试验) [Master's dissertation, Tohoku University of Agriculture]. https://kns.cnki.net/kns8/defaultresult/index.

[11] Jackson, R.L., Green, I. (2005). A finite element study of elasto-plastic hemispherical contact against a rigid flat. *Journal of Tribology*, Vol.127, pp. 343-354, USA.

[12] Jian Z., (2008). *Assessment Technology and Genetic Analysis for Tuber Browning in Potato (Solanum tuberosum)* (*马铃薯块茎损伤评价技术研究及损伤变色性状的遗传分析*) [Doctoral dissertation, Chinese Academy of Agricultural Sciences]. China National Knowledge Infrastructure. https://kns.cnki.net/kns8/defaultresult/index.

[13] Jian M., Chun W., Sheng X., Wei D., Shao Q., Jing L., (2017). Measurement test analysis of potato restitution coefficient (马铃薯恢复系数测定试验分析). *Journal of China Agricultural University*, Vol.09, pp.93-100, Beijing/ China.

[14] Li L., Zhi W., (2007). Dropping Impact Mechanical Characteristics of Apple (苹果跌落冲击力学特性研究). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 02, pp.254-258, Beijing/China.

[15] Ito, M., Sakai, K., Hata, S., Takai, M. (1994). Technical Notes: Damage to the Surface of Potatoes from Collision. *Transactions of the ASAE*, Vol. 37, pp. 1431-1433, USA.

[16] Parks R, Anderson G, Zheng D., (1990). Artificial Potatoes for Damage Research (用于损伤研究的人造马铃薯). *Advances in Mechanics*, Vol. 03, pp. 425-430, Beijing/China.

[17] Peters, R. (1996). Damage of potato tubers, a review. *Potato research*, Vol. 39, pp. 479-484, Netherlands.

[18] Mathew, R., Hyde, G. M. (1997). Potato impact damage thresholds. *Transactions of the ASAE*, Vol. 40, pp. 705-709, USA.

[19] Mayer, V., Vejchar, D., Pastorková, L. (2017). Measurement of potato tubers resistance against mechanical loading. *Research in Agricultural Engineering*, Vol. 1, pp. 22-31, Czech Republic.

[20] Evans, S. D., McRae, D. C. (1998). Quantifying damage as percentage potato tuber volume lost per peeler stroke. *Potato research*, Vol. *41, pp. 277-287,* Netherlands.

[21] Shan C., Yi Z., Jun W., Jian W., (2003). Mechanical parameters of impact occurred due to fruit fall in relation to bruise suffered by fruit (梨的下落碰撞冲击加速度特性研究). *Journal of Zhejiang University (Agriculture and Life Sciences),* Vol. 03, pp. 105-108, Zhejiang/China.

[22] Shi S., Fang W., Hong W., Zheng H., (2010). Study on development of potato harvest machinery in China (我国马铃薯收获机械研制与发展的研究). *Journal of Chinese Agricultural Mechanization*, Vol. 03, pp. 34-39, Jiangsu/China.

[23] Wei D., Chun Wang., Sheng X., (2020). Test research on the impact peak force and damage depth of potato, *INMATEH-Agricultural Engineering*, Vol. 61, pp. 105-114, Bucharest/Romania.

[24] Zhi L., (2017). *Research on Potato Collision Problem and Key Mechanism of Sorting Equipment* (马铃薯碰撞问题及分选装备关键机构研究). [Master’s dissertation, Zhejiang University]. China National Knowledge Infrastructure. https://kns.cnki.net/kns8/defaultresult/index.