EXPERIMENTAL STUDY OF LYCIUM BARBARUM BRUISING DURING VIBRATION HARVESTING
/
枸杞振采收集过程中果实碰撞损伤分析与试验

Qingyu CHEN[1)], Rui KANG[2)], Naishuo WEI[1)], Yunlei FAN[1)], Zeyu WANG[1)], Jianguo ZHOU[1)], Lingxin BU[3)], Yu CHEN[1)], Jun CHEN *[1)]

[1)] College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, China;
[2)] German-Sino School of Business & Technology, FOM University of Applied Sciences, Essen 45141, Germany;
[3)] College of Mechatronic Engineering, North Minzu University, Yinchuan, Ningxia 750021, China
Tel: +86 135721917773; E-mail: chenjun_jdxy@nwsuaf.edu.cn
DOI: https://doi.org/10.35633/inmateh-73-46

***Keywords:** L. barbarum; vibration harvesting; high-speed photography; drop test; explicit dynamics; response surface method*

ABSTRACT

Lycium barbarum L. (L. barbarum) is an economic crop with high added value and profit. Vibration harvesting is a suitable mechanized harvesting method for L. barbarum. It bruises easily during harvesting due to the softness and vulnerability of fresh ripe fruit, resulting in economic losses. This study analyzed the fruit drop and collision during vibration harvesting. High-speed photography was used to obtain the impact speed and angle of the falling fruit, and a kinematic analysis of the collision with the collection surface was conducted. The majority of the fruit had an impact speed of 3-6 m/s and an impact angle of 30-90° with the collection surface. A drop test was conducted to assess fruit bruising, and the impact speed was converted to the drop height. An orthogonal rotation experiment was conducted, and mathematical model was established between the drop height, impact angle, and impact material, and the fruit bruise rate, maximum impact force, recovery coefficient, and impact time. The effects of the factors on the fruit bruise rate, maximum impact force, recovery coefficient, and impact time were analyzed. The test results show that a vibration harvesting device for L. barbarum should be designed to reduce the height between the fruit and the collection surface and utilize a tilted collection surface and high cushioning materials to reduce the fruit bruising. This study provides guidance for subsequent research on the bruising of L. barbarum during vibration harvesting and harvester design.

摘要

枸杞作为一种经济作物，具有较高的附加值和利润。振动采收是枸杞机械化采收的适宜方法，由于枸杞鲜果柔嫩易损，采收过程中容易损伤造成经济损失。本研究针对枸杞振动采收中的果实跌落收集过程进行研究，通过高速摄影技术获取果实振采脱落速度与角度，对果实脱落后碰撞过程进行运动学分析，研究发现绝大多数枸杞果实与收集面的撞击速度在 3~6m/s，撞击角度为 30~90°。采用跌落试验的方法进行损伤研究，将撞击速度转变为跌落高度。通过三因素三水平二次正交旋转组合试验，建立了跌落高度、碰撞角度、碰撞材料与果实损伤率、最大冲击力、恢复系数和碰撞时间之间的数学模型，分析各因素对果实损伤率、最大冲击力、恢复系数和碰撞时间的影响。分析实验结果发现，较低的跌落高度与碰撞角度，以及添加更具缓冲能力的碰撞材料能够有效减少果实损伤，为后续枸杞损伤研究与采收机的设计提供参考。

INTRODUCTION

Lycium barbarum L. (*L. barbarum*) is a deciduous shrub belonging to the Lycium genus in the Solanaceae family. The fruit contains many nutritional components, such as polysaccharides, fatty acids, carotenoids, and phenolic compounds, that nourish the liver and kidneys, improve vision, enhance immunity, and delay aging (*Xiao et al., 2022; Ma et al., 2022*).

Qingyu Chen, Ph.D. Stud. Eng.; Rui Kang, M.S. Eng.; Naishuo Wei, PH.D. Stud. Eng.; Yunlei Fan, PH.D. Stud. Eng.; Zeyu Wang, M.S. Stud. Eng.; Jianguo Zhou, Ph.D. Stud. Eng.; Lingxin Bu, Ph.D. Eng.; Yu Chen, Ph.D. Eng.; Jun Chen, Prof. Ph.D. Eng.

As a valuable tonic in traditional Chinese medicine, *L. barbarum* is processed in various ways, including drying, making tea, pulping, and brewing (*Ma et al., 2018; Bora et al., 2019*). China is the largest producer of *L. barbarum*. It is mainly planted in Ningxia, Qinghai, and Xinjiang due to favorable soil, climate, and temperature (*Shen et al., 2016; Skenderidis et al., 2019*).

As an economic crop, *L. barbarum* has high added value and profit. As the planting area and production have increased, mechanized harvesting will become common in recent years (*Zhao et al., 2021; Chen et al., 2021; Chen et al., 2022a*). Field trials have demonstrated that vibration harvesting can substantially improve harvest efficiency, with a ripe fruit picking rate of over 90%, making it a suitable mechanized harvesting method (*Chen et al., 2019; Zhang et al., 2018; He et al., 2017; Bu et al., 2020; Hu et al., 2020*). In vibration harvesting, the fruit is subjected to a force greater than its binding force, causing it to fall off and land on the collection device. Due to the softness and vulnerability of fresh fruit, the impact can cause bruising or skin rupture, resulting in bruised fruit, accelerated spoilage, and blackening of the bruised area after drying, affecting its market value and economic benefits (*Zhao et al., 2019*). Therefore, it is necessary to develop a method to reduce fruit bruising during vibration harvesting.

Research methods for assessing fruit bruising include drop, pendulum, compression, and electronic fruit. Measurement methods include the use of impact force sensors, high-speed photography, and photosensitive lamination (*Öztekin & Gungor, 2020; Opara & Pathare, 2014; Stropek & Golacki, 2020*). *Hussein et al. (2020)* used drop tests to analyze the impact of fruit collision on the level of fruit bruising. *Wang et al. (2020)* utilized a pendulum test to assess the impact of lychee fruit and established a method to predict the bruising degree based on the impact energy. *Chen et al. (2018)* studied the bruise characteristics of thick-skinned citrus fruit under different load conditions and the ability of different materials to reduce fruit bruising. *Xu et al. (2015)* used a micro-impact recorder to quantify the mechanical impact of blueberries in a packaging line. However, the electronic fruit is not suitable for *L. barbarum* fruits due to their small size, low weight, and unique shape. The compression test is typically used to analyze the static pressure of mechanical hands acting on fruits. This test is not suitable for assessing bruising occurring during collisions. The pendulum test is commonly used to analyze the bruise area and volume of fruits. However, this process is cumbersome when many tests are conducted. Therefore, it is more appropriate to use drop test to study the bruise rate of *L. barbarum* fruit during vibration harvesting *(Zulkifli et al., 2020; Celik et al., 2017*).

Linden et al. (2006) found that tomato fruit absorbs kinetic energy when struck, and when the energy exceeds the tissue failure threshold, mechanical bruising will occur, leading to skin cracking in severe cases. *Bao et al. (2017)* indicated that different drop heights result in different energy intensities absorbed by the blueberry fruit, with higher heights resulting in a higher impact energy and increased fruit bruising. For the apple and peach, the addition of cushioning materials can absorb part of the impact energy. Different materials have different densities, elasticities, and abilities to reduce fruit bruising (*Jarimopas et al., 2007; Ahmadi et al., 2010*). In addition, *Zhou et al. (2016)* discovered that the collision angle can affect fruit bruising of sweet cherry.

This study analyzed the impact process between falling *L. barbarum* and the collection device during vibration harvesting, and evaluated the relationship between fruit damage indicators and collection parameters through drop test. This provides a new analysis method and experimental reference for subsequent vibration harvesting damage experiments during the collection process.

MATERIALS AND METHODS

Response analysis of fruit drop

The working principle of the *L. barbarum* vibration harvester is to convert the uniform rotation of the motor into the reciprocating motion of the vibrating rod using a transmission. The vibrating rod causes the branches to swing. When the applied force exceeds the binding force of the fruit and the fruit stem, the fruit falls off. As shown in Figure 1, a high-speed camera (I-Speed LT, Olympus Co., Ltd., Japan; 1280 × 1024 resolution; 10,000 frames per second (fps) maximum) was used to record the fruit drop at 1,000 fps as the vibration harvester was operating. The vibration harvester is handheld and portable, mainly consists of a handle, a shell, a motor, a crank-swinging lever, a clamping rob and a vibrating rob. The experiment and operating parameters (swing angle of 49.58°, swing radius of 72.53 mm, and swing frequency of 11.21 Hz) of the vibration harvester have been described in the paper (Chen et al., 2022b). I-Speed software was used to track the dropping fruit and obtain the initial velocity and angle of the fruits. A total of 109 groups of data were collected.

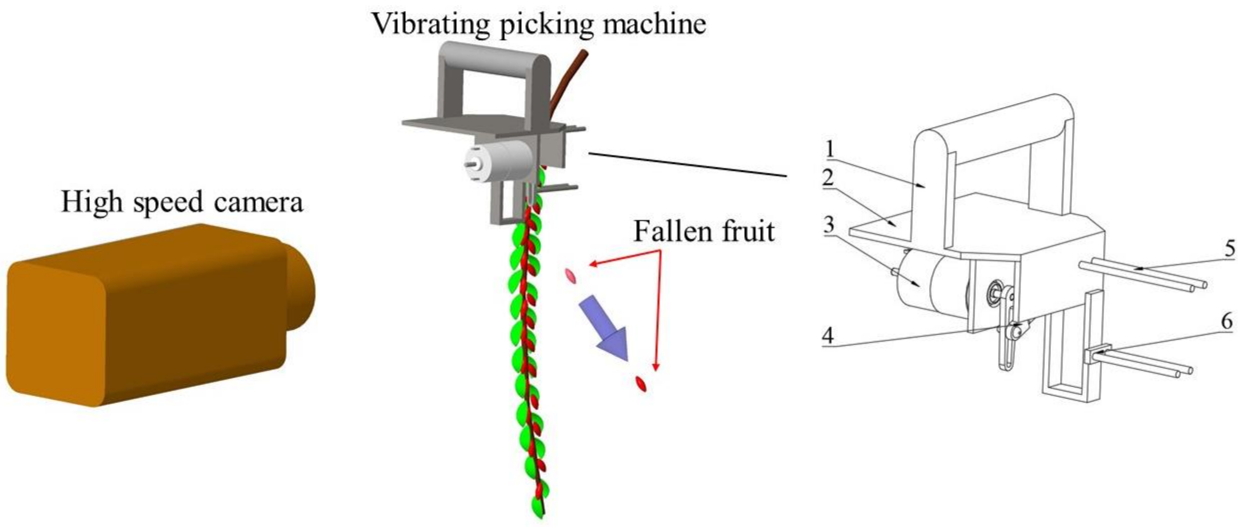


Fig. 1 - Schematic diagram of fruit drop
(1) hand shank, (2) shell, (3) DC motor, (4) a crank-swinging lever, (5) clamping rob, (6) vibrating rod.

Analysis of collision after fruit detachment

After the fruit falls off, it drops at a certain speed and angle with a parabolic motion due to gravity until it collides with the collection surface. The reason for bruising after detachment is the collision between the fruit and the plane. This article focuses on the collision between the fruit and the plane.

In vibration harvesting, the fallen fruit has a certain initial velocity, the initial direction of motion can be oblique upward or oblique downward. The schematic diagram of the motion analysis is shown in Figure 2. The air resistance is ignored.

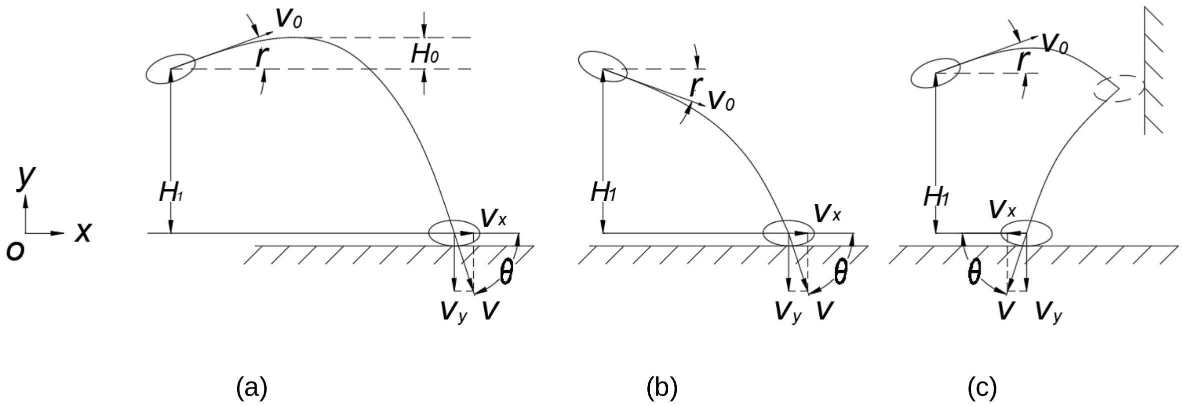


Fig. 2 - Schematic diagram of fruit movement after detachment

If the motion is oblique upward (Figure 2a), the fruit moves upward and decelerates. After it reaches the highest point, it moves downward, accelerates, and collides with the collection surface.

The maximum height in the vertical direction is defined as follows:

$$H_0 = \frac{V_0^2 \sin^2 r}{2g} \tag{1}$$

where:

H_0 is the height the fruit moves upward, m; V_0 is the instantaneous velocity of the fruit after detachment, m/s; r is the angle between the fruit's direction of motion and the horizontal plane, °; g is the acceleration of gravity, which is 9.8 m/s².

After the fruit has reached the maximum height, it falls to the collection surface with a vertical velocity of:

$$V_y = \sqrt{2g(H_0 + H_1)} = V_0 \sin r + \sqrt{2gH_1} \tag{2}$$

where: V_y is the vertical velocity of the fruit when it impacts the collection surface, m/s; H_1 is the height of the fruit from the collection surface, m.

If the detachment direction is oblique downward (Figure 2b), the fruit drops with uniform acceleration until it collides with the collection surface. The maximum vertical velocity is:

$$V_y = V_0 \sin r + \sqrt{2gH_1} \tag{3}$$

Therefore, the maximum vertical velocity at which the fruit collides with the collection surface is not affected by the detachment direction.

The fruit moves at a constant speed in the horizontal direction, and if it collides with the wall of the collection device or the harvesting equipment, the post-separation velocity of the fruit is related to the coefficient of restitution (the ratio of the separation velocity after collision to the approach velocity before collision):

$$V_x = e^n V_0 \cos r \tag{4}$$

where: V_x is the horizontal velocity of the fruit as it falls to the collection surface, m/s; e is the coefficient of restitution after the fruit has collided with the wall; n is the number of collisions. e depends on the collision material, and it has a value of 0.2-0.8.

The final collision velocity of the fruit as it hits the collection surface is:

$$V = \sqrt{V_y^2 + V_x^2} = \sqrt{(V_0 \sin r + \sqrt{2gH_1})^2 + (e^n V_0 \cos r)^2} \tag{5}$$

where: V is the final collision velocity of the fruit as it hits to the collection surface, m/s.

The maximum collision velocity of the fruit as it hits the collection surface is:

$$V_{\max} = \sqrt{V_{y\max}^2 + V_{x\max}^2} = \sqrt{(V_0 \sin r + \sqrt{2gH_1})^2 + (V_0 \cos r)^2} \tag{6}$$

where:

V_{max} is the vertical maximum collision velocity of the fruit as it hits to the collection surface, m/s; V_{ymax} is the vertical maximum collision velocity of the fruit as it hits to the collection surface, m/s; V_{xmax} is the horizontal maximum collision velocity of the fruit as it hits to the collection surface, m/s.

The impact angle of the fruit as it hits the collection surface is:

$$\theta = \arctan \frac{V_y}{V_x} \tag{7}$$

where: θ is the impact angle of the fruit as it hits the collection surface, °.

Kinematic analysis of the collision after detachment shows that the maximum velocity and angle of collision between the fruit and the collection surface depend on the initial velocity and angle of fruit detachment and the height of the fruit from the collection surface. According to formulas 6 and 7, combined with the initial velocity and angle of the fruit obtained, the velocity and angle of the fruit hitting the collection surface can be obtained, providing data support for bruise experiment.

Bruise experiment

A drop test is a common method for assessing fruit bruising. Since it is difficult to achieve a stable initial velocity and angle for *L. barbarum* fruits in experiments, the movement of the fruit from the oblique throwing of the bodies was converted into the free fall movement, the collision velocity and angle are converted into the drop height of the fruits (by formula 8) and the angle of the collision plane (by adjusting the angle of the plate change the collision angle), respectively.

According to the free-fall formula, the following can be derived:

$$H = \frac{v^2}{2g} \tag{8}$$

where: H is the drop height of the fruit, m; v is the collision velocity of the fruit, m/s.

The fruit used in the experiment was obtained from the Ningxia Zhengqihong L. *barbarum* Industry Development Co., Ltd., Gangou Village, Sanying Town, Yuanzhou District, Guyuan City, Ningxia Hui Autonomous Region (36°17′32.9″N, 106°6′41.5″E). The variety used was Ningqi 7.

The shrubs were artificially pruned into standardized hedge cultivation mode, with the shrubs' age of 3-4 years. The experiment was conducted on July 10, 2023. L*. barbarum* shrubs with good growth conditions, no pests or diseases, and no damage were selected. The branches were cut down in the field and collected to ensure the freshness of the fruits. Ripe fruits were picked and used immediately in the experiment.

As shown in Figure 3, the experimental device consisted of a fruit guide tube, an impact sensor (model: DYZ-100, range: 0-20N, accuracy: 0.3%, Bengbu Dayang Sensor System Engineering Co., Ltd.), a portable force measurement instrument (model: DY920, accuracy: 0.05%, rate: 3200 times/second, Bengbu Dayang Sensor System Engineering Co., Ltd.), and a high-speed camera. The guide tube was installed vertically; it was replaceable, and the position could be adjusted to ensure that the fruits fell from the same height onto the same area of the collection device. The impact sensor was cushioned with 5-mm thick material, and the position and angle were adjustable. In addition, a sponge was placed around the collision material to prevent secondary bruising.

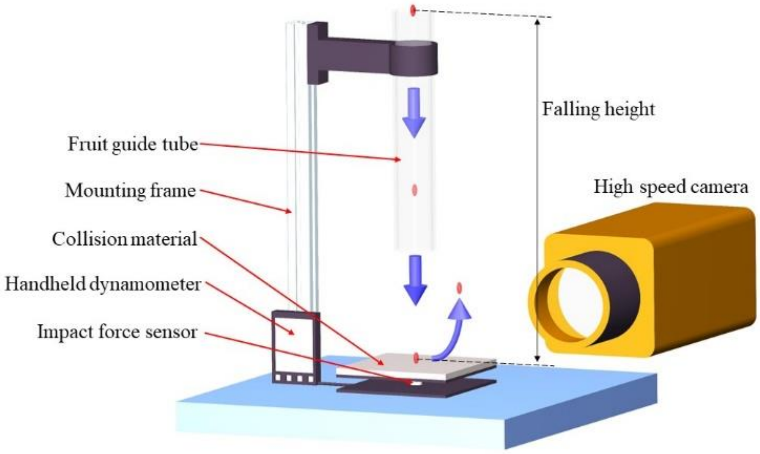
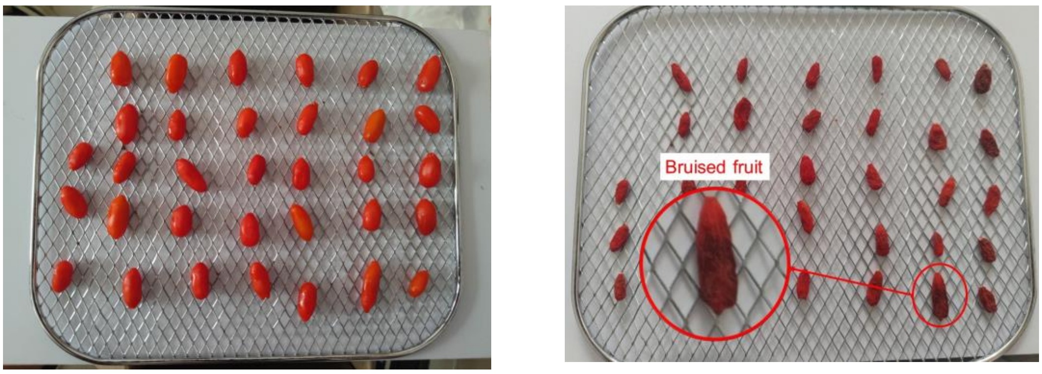


Fig. 3 - Schematic diagram of the fruit drop test

Fruit bruise assessment

The degree of fruit bruising is directly related to the energy absorbed by the fruit during the impact. The potential energy of the fruit during the impact is converted into kinetic energy, and elastic-plastic deformation of the fruit occurs, resulting in bruising (Bai et al., 2017). After the fruit collides with the collision plane, the color of the bruised area does not change significantly, and the bruised area is soft and flat. After the fruit dries, the surface becomes black, resulting in economic losses. Since the most *L. barbarum* are made into dried fruits and sold afterwards, all samples were dried after the drop test according to the Agricultural Industry Standard (NY/T2966-2016) of China, which specifies standards for harvesting, cleaning, dewaxing, draining, loading, drying, cooling, unloading, and removing impurities. The fresh fruits were immersed for 10 s in a solution of food-grade sodium bicarbonate (baking soda) with a concentration of 2% to remove wax. The fruit was dried using a small household fruit dryer (model: MR6255, Morphy Richards UK Ltd.). After drying, fruit with a color that did not meet the standard requirements (some areas are black, clearly different from other fruits) were manually selected and were considered bruised fruit. The fruits before and after drying are shown in Figure 4.



(a) Before drying **(b) After drying**

Fig. 4 - Drying detection of fruit bruise

The main purpose of this experiment was to investigate the level of bruising occurring after vibration harvesting of ripe fruits. The experimental indicators included the fruit bruise rate I_S, maximum impact force I_F (peak force during impact process, measured by force measurement instrument), restitution coefficient I_R (the ratio of velocity after rebound to velocity before impact, measured by high-speed camera), and collision time I_T (the time of contact between the fruit and the collection surface, measured by high-speed camera). The calculation formula for the fruit bruise rate is as follows:

$$I_S = \frac{N_s}{N} \times 100\% \tag{9}$$

where: N is the total number of dried fruits, and N_s is the number of bruised dried fruits.

RESULTS AND ANALYSIS

Analysis of fruit drop

Figure 5 shows a scatterplot between the initial velocity and angle of the fruit after vibration harvesting. The collision speed of the fruit as it hit the collection surface was related to the height of the fruit. Based on the growing parameters and the harvesting conditions of ripe fruits, the drop height was set at 0.5 m. Calculated by combining formulas 6 and 7, the scatterplot between the collision speed and angle of the fruit hit the collection surface is shown in Figure 6. Most of the fruit had an impact velocity of 3-6 m/s and an impact angle of 30-90°. Based on the analysis results and formula 8, 60-180 cm and 30-90 ° were used as experimental parameters for response surface analysis.

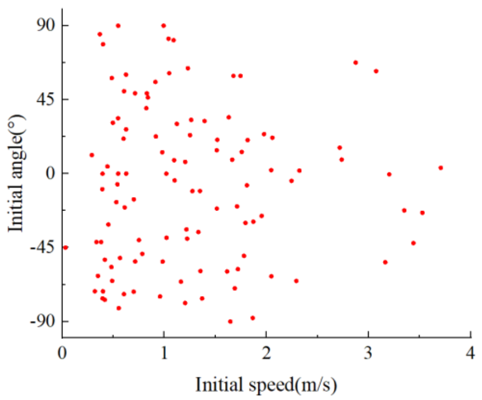


Fig. 5 - Scatterplot between the initial velocity speed and angle of the fruit

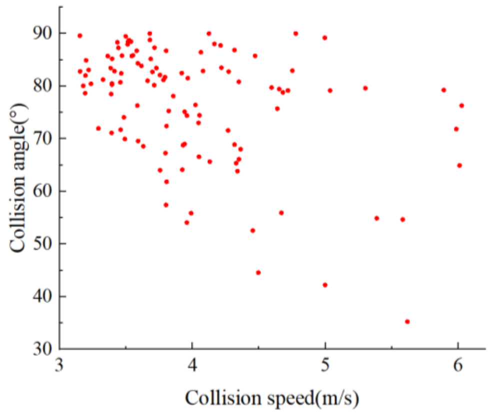


Fig. 6 - Scatterplot between the collision speed and angle of the fruit

Experimental protocol and results

A response surface analysis was conducted to evaluate the effects of different variables. A quadratic orthogonal rotation experiment was used. The factor coding is listed in Table 1, and the experimental protocol and results are presented in Table 2. Seventeen groups of experiments were conducted. The average value of the test data was used as the result of this group. The design of the experimental protocol and the analysis of the results were performed using the Design Expert 12 software.

Table 1

Codes of factors

Code	Drop height / [cm]	Collision angle / [°]	Collision material
-1	60	30	1
0	120	60	2
1	180	90	3

Table 2

Experiment schemes and results

	Dropping height A	Impact angle B	Impact material C	Fruit bruise rate I_S / %	Maximum impact force I_F / N	Recovery coefficient I_R	Impact time I_T/ms
1	-1	-1	0	16.67	0.61	0.71	5

	Dropping height A	Impact angle B	Impact material C	Fruit bruise rate I_S / %	Maximum impact force I_F / N	Recovery coefficient I_R	Impact time I_T/ms
2	1	-1	0	35.56	1.55	0.34	6
3	-1	1	0	32.43	0.87	0.34	7
4	1	1	0	78.94	2.65	0.24	7
5	-1	0	-1	6.67	0.95	0.55	3
6	1	0	-1	36.36	1.86	0.39	2
7	-1	0	1	51.85	1.01	0.40	3
8	1	0	1	77.27	2.03	0.26	4
9	0	-1	-1	10.34	0.89	0.62	3
10	0	1	-1	36.36	1.77	0.41	3
11	0	-1	1	42.86	1.47	0.48	2
12	0	1	1	62.50	2.17	0.36	6
13	0	0	0	54.05	1.58	0.37	6
14	0	0	0	31.82	1.79	0.46	5
15	0	0	0	52.63	1.42	0.37	3
16	0	0	0	70.97	1.63	0.54	4
17	0	0	0	41.38	1.52	0.34	4

Experimental results

Regression equations were established to fit the experimental results. The fruit bruise rate I_S, maximum impact force I_F, and recovery coefficient I_R were the dependent variables, and dropping height *A*, impact angle *B* and impact material *C* were the independent variables.

The polynomial regression equations are as follows:

$$I_S = 44.20 + 13.46A + 14.70B + 18.09C + 3.70AB - 1.07AC - 1.60B \tag{10}$$

$$I_F = 1.52 + 0.58A + 0.37B + 0.15C + 0.21AB + 0.03AC - 0.05BC \tag{11}$$

$$I_R = 0.42 - 0.09A - 0.11B - 0.06C + 0.08AB + 0.01AC + 0.03BC \tag{12}$$

Analysis of variance was performed; the results are listed in Table 3. The results indicate that the p-values of the fruit bruise rate, maximum impact force, and recovery coefficient are less than 0.05, indicating that the models are statistically significant. Factors *A*, *B*, and *C* had significant effects on the fruit bruise rate, maximum impact force, and recovery coefficient ($p<0.05$), and factor *AB* had a significant effect on the maximum impact force and recovery coefficient. The other factors had non-significant effects. The p-values of the lack-of-fit term were greater than 0.05, indicating no lack-of-fit factors in the regression equations.

The response surfaces of the parameters are shown in Figures 7-9. Equation (10) and the results in Table 3 indicate that the collision material had the greatest influence on the fruit bruise rate, followed by the drop height and the collision angle. Equation (11) and the results in Table 3 show that the drop height had the greatest influence on the maximum impact force, followed by the collision angle and the collision material. Equation (12) and the results in Table 3 demonstrate that the collision angle had the greatest influence on the recovery coefficient, followed by the drop height and the collision material.

As shown in Figures 7a, 8a, and 9a, as the drop height increased, the fruit bruise rate and maximum impact force increased, whereas the recovery coefficient decreased. As the drop height increased, the impact velocity of the fruit increased, resulting in higher kinetic energy and a greater impact force. The fruit underwent elastic deformation and plastic deformation due to the impact, increasing the energy required for the fruit to undergo plastic deformation, causing a bruised area, resulting in an increase in fruit bruise rate (*Fu et al., 2017*). Subsequently, a decrease in the energy of the fruit's rebound, resulting in a decrease in the recovery coefficient occurred.

As shown in Figures 7b, 8b, and 9b, as the collision material changed from 1 to 3, the fruit bruise rate and maximum impact force increased, whereas the recovery coefficient decreased. The reason is that the kinetic energy of the fruit is converted into elastic deformation energy of the fruit and the collision material during the collision due to the elasticity of the collision material. If the collision material has low elasticity, the impact force is higher, and less elastic potential energy is retained, resulting in greater plastic deformation energy of the fruit (*Xia et al., 2020; Guan et al., 2023*). Thus, the fruit bruise rate increased, and the recovery coefficient decreased.

As shown in Figures 7c, 8c, and 9c, as the collision angle increased, the fruit bruise rate and the maximum impact force increased, whereas the recovery coefficient decreased. Most studies on the collision angle have focused on its effect on the degree of fruit bruising (*Zhou et al., 2019; Bao et al., 2017*).

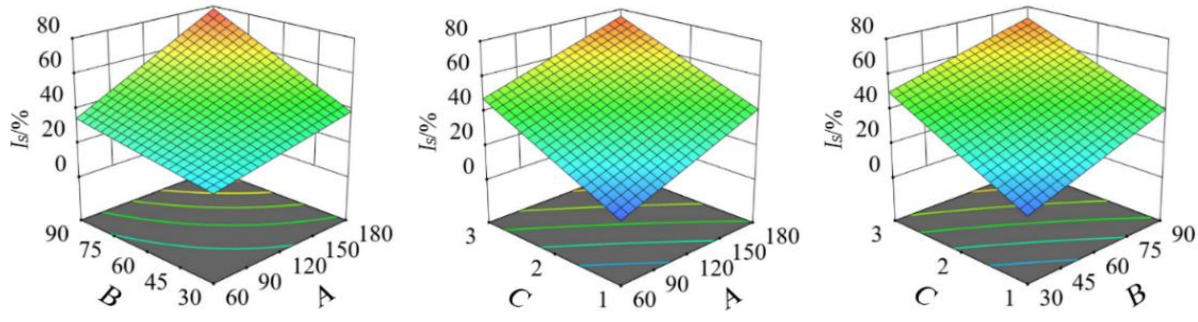


Fig. 7 - Response surface of influence of various factors on the fruit bruise rate

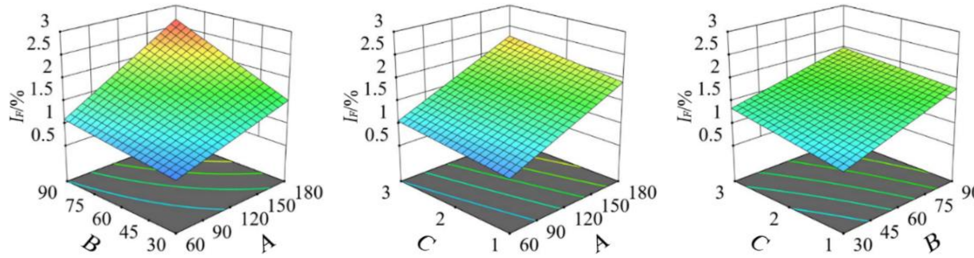


Fig. 8 - Response surface of influence of various factors on the maximum impact force

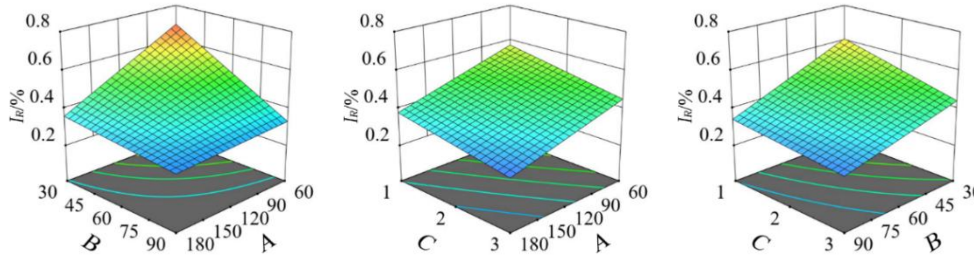


Fig. 9 - Response surface of influence of various factors on the restitution coefficient

Table 3

Variance analysis

	Sources of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	p
Fruit bruise rate	model	6012.73	6	1002.12	7.32	0.0033
	A	1815.33	1	1815.33	13.27	0.0045
	B	1372.88	1	1372.88	10.03	0.01
	C	2619.07	1	2619.07	19.14	0.0014
	AB	190.72	1	190.72	1.39	0.2651
	AC	4.56	1	4.56	0.0333	0.8588
	BC	10.18	1	10.18	0.0744	0.7906
	lack of fit	500.64	6	83.44	0.3846	0.8579

	Sources of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	p
	pure error	867.73	4	216.93		
	total sum	7381.11	16			
Maximum impact force	model	4.15	6	0.6923	21.77	<0.0001
	A	2.7	1	2.7	84.99	<0.0001
	B	1.08	1	1.08	33.98	0.0002
	C	0.183	1	0.183	5.75	0.0374
	AB	0.1764	1	0.1764	5.55	0.0403
	AC	0.003	1	0.003	0.0951	0.7641
	BC	0.0081	1	0.0081	0.2547	0.6247
	lack of fit	0.2425	6	0.0404	2.14	0.2406
	pure error	0.0755	4	0.0189		
	total sum	4.47	16			
Recovery coefficient	model	0.2097	6	0.0349	7.84	0.0025
	A	0.0685	1	0.0685	15.35	0.0029
	B	0.0903	1	0.0903	20.25	0.0011
	C	0.0253	1	0.0253	5.68	0.0384
	AB	0.0225	1	0.0225	5.05	0.0485
	AC	0.0001	1	0.0001	0.0224	0.8839
	BC	0.003	1	0.003	0.6783	0.4294
	lack of fit	0.0173	6	0.0029	0.4215	0.835
	pure error	0.0273	4	0.0068		
	total sum	0.2543	16			

Collision time

Due to the limited frame rate of high-speed cameras, the accuracy of the contact time obtained from experiments is at the millisecond level, resulting in lack of detailed data. The experimental results and the Design-Expert 12 software were used to perform quadratic regression fitting.

The polynomial regression equation with the collision time I_T as the response function is:

$$I_T = 4.4 + 0.125A + 0.875B + 0.5C - 0.25AB + 0.5AC + 1BC + 0.675A^2 + 1.18B^2 - 2.08C^2 \qquad (13)$$

The result of the analysis of variance is listed in Table 4. p-values of the collision time regression model were less than 0.05, indicating that the model was statistically significant. Factors B, B^2, and C^2 had a significant effect on the fruit bruise rate ($p<0.05$), whereas the other factors were not significant. The p-value of the lack-of-fit term was greater than 0.05, indicating no lack-of-fit factors in the regression equation.

As shown in Figure 10, as the collision angle increased, the collision time first decreased and then increased. When the angle is small, the fruit slides after contacting the collision plane.

Ripe fruit is relatively slender and will roll when subjected to a force. A smaller collision angle caused the fruit to collide with the collision plane a second time, making it difficult to distinguish the collision occurrences and increasing the collision time. When the collision angle was greater than or equal to 60°, the fruit only collided once before rebounding and leaving the collision plane.

When the collision angle was 60°, the fruit was sliding after it collided with the collision plane, leaving the contact surface and decreasing the contact time.

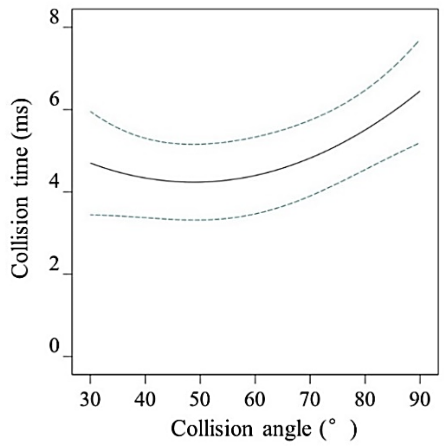


Fig. 10 - Influence of collision angle on collision time

Table 4

Variance analysis of the impact time

Sources of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F	p
Model	38.08	9	4.23	5.43	0.0181
A	0.125	1	0.125	0.1606	0.7006
B	6.13	1	6.13	7.87	0.0263
C	2	1	2	2.57	0.153
AB	0.25	1	0.25	0.3211	0.5886
AC	1	1	1	1.28	0.2944
BC	4	1	4	5.14	0.0578
A^2	1.92	1	1.92	2.46	0.1605
B^2	5.81	1	5.81	7.47	0.0292
C^2	18.13	1	18.13	23.28	0.0019
lack of fit	0.25	3	0.0833	0.0641	0.9761
pure error	5.2	4	1.3		
total sum	43.53	16			

Correlation analysis

The recovery coefficient is typically used to evaluate the degree of fruit bruising. The correlation between the fruit bruise rate, maximum impact force, recovery coefficient, and collision time was analyzed using Pearson correlation analysis by SPSS Statistics 27 software. Due to the insufficient sample size of less than 30, the normality of the data was assessed. The test results showed that all four datasets were normally distributed.

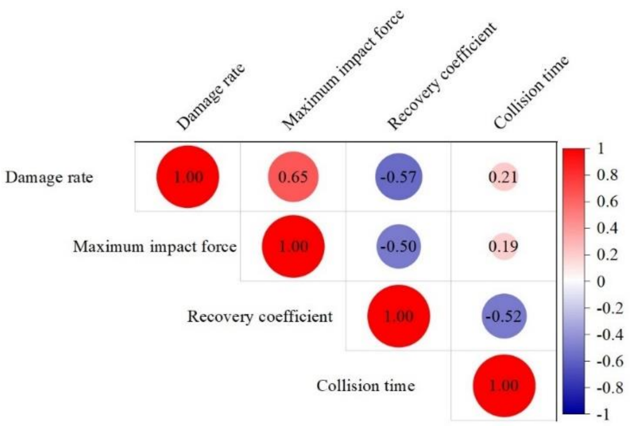


Fig. 11 - Correlation coefficient between various indicators

As shown in Figure 11, Pearson correlation analysis showed that the fruit bruise rate was significantly negatively correlated with the recovery coefficient (p=0.003) and significantly positively correlated with the maximum impact force (p<0.001). The recovery coefficient was significantly negatively correlated with the maximum impact force (p=0.003). However, the collision time was not significantly correlated with the fruit bruise rate, the maximum impact force, or the recovery coefficient (p>0.05). A significant correlation existed between the fruit bruise rate, the maximum impact force, and the recovery coefficient, indicating that the maximum impact force and recovery coefficient can be used to replace the fruit bruise rate to evaluate the bruise severity of *L. barbarum* fruits.

Based on the above, in order to reduce fruit bruise during vibration harvesting, the design of vibration harvester should consider reducing the height between the fruit and the collection surface, reducing the speed at which the fruit is dropped, making the fruit collide with the collection surface at a smaller angle, and using softer collection material.

CONCLUSIONS

This study analyzed the collision bruise during the falling and collection process of *L. barbarum* fruits after vibration harvesting. The following experimental results and conclusions were obtained:

(1) High-speed photography was used to obtain the initial velocity and angle of fruits after vibration harvesting. A kinematic analysis of the fruit's collision with the collection surface was performed. The impact speed of most fruits was 3-6 m/s, and the impact angle was 30-90°.

(2) A drop test was adopted based on fruit impact speed and angle, and an orthogonal rotation experiment was conducted to establish a mathematical model between the drop height, collision angle, collision material, and the fruit bruise rate, maximum impact force, recovery coefficient, and collision time. The collection parameters had significant effects on the fruit bruise rate, maximum impact force, and recovery coefficient, whereas the collision angle had a significant effect on the collision time.

(3) The correlation between the fruit bruise rate, maximum impact force, recovery coefficient, and collision time was analyzed. The experimental results indicated a significant correlation between the fruit bruise rate, maximum impact force, and recovery coefficient. The maximum impact force and recovery coefficient can be used to replace the fruit bruise rate to evaluate the degree of bruising of *L. barbarum* fruits.

(4) This study indicated that reducing the height between the fruit and the collection surface and using a tilted collection surface and materials with high cushioning capabilities substantially reduced fruit bruising during vibration harvesting. The results provide a basis for the research and design of vibration harvesting machines to reduce fruit bruising.

ACKNOWLEDGEMENT

This study was supported by the National Natural Science Foundation of China (32272001) and Key Research and Development Program of Ningxia Hui Autonomous Region (2022BBF01002).

REFERENCES

[1] Ahmadi, E., Ghassemzadeh, H. R., Sadeghi, M., Mohammad, M., & Zarif, N. S. (2010). The effect of impact and fruit properties on the bruising of peach. *Journal of Food Engineering, 97*(1), 110-117. https://doi.org/10.1016/j.jfoodeng.2009.09.024

[2] Bao, Y., Yang, C., Zhao, Y., Zhao, Y., Liu, X., & Guo, Y. (2017). Collision injury assessment of mechanical harvesting blueberry fruit based on collision deformation energy. *Transactions of the Chinese Society of Agricultural Engineering*, *33*(16), 283-292. http://dx.doi.org/10.11975/j.issn.1002-6819.2017.16.037

[3] Bora, P., Ragaee, S., & Abdel-Aal, E-S. M. (2019). Effect of incorporation of goji berry by-product on biochemical, physical and sensory properties of selected bakery products. *LWT*, *112*, 108225. https://doi.org/10.1016/j.lwt.2019.05.123

[4] Bu, L., Hu, G., Chen, C., Sugirbay, A., & Chen, J. (2020). Experimental and simulation analysis of optimum picking patterns for robotic apple harvesting. Scientia *Horticulturae*, *261*, 108937. https://doi.org/10.1016/j.scienta.2019.108937

[5] Celik, H. K. (2017). Determination of bruise susceptibility of pears (Ankara variety) to impact load by means of FEM-based explicit dynamics simulation. *Postharvest Biology and Technology*, *128*, 83-97. http://dx.doi.org/10.1016/j.postharvbio.2017.01.015

[6] Chen, H., Yin, Y., Pan, H., Bao, X., Li, S., Xu, Q., & Xu, X. (2018). Loss factor analysis of mechanical damage and cushioning protection measure for Citrus reticulate Blanco. *Transactions of the Chinese Society of Agricultural Engineering*, *34*(1), https://doi.org/258-266.10.11975/j.issn.1002-6819.2018.01.035

[7] Chen, J., Zhao, J., Chen, Y., Bu, L., Hu, G., & Zhang, N. (2019). Design and Experiment on Vibrating and Comb Brushing Harvester for *Lycium barbarum*. *Transactions of the Chinese Society for Agricultural Machinery*, *50*(01), 152-161+95. https://doi.org/10.6041/j.issn.1000-1298.2019.01.016

[8] Chen, Q., Zhang, S., Hu, G., Zhou, J., Zhao, J., Chen, Y., Chen, J., Gao, S., Chen, Y., & Shi,T. (2022a). Parameter Optimization of the Harvest Method in the Standardized Hedge Cultivation Mode of *Lycium barbarum* Using Response Surface Methodology. *Horticulturae*, *8*(4), 308. https://doi.org/10.3390/horticulturae8040308

[9] Chen, Q., Zhang, S., Wei, N., Li, P., Hu, G., & Chen, J. (2022b). Parameter Optimization of the Swing Harvesting of *Lycium barbarum* L. Based on Response Surface Methodology; *Proceedings of the 2022 Chinese Automation Congress, CAC 2022, November 25, 2022 - November 27, 2022, Xiamen, China,* https://doi.org/10.1109/CAC57257.2022.10055703

[10] Chen, Y., Zhao, J., Hu, G., & Chen, J. (2021). Design and Testing of a Pneumatic Oscillating Chinese L. *barbarum* Harvester. *Horticulturae*, *7*(8), 214. https://doi.org/10.3390/horticulturae7080214

[11] Fu, H., He, L., Ma, S., Manoj, K., Chen, D., Zhang, Q., Wang, S. (2017). 'Jazz' Apple Impact Bruise Responses to Different Cushioning Materials. *Transactions of the ASABE*, *60*(2), 327-36. https://doi.org/10.13031/trans.11946

[12] Guan, X., Li, T., Zhou, F. (2023). Determination of bruise susceptibility of fresh corn to impact load by means of finite element method simulation. *Postharvest Biology and Technology*, *198*, 112227. https://doi.org/10.1016/j.postharvbio.2022.112227

[13] He, M., Kan, Z., Li, C., Wang, L., Yang, L., & Wang, Z. (2017). Mechanism analysis and experiment on vibration harvesting of L. *barbarum*. *Transactions of the Chinese Society of Agricultural Engineering*, *33*(11), 47-53. https://doi.org/10.11975/j.issn.1002-6819.2017.11.006

[14] Hu, G., Bu, L., & Chen, J. (2020). Simulation to determination of significant parameters on apple stress for combing harvesting in trellis trained trees. Scientia *Horticulturae*, *274*, 109654. https://doi.org/10.1016/j.scienta.2020.109654

[15] Hussein, Z., Fawole, O. A., & Opara, U. L. (2019). Bruise damage susceptibility of pomegranates (Punica granatum, L.) and impact on fruit physiological response during short term storage. *Scientia Horticulturae*, *246*, 664-674. https://doi.org/10.1016/j.scienta.2018.11.026

[16] Hussein, Z., Fawole, O. A., & Opara, U. L. (2020). Harvest and Postharvest Factors Affecting Bruise Damage of Fresh Fruits. *Horticultural Plant Journal*, *6*(1), 1-13. https://doi.org/10.1016/j.hpj.2019.07.006

[17] Jarimopas, B., Singh, S. P., Sayasoonthorn, S., & Jagjit, S. (2007). Comparison of package cushioning materials to protect post-harvest impact damage to apples. *Packaging Technology and Science*, *20*(5), 315-24. https://doi.org/10.1002/pts.760

[18] Linden, V. V., Ketelare, D. B., Desmet, M., & Baerdemaeker, D. J. (2006). Determination of bruise susceptibility of tomato fruit by means of an instrumented pendulum. *Postharvest Biology and Technology*, *40*(1), 7-14. http://dx.doi.org/10.1016/j.postharvbio.2005.12.008

[19] Ma, A., Carradori, S., Casadei, M. A., Paolicelli, P., Petralito, S., Ragno, R., & Cesa, S. (2018). *Lycium barbarum* polysaccharides: Extraction, purification, structural characterisation and evidence about hypoglycaemic and hypolipidaemic effects. A review. *Food Chemistry*, *254*, 377-389. https://doi.org/10.1016/j.foodchem.2018.01.176

[20] Ma, R., Zhang, X., Thakur, K., Zhang, J., & Wei, Z. (2022). Research progress of *Lycium barbarum* L. as functional food: phytochemical composition and health benefits. *Current Opinion in Food Science*, *47*, 100871. https://doi.org/10.1016/j.cofs.2022.100871

[21] Opara, U., & Pathare, P. (2014). Bruise damage measurement and analysis of fresh horticultural produce—A review. *Postharvest Biology and Technology*, *91*, 9-24. http://dx.doi.org/10.1016/j.postharvbio.2013.12.009

[22] Öztekin, Y., & Gungor, B. (2020). Determining impact bruising thresholds of peaches using electronic fruit. *Scientia Horticulturae*, *262*, 109046. https://doi.org/10.1016/j.scienta.2019.109046

[23] Shen, T., Zhou, X., Shi, J., Li, Z., Huang, X., Xu, Y., & Chen, W. (2016). Determination Geographical Origin and Flavonoids Content of L. *barbarum* Using Near-Infrared Spectroscopy and Chemometrics. *Food analytical methods*, *9*, 68-79. https://doi.org/10.1007/s12161-015-0175-x

[24] Skenderidis, P., Lampakis, D., Giavasis, I., Leontopoulos, S., Petrotos, K., Hadjichristodoulou, C., & Tsakalof, A. (2019). Chemical Properties, Fatty-Acid Composition, and Antioxidant Activity of L. *barbarum* (*Lycium barbarum* L. and *Lycium* chinense Mill.) Fruits. *Antioxidants*, *8*(3), 60. https://doi.org/10.3390/antiox8030060

[25] Stropek, Z., & Golacki, K. (2020). Bruise susceptibility and energy dissipation analysis in pears under impact loading conditions. *Postharvest Biology and Technology*, *163,* 111120. https://doi.org/10.1016/j.postharvbio.2020.111120

[26] Wang, W., Zhang, S., Fu, H., Lu, H., & Yang, Z. (2020). Evaluation of litchi impact damage degree and damage susceptibility. *Computers and Electronics in Agriculture*, *173*, 105409. https://doi.org/10.1016/j.compag.2020.105409

[27] Xia, M., Zhao, X., Wei, X., Guan, W., Wei, X., Xu, C., Mao, L. (2020). Impact of packaging materials on bruise damage in kiwifruit during free drop test. *Acta Physiologiae Plantarum*, *42*(7), 119. https://doi.org/10.1007/s11738-020-03081-5

[28] Xiao, Z., Deng, Q., Zhou, W., & Zhang, Y. (2022). Immune activities of polysaccharides isolated from *Lycium barbarum* L. What do we know so far?. *Pharmacology & Therapeutics*, *229*, 107921. https://doi.org/10.1016/j.pharmthera.2021.107921

[29] Xu, R., Takeda, F., Krewer, G., & Li, C. (2015). Measure of mechanical impacts in commercial blueberry packing lines and potential damage to blueberry fruit. *Postharvest Biology and Technology*, *110*, 103-113. http://dx.doi.org/10.1016/j.postharvbio.2015.07.013

[30] Zhang, W., Zhang, M., Zhang, J., & Li, W. (2018). Design and experiment of vibrating L. *barbarum* harvester. *Transactions of the Chinese Society for Agricultural Machinery*, *49*(7), 97-102. https://doi.org/10.6041/ j.issn.1000-1298.2018.07.012

[31] Zhao, J., Ma, T., Inagaki, T., Chen, Q., Gao, Z., Sun, L., Cai, H., Chen, C., Li, C., Zhang, S., Tsuchikawa, S., & Chen, J. (2021). Finite Element Method Simulations and Experiments of Detachments of *Lycium barbarum* L. *Forests*, *12(6)*, 699. https://doi.org/10.3390/f12060699

[32] Zhao, J., Sugirbay, A., Chen, Y., Zhang, S., Liu, F., Bu, L., Chen, Y., Wang, Z., & Chen, J. (2019). FEM explicit dynamics simulation and NIR hyperspectral reflectance imaging for determination of impact bruises of *Lycium barbarum* L. *Postharvest Biology and Technology*, *155*, 102-110. https://doi.org/10.1016/j.postharvbio.2019.05.024

[33] Zhou, J., He, L., Karkee, M., & Zhang, Q. (2016). Effect of catching surface and tilt angle on bruise damage of sweet cherry due to mechanical impact. *Computers and Electronics in Agriculture*, *121*, 282-289. https://doi.org/10.1016/j.compag.2016.01.004

[34] Zulkifli, N., Hashim, N., Harith, H. H., & Shukery, M. F. M. (2020). Finite element modelling for fruit stress analysis - A review. *Trends in Food Science & Technology*, *97*, 29-37. https://doi.org/10.1016/j.tifs.2019.12.029