PARAMETER OPTIMISATION AND EXPERIMENT ON THE COMBING OF *Cerasus humilis*
/
钙果梳脱部件参数优化与试验

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ABSTRACT

In this paper, the mechanical injury evaluation standard of Cerasus humilis was established based on extrusion deformation energy and fruit storage days. The key factors affecting extrusion deformation were determined by analysing the contact force during combing. The single-factor test and three-factor, three-level quadratic regression orthogonal test were carried out by using the fruit removal rate and damage rate as the evaluation indices and the comb distance, combing speed and comb rod radius as the influencing factors. Results showed that the fruit removal rate decreased and the damage rate initially decreased and then increased with the increase in comb distance; with the increase in combing speed, the fruit removal rate remained unchanged and the damage rate increased; with the increase in comb rod radius, the fruit removal rate initially increased and then decreased, while the damage rate initially decreased and then increased. The order of influence on the fruit removal rate was comb rod radius > comb distance > combing speed. The order of influence on the damage rate was combing speed > comb distance > comb rod radius. Response surface methodology obtained the following optimal parameters: comb distance of 9 mm, combing speed of 340 mm/s and comb rod radius of 8 mm. A validation test was carried out on a combing test bench under the optimised parameters. The fruit removal rate was 96.89% and the damage rate was 6.36%. These values were consistent with the results of optimum parameters; thus, the regression model was reliable.

摘要

本文基于挤压变形能和果实存放天数，建立钙果机械损伤评价标准，分析钙果在梳脱过程中的接触受力，确定影响挤压变形的关键因素。以脱净率和损伤率为评价指标，以梳齿间距、梳脱速度和梳齿杆半径为影响因素分别进行单因素试验和三因素三水平二次回归正交试验，结果表明：当梳齿间距增大时，脱净率降低，损伤率先减小后增加；梳脱速度增加时，脱净率基本保持不变，损伤率逐渐增大；梳齿曲率半径增加时，脱净率先增加后减小，损伤率先减小后增加。对脱净率的影响显著顺序为：曲率半径>梳齿间距>梳脱速度；对损伤率的影响显著顺序为：梳脱速度>梳齿间距>曲率半径。基于响应面法进行参数优化，得到最佳组合参数：梳齿间距为9 mm，梳脱速度为340 mm/s，曲率半径为8 mm。以优化后的参数组合，在梳脱试验台上进行验证试验，其结果为：脱净率96.89 %，损伤率6.36 %，与优化参数结果基本吻合，回归模型可靠。

INTRODUCTION

Cerasus humilis is a unique fruit tree resource in China. It has high calcium content in pulp and a developed root system, so it has high development potential. *C. humilis* fruits are small and numerous, and their bushes are low and lodging. Fruits rot in 10–20 days after ripening if not harvested on time, result in serious economic losses. Large-scale planting bases need to employ a large number of manpower, which restricts large-scale development. Therefore, studies on the mechanised harvesting of *C. humilis* are necessary and the harvesting components are the primary research contents for designing *C. humilis* harvester.

Extensive research has been made on picking small berries. The vibration principle is mainly used in the literature. A vibration rod is used to knock fruit off or vibrate the trunk of the plant to cause fruit swing and loss *(Peterson et al., 1997; Peterson et al., 2003; Wang et al., 2009)*. *C. humilis* branches are soft and easy to lodge, which is not conducive to vibration transmission. Therefore, harvesting devices must be designed depending on the growth characteristics of *C. humilis*. The double-roller stripping device of *C. humilis* adopts the method of staged harvesting. Branches are cut off, collected and transported to the stripping device. The fruit is stripped off by the impact of the pick roller. This harvesting method damages the branches and easily affects the quality of newly germinated basal shoots in the next year, thereby reducing yield *(Liu., 2014; Sun., 2016)*. Comb-type *C. humilis* harvester has a high removal rate and low damage rate, which indicates that the comb stripping method can meet the requirements of *C. humilis* harvesting *(Zhang et al., 2018)*. The comb structure is widely used in cutting tables and the threshing mechanism of rice, rape, camellia and other crops *(Yuan et al., 1998; Chen et al., 1999; Ji et al., 2016; Gao et al., 2013)*. The clearance of comb rod is larger than the stalk diameter but smaller than the fruit diameter. Fruits are picked by the impact force of the comb rod *(Zhang et al., 2014)*. Research on the root soil-removing device of knotweeds shows that it is effective in separating roots and soils by using the linear comb-type soil-removing roller finger *(Chen et al., 2015)*. In the field of edible chrysanthemum harvesting, combs can also be used to achieve differential harvesting *(Ji et al., 2016; Ji et al., 2017)*. Combs can apply vibration to improve the harvesting efficiency *(Xu et al., 2018)*. The comb does not directly act on branches during fruit removal, which can reduce damage to branches *(Li et al., 2015)*, but directly acts on fruits, which may increase the damage of *C. humilis* and lead to fruit leakage.

Considering that the comb stripping method meets the requirements of *C. humilis* harvesting, this study analysed the comb as the end-effector of *C. humilis* harvester. To improve the removal rate and reduce the damage rate of *C. humilis*, the combing parameters were optimised to provide reference for the design and optimisation of *C. humilis* harvesting machinery.

MATERIALS AND METHODS

Materials

Sampling was conducted on September 15, 2017. The sampling site was Juxin Modern Agriculture Base in Taigu County, Shanxi Province, China (E 112°29′, N 37°23′), and the variety was 'Nongda 4'. At this time, *C. humilis* of this variety matured for 3–4 days and was in the stage of large-scale harvesting. The average diameter of roots was 6.78 mm, whereas the average diameter of fruits was 21.56 mm. The average damage force was 24.6 N, whereas the average fruit removal force was 8.82 N.

Instrument and device

The experiment was carried out on a self-made experiment bench to simulate the combing process with the simplest structure. The device is shown in Fig. 1. The setup included a frame, comb rod fixture, five sets of combing devices with different specifications (self-made) and branch traction device (self-made).

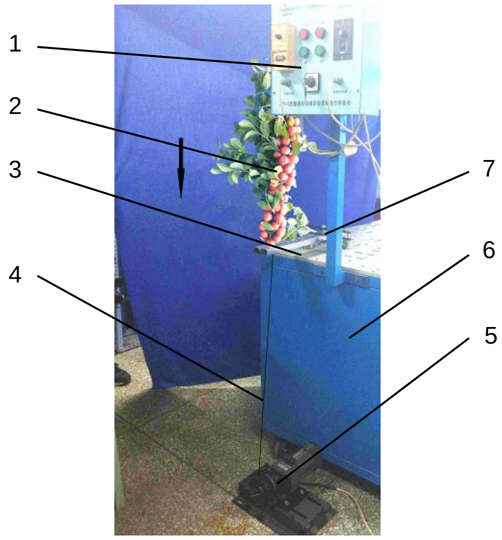


Fig. 1 - Experimental device of fruit comb threshing

1- Speed control panel; 2- Branch with fruits; 3- Comb rods; 4- Wire rope; 5- Gear motor; 6- Frame; 7- Comb rod fixture

The combing device was mainly composed of comb rods and their fixture. The comb rods were circular pipes and the fixture included the base, gap adjusting block and pressing plate. The base and pressing plate were fixed on the frame by bolts and two rods were placed horizontally in the middle. The gap adjusting block was placed between the rods. The structure was used to fix the rod and adjust the gap between the rods. The clamping diameter of the device was 0–30 mm, whereas the gap adjustment ranged from 0 mm to 40 mm.

The branch traction device mainly consisted of a winch, wire rope and speed reduction motor (90YYJ-60). The winch was fixed on the output shaft of the reducer motor and placed directly below the comb rods to ensure that the wire rope drew branches vertically through the clearance of the comb rods. Before the test, a circular groove was made at the root of the branch to prevent the branch from slipping, and the other end of the wire rope was connected with the winch. The speed range of the traction device was 0–800 mm/s.

Experimental factor

The clearance of comb rods was larger than the branch diameter but smaller than the diameter of *C. humilis*. When the comb rods moved relative to the branches, the calcium fruit branches were combed. Previous experiments found that the fruit was extruded under the force of comb rods, which resulted in the fruit being stuck in the crack of comb teeth, causing damage or leakage.

As shown in Fig. 2, the force of comb rod on fruit was T, and its vertical and horizontal components were as follows:

$$\begin{cases} T_y = T \cdot \sqrt{1 - \left(\dfrac{D+2R_1}{d+2R_1}\right)^2} \\ T_x = T \cdot \dfrac{D+2R_1}{d+2R_1} \end{cases} \tag{1}$$

Where:

T is the force of comb rod on fruit, [N];

Ty is the vertical force of comb rod on fruit, [N];

Tx is the horizontal force of comb rod on fruit, [N];

d is *C. humilis* diameter, [mm];

D is Comb distance, [mm];

R_1 is Comb curvature radius, [mm].

In order to shed the fruit, it is necessary to satisfy the following requirements:

$$2T_y \geq F \tag{2}$$

Where:

F is fruit removal force, [N].

So：

$$T \geq \frac{F}{2} \cdot \frac{1}{\sqrt{1 - \left(\dfrac{D+2R_1}{d+2R_1}\right)^2}} \tag{3}$$

On the right side of the inequality is the critical force that the comb rods need to remove fruits, which is related to comb distance D and comb rod radius R_1. A large comb distance D and comb rod radius R_1 correspond to high critical force, which can easily damage fruits and is not conducive to the combing operation.

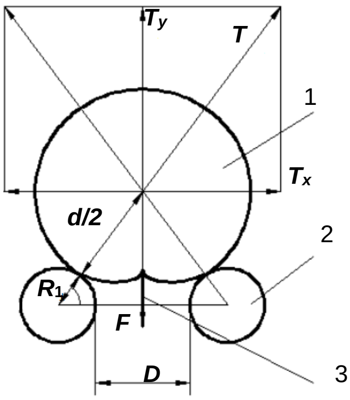


Fig. 2 - Forces on *C. humilis* fruit

1- C. humilis ; 2- Comb rods; 3- Stalk

With *C. humilis* as the research object, the following assumptions were made *(Bao et al., 2017)*: *C. humilis* was simplified into homogeneous and isotropic spheres. Its deformation was much smaller than its size, and its contact surface was continuous and uncoordinated. When the fruit came into contact with the comb rod, as shown in Fig. 3, deformation δ occurred in the two contact centres. The force between them is T, and δ is as follows:

$$\delta = \left(\frac{9P^2}{16RE^{*2}} \right)^{1/3} \tag{4}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{5}$$

$$\frac{1}{E^*} = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \tag{6}$$

Where:

δ is extrusion deformation, [mm];
T is contact force between fruit and comb rod, [N];
R is equivalent radius, [mm];
E^* is equivalent modulus of elasticity, [MPa];
R_1 is comb rod radius, [mm];
R_2 is fruit radius, [mm];
μ_1 is Poisson ratio of fruits;
μ_2 is Poisson ratio of comb rod;
E_1 is Elastic modulus of fruit, [MPa];
E_2 is Elastic modulus of comb rod, [MPa].

To prevent the fruit from becoming stuck in the comb gap, it is necessary to make:

$$2\delta \frac{2R_1 + D}{2R_1 + d} \le d - D \tag{7}$$

So:

$$T \le \sqrt{\frac{16RE^{*2}(d-D)^3}{9\left(2\frac{D+2R_1}{d+2R_1}\right)^3}} \tag{8}$$

On the right side of the inequality is the critical force that does not produce leakage, which is related to D and R_1. A small D and R_1 correspond to high critical force. Fruit cannot easily become stuck in the comb clearance, which is conducive to the combing operation.

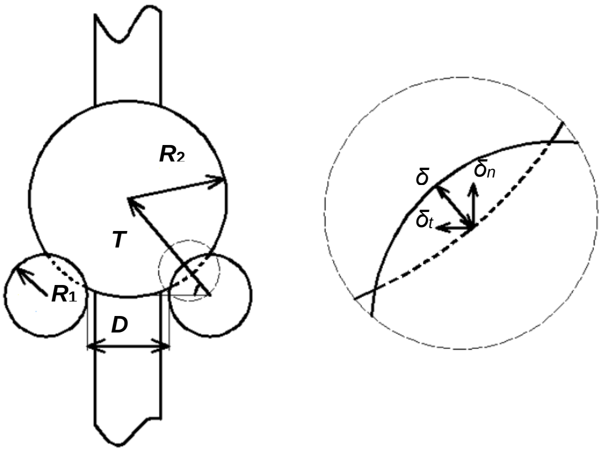


Fig. 3 - Extrusion force schematic of fruits and comb rods

The combing speed was found to affect extrusion between *C. humilis*. Therefore, the experimental factors selected in this paper were D, R_1 and combing speed.

Performance evaluation of combing

a. No compression deformation

b. Causing compression deformation

Fig. 4 - Schematic of C. humilis combing deformation

Apart from breaking, some fruits decay and deteriorate at 1–2 days after combing. This phenomenon is caused by damage of the internal structure of the fruit, and mechanical damage occurs before the fruit breaks down, as shown in Fig. 4. On the basis of the relationship between collision deformation energy and fruit collision damage, the work done by the compression force in the direction of compression deformation is transformed into fruit deformation energy. When fruit deformation accumulates a certain value, the fruit suffers from mechanical damage *(Bao et al., 2017)*.

C. humilis fruits were selected as samples and the quasi-static compression test was carried out by using a CMT-6104 computer-controlled electronic universal testing machine (Shenzhen New Sans Material Testing Co., Ltd., accuracy ±5% and resolution ±100 000 yards). The test fruits were placed on a plane and compressed using a flat-plate indenter. The loading rate was 20 mm/min and the maximum loading displacement was 10 mm. The deformation–force curve was obtained as shown in Fig. 5. Assuming that the deformation curve equation is $F=F(\Delta)$, then

$$E = \int_0^{\Delta} F(\Delta) d\Delta \qquad (9)$$

Where: Δ is fruit deformation, [mm];

E is fruit deformation energy, [J];

F is a deformation curve equation.

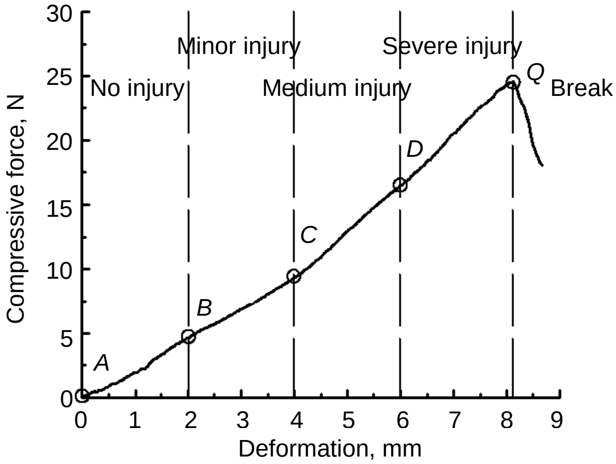


Fig. 5 - Deformation–force curve of *C. humilis*

After the samples were removed from the testing machine, the softening degree of the compressed part was assessed based on the deformation of each stage and the damage degree was determined. In curve *AB* segment, the storage deformation energy of fruit was low and the fruit was not damaged. Mechanical damage occurred when the sample was compressed to point *B*. In curve *BC* segment, the fruit softened slightly, resulting in minor damage. In curve *CD* segment, the fruit softened moderately, resulting in medium damage. In curve *DQ* segment, the fruit softened severely, resulting in severe damage. When compressing the sample to point *Q*, the fruit broke, fruit deformations increased, but stress decreased sharply. On the basis of fruit deformation energy and storage time after compression, the mechanical injury evaluation standard of *C. humilis* was obtained (Table 1).

Table 1

Mechanical injury evaluation standard of *C. humilis*

Position on curve	Deformation *Δ*	Deformation energy *E*	Injury evaluation	Storage time
	[mm]	[10^{-3}J]	[m/s]	[d]
AB	0~2	0~4.20	No injury	>10
BC	2~4	4.20~17.99	Minor injury	7~10
CD	4~6	17.99~43.75	Medium injury	3~4
DQ	6~8.1	43.75~87.81	Severe injury	0~1
Q	>8.1	>87.81	Break	0

C. humilis fruits with minor and severe injuries were selected and placed for 24 h for observation and comparison, as shown in Fig. 6. The fruit with minor injury was still bright in appearance. Beside the contact zone, the pulp could maintain its original firmness (Fig. 6a). After cutting the fruit, the boundary between the pulp and core was obvious (Fig. 6c). The colour of the subcutaneous pulp in the contact deformation area became dark. This finding indicated that the pulp in the extrusion area was damaged. The appearance of severely injured fruits became dark and soft, as shown in Fig. 6b. After cutting the fruit, as shown in Fig. 6d, no obvious boundary was observed between the pulp and core. This finding suggested that the fruit was close to deterioration at this time and it was likely to break up during transportation. This phenomenon was considered fruit damage.

a. Appearance of minor injury *b. Appearance of severe injury*

c. Section of minor injury *d. Section of severe injury*

Fig. 6 - Internal injury comparison of *C. humilis*

Therefore, in this experiment, the fruit removal rate *μ* and damage rate *η* were selected as the evaluation indices of combing performance.

$$\mu = \frac{N_1}{N} \tag{10}$$

$$\eta = \frac{N_2 + N_3}{N_1} \tag{11}$$

Where:

μ is the fruit removal rate, [%];
η is the damage rate, [%];
N is the total number of fruits on the branch before the experiment.
N_1 is the number of fruits removed;
N_2 is the number of fruits that have been broken;
N_3 is the number of deteriorated fruits after 24 hours.

Experiment design

Design of single factor experiment

To clarify the effects of comb distance, combing speed and comb rod radius on the fruit removal rate and damage rate, single-factor experiments were designed. The experimental factors and levels are shown in Table 2.

Table 2

Scheme of single factor experiment

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Comb distance [mm]	8	9	10	11	12	10					10				
Combing speed [mm/s]	300					200	250	300	350	400	300				
Comb rod radius[mm]	8					8					4	6	8	10	12

Design of orthogonal experiment

To study the influences of interactive factors on the performance of combing, a three-factor, three-level orthogonal experiment was carried out based on the Box–Behnken centre combination method *(Golub et al., 2018)*. Comb distance, combing speed and comb rod radius were used as factors. Fruit removal rate and damage rate were utilised as indices. The experimental factors and levels are shown in Table 3.

Table 3

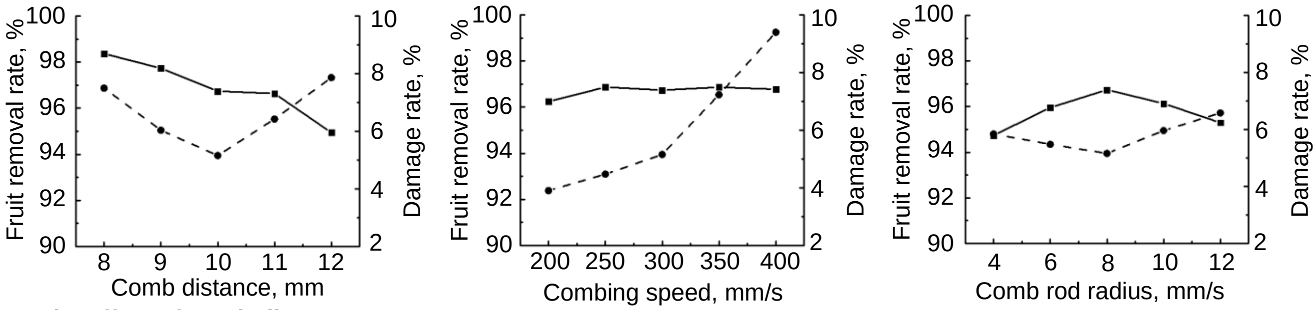
Coding schedule of experimental factors

Coded value	Comb distance [mm]	Combing speed [mm/s]	Comb rod radius [mm]
	X_1	X_2	X_3
Lower level (-1)	8	200	4
Middle level (0)	10	300	8
Upper level (1)	12	400	12

RESULTS

Results and analysis of single factor experiment

The results of the single-factor experiment are shown in Fig. 7. Fig. 7a shows the relationship between comb distance and the fruit removal rate and damage rate. As the comb distance increased, the fruit removal rate decreased from 98.36% to 94.94% and the damage rate decreased from 7.50% to 5.16% and then increased to 7.86%. Fig. 7b shows the relationship between combing speed and the fruit removal rate and damage rate. With the increase in combing speed, the variation trend of the fruit removal rate was not obvious, and the difference between the maximum and minimum values of the fruit removal rate was only 0.63%. The damage rate increased from 3.90% to 9.40%. Fig. 7c shows the relationship between comb rod radius and the fruit removal rate and damage rate. With the increase in comb rod radius, the fruit removal rate increased from 94.74% to 96.74% and then decreased to 95.30%, whereas the damage rate decreased from 5.84% to 5.16% and then increased to 6.58%.



a. The effect of comb distance on lifting ***b. The effect of combing speed on lifting*** ***c. The effect of comb rod radius on lifting***

■ Fruit removal rate ● Damage rate

Fig. 7 - Results of single-factor experiment

Results and analysis of orthogonal experiment

Orthogonal experiments were designed by Design Expert software based on the Box–Behnken centre combination method. The experimental results are shown in Table 4, and the findings of variance analysis are shown in Table 5. The quadratic regression models of the fruit removal rate μ and damage rate η were extremely significant, while the lack of fit was not significant. The determinant coefficients R^2 of the regression equation were 0.9475 and 0.9943. The predicted values of the regression model fitted well with the actual values. The regression model could be used to predict and analyse the effects of comb distance, combing speed and comb rod radius on the fruit removal rate and damage rate.

The quadratic polynomial regression models among the comb distance, combing speed, comb rod radius and fruit removal rate and damage rate were established. After eliminating the insignificant factors, the regression equation was obtained as follows:

$$\mu = 96.74 - 2.04X_1 + 0.42X_3 - 0.76X_1X_3 - 2.23X_3^2 \tag{12}$$

$$\eta = 5.16 + 2.84X_2 + 0.38X_3 - 0.24X_1X_2 - 0.23X_2X_3 + 2.21X_1^2 + 1.62X_2^2 + 1.14X_3^2 \tag{13}$$

Where:

X_1 is comb distance, [mm];
X_2 is combing speed, [mm/s];
X_3 is comb rod radius, [mm];
μ is the fruit removal rate, [%];
η is the damage rate, [%].

Table 4

The orthogonal experimental results

No.	Comb distance X_1 [mm]	Combing speed X_2 [mm/s]	Comb rod radius X_3 [mm]	Fruit removal rate μ [%]	Damage rate η [%]
1	-1	-1	0	98.57	5.89
2	1	-1	0	95.15	6.18
3	-1	1	0	98.17	12.26
4	1	1	0	94.02	11.61
5	-1	0	-1	94.86	8.16
6	1	0	-1	91.98	8.21
7	-1	0	1	97.51	8.93
8	1	0	1	91.61	8.74
9	0	-1	-1	94.73	4.53
10	0	1	-1	94.26	10.44
11	0	-1	1	95.24	5.85
12	0	1	1	94.83	10.83
13	0	0	0	96.48	4.89
14	0	0	0	97.12	5.05
15	0	0	0	96.69	5.28
16	0	0	0	96.07	5.34
17	0	0	0	97.33	5.22

Table 5

ANOVA

Sources	DF	MS	*F* Value	*P* Value	Sources	DF	MS	*F* Value	*P* Value
Model 1	9	6.74	33.06	<0.0001**	**Model 2**	9	11.89	313.06	<0.0001**
X_1	1	33.42	163.88	<0.0001**	X_1	1	0.031	0.82	0.3945
X_2	1	0.73	3.56	0.1011	X_2	1	64.35	1694.21	<0.0001**
X_3	1	1.41	6.92	0.0339*	X_3	1	1.13	29.81	0.0009**
$X_1 X_2$	1	0.31	0.65	0.4455	$X_1 X_2$	1	0.22	5.82	0.0467*
$X_1 X_3$	1	2.28	11.18	0.0124*	$X_1 X_3$	1	0.014	0.38	0.5576
$X_2 X_3$	1	0.0009	0.004	0.9489	$X_2 X_3$	1	0.22	5.69	0.0485*

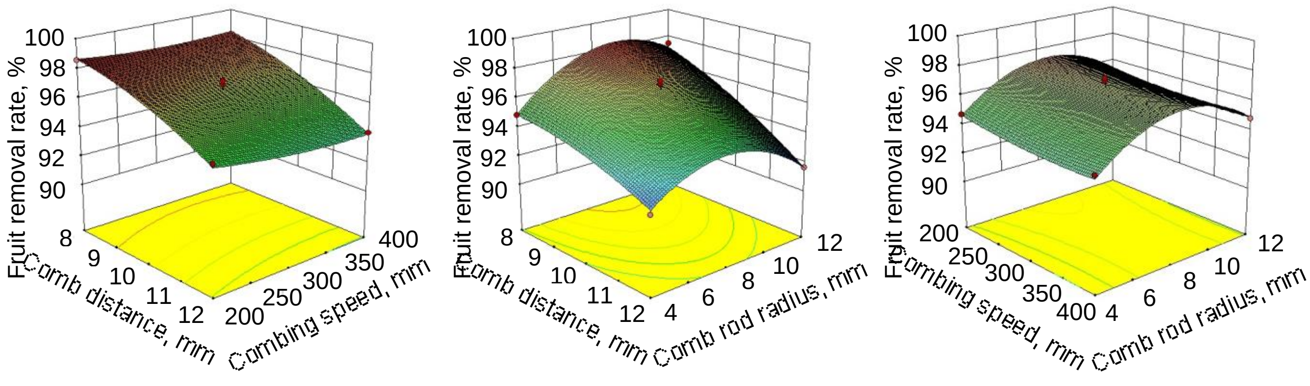
Sources	DF	MS	*F* Value	*P* Value	Sources	DF	MS	*F* Value	*P* Value
X_1^2	1	1.13	5.54	0.0509	X_1^2	1	20.63	542.98	<0.0001**
X_2^2	1	0.28	1.37	0.2807	X_2^2	1	10.99	289.38	<0.0001**
X_3^2	1	20.94	102.71	<0.0001**	X_3^2	1	5.48	144.25	<0.0001**
Residual	7	0.20			**Residual**	7	0.038		
Lack of Fit	3	0.14	0.55	0.6756	**Lack of Fit**	3	0.044	1.29	0.3932
Pure Error	4	0.25			**Pure Error**	4	0.034		
Total	16				**Total**	16			

*Note: P < 0.01 (extremely significant, **), P < 0.05 (significant, *);*
Model 1 is variance analysis of fruit removal rate;
Model 2 is variance analysis of damage rate.

Analysis of the effect of experimental factors on fruit removal rate

The response surface of comb distance X_1, combing speed X_2 and comb rod radius X_3 to the fruit removal rate μ is shown in Figs. 8a–8c. When the comb rod radius was 8 mm, the fruit removal rate decreased with the increase in comb distance and combing speed. However, the variation range of the response surface along the comb distance was large indicating that the comb distance had more influence than the combing speed (Fig. 8a). When the combing speed was 300 mm/s, the fruit removal rate decreased with the increase in comb distance. With increased comb rod radius, the fruit removal rate increased initially before decreasing obviously with the increase in comb rod radius, indicating that the comb rod radius had a larger effect on the fruit removal rate than the comb distance (Fig. 8b). When the comb distance was 10 mm, the fruit removal rate initially increased before decreasing, and the effect of combing speed on the fruit removal rate was not obvious (Fig. 8c).

As indicated by the change range of the response value of the experimental factors to the fruit removal rate, the order of influence of the experimental factors on the fruit removal rate was $X_3 > X_1 > X_2$. The overall influence trend was that the comb distance X_1 was small and the comb rod radius was moderate, thereby increasing the fruit removal rate. During combing, *C. humilis* fruits were extruded inward by the comb rod. With the increase in comb distance, the transverse deformation increased, which easily led to fruit leakage. When the comb rod radius was small, the comb rods easily deformed and the comb distance was difficult to guarantee, which indirectly resulted in the increase in comb distance. When the comb rod radius was large, the position of *C. humilis* fruits in the comb rod was ‘deep’, and fruits easily became stuck in the comb rod clearance. Fruit stuck in clearance played the role of combing other fruits on the branch, and leaked out under the extrusion of the adjacent fruits. The effect of combing speed on the fruit removal rate was not obvious.



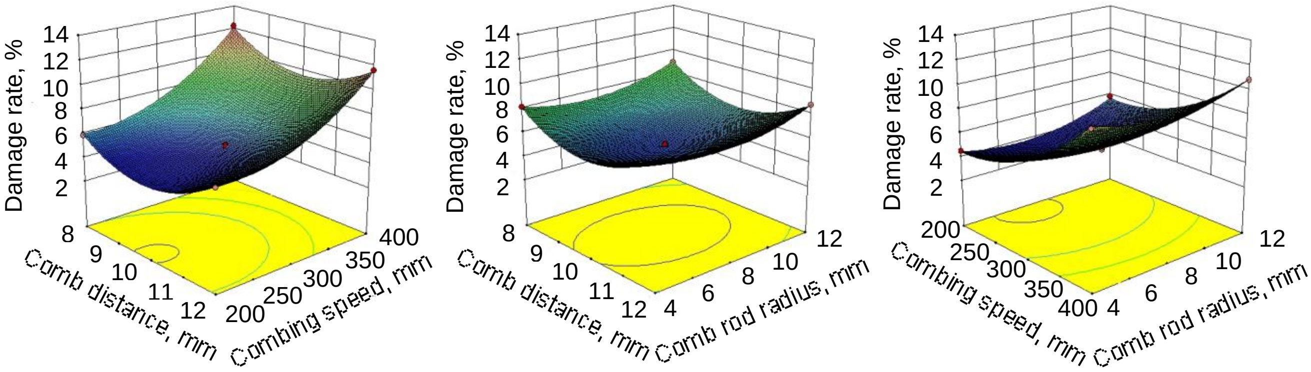
a.$\mu(X_1,X_2,8)$ **b.$\mu(X_1,300,X_3)$** **c.$\mu(10,X_2,X_3)$**

Fig. 8 - Response surface of various factors on the fruit removal rate

Analysis of the effect of experimental factors on damage rate

The response surface of comb distance X_1, combing speed X_2 and comb rod radius X_3 to the damage rate η is shown in Figs. 9a–9c. When the comb rod radius was 8 mm, the damage rate decreased first and then increased with the increase in comb distance and increased considerably with the increase in combing speed (Fig. 9a). When the combing speed was 300 mm/s, the damage rate decreased first and then increased with the increase in comb distance and comb rod radius (Fig. 9b). When the comb distance was 10 mm, the damage rate increased with the increase in combing speed, and the damage rate decreased first and then increased with the increase in comb rod radius (Fig. 9c).

As indicated by the change range of the response value of the experimental factors to the damage rate, the order of the experimental factors influence on the damage rate was $X_2 > X_1 > X_3$. The overall influence trend was that the damage rate was low when X_1 and X_3 were moderate and the combing speed was slow. When the comb distance is small, fruit discharge hardly occurs but, blockage of the comb rod may easily occur and increase fruit damage. When the comb distance is large, fruits can easily become stuck in the comb rod clearance, resulting in internal damage of fruit. A high combing speed corresponds to an obvious extrusion effect between fruits, resulting in fruit damage. When the comb rod radius is small, the extrusion stress of comb rod on fruit is large, and the fruit is easily damaged. When the comb rod radius is large, the angle between the extrusion force and horizontal direction decreases, and the transverse deformation of fruit increases, thereby increasing the damage rate.



a.η(X1,X2,8) ***b.η(X1,300,X3)*** ***c.η(10,X2,X3)***

Fig. 9 - Response surface of various factors on damage rate

Parameter optimisation and validation

To ensure enhanced performance of the combing parts, this paper aimed to achieve a high fruit removal rate, low damage rate and high efficiency and optimised combing parts. The optimal numerical module in Design Expert software was used to solve the optimisation problem. Its objective function and constraints are as follows:

$$\begin{cases} \max Y_1 \\ \min Y_2 \\ \max X_2 \\ X_1 \in [8\text{mm},12\text{mm}] \\ X_3 \in [4\text{mm},12\text{mm}] \end{cases} \tag{14}$$

After optimisation, the optimum combination of parameters was obtained as follows: comb distance of 9.29 mm, combing speed of 335.4 mm/s, comb rod radius of 8.22 mm. Predicted value of the fruit removal rate was 97.37% and damage rate was 6.71%.

The validation test was carried out on a fruit comb threshing experimental device with parameter combination (the comb distance was 9 mm, the combing speed was 340 mm/s and the comb rod radius was 8 mm). The experiment was repeated five times to obtain the average value. Results showed that the fruit removal rate was 96.89% and the damage rate was 6.36%. These values were consistent with the result of optimisation parameters. Moreover, the regression model was reliable.

CONCLUSIONS

1) The mechanical injury evaluation standard of *C. humilis* was established based on the extrusion deformation energy and fruit storage days. The contact force of *C. humilis* during combing was analysed. The key factors affecting extrusion deformation were comb distance, combing speed and comb rod radius.

2) The results of single-factor experiment showed that the fruit removal rate decreased, and the damage rate first decreased and then increased with the increase in comb distance. The fruit removal rate remained unchanged, and the damage rate gradually increased with the increase in combing speed. The fruit removal

rate first increased and then decreased with the increase in comb rod radius, and the damage rate first decreased and then increased.

3) Response surface analysis demonstrated that the order of influence on the fruit removal rate was comb rod radius > comb distance > combing speed, and the order of influence on the damage rate was combing speed > comb distance > comb rod radius.

4) With high fruit removal rate, low damage rate and high work efficiency as optimisation objectives, the following optimum parameters were obtained: comb distance of 9.29 mm, combing speed of 335.4 mm/s, comb rod radius of 8.22 mm. Predicted value of the fruit removal rate was 97.37% and damage rate was 6.71%. With the optimised parameters (comb distance of 9 mm, combing speed of 340 mm/s and comb rod radius of 8 mm), the validation experiment was carried out. The results showed that the fruit removal rate was 96.89% and the damage rate was 6.36%, which were basically consistent with the optimised parameters, Moreover, the regression model was reliable.

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REFERENCES

[1] Bao Y.D., (2017), Collision injury assessment of mechanical harvesting blueberry fruit based on collision deformation energy. *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 33, Issue 16, pp. 283-292;

[2] Chen S.R., (1999), Process simulation on stripping rotor with triangle plate teeth. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol.15, Issue 1, pp. 59-62, Beijing/P.R.C;

[3] Chen X.S., (2015), Design and experiment of roots-soil separating device of knotweeds. *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 46, Issue 7, pp. 59-65, Beijing/P.R.C;

[4] Golub G.A., (2018), Research on a boiler furnace module effectiveness working on small fracture wastes. *INMATEH-Agricultural Engineering*, Vol. 55, No.2, pp.9-18, Bucharest/Romania;

[5] Gao Z.C., (2013), Development and test of picking actor in oil-tea camellia fruit picking machine of tooth comb type. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol. 29, Issue 10, pp. 19-25, Beijing/P.R.C;

[6] Ji C.Y., (2016), Structure design and experiment of hand-push chrysanthemum morifolium comb-teeth picking machine. *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 47, Issue 7, pp. 143-150, Beijing/P.R.C;

[7] Ji C.Y., (2017), Design and experiment of shear-sucting mountain chrysanthemum picking machine. *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 48, Issue 11,pp. 137-145, Beijing/P.R.C;

[8] Ji M.Y., (2016), Design of rapeseed harvester combined stripping table with cutting table. *Journal of Huazhong Agricultural University*, Vol. 35, Issue 5, pp. 117-124, Beijing/P.R.C;

[9] Li C., (2017). Design and experiment of wine grape trellis travelling stripping platform. *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 48, Issue 2, pp. 98-103, Beijing/P.R.C;

[10] Liu H.F., (2013), Experimental study on technical parameters of Cerasus humilis picking device. *Journal of Shanxi Agricultural University (Natural Science Edition)*, Vol.33, Issue 4, pp. 342-345, Jinzhong/ P.R.C;

[11] Peterson D L., (1997), Fresh market quality blueberry harvester. *Transactions of the ASAE*, Vol. 40, Issue 3, pp.535-540, WA/USA;

[12] Peterson D L., (2003), Fresh-Market Quality Tree Fruit Harvester Part I: Sweet Cherry. *Applied Engineering in Agriculture*, Vol. 19, Issue 5, pp.539-544, WA/USA;

[13] Sun Z.B., (2016), Experiment on physical parameter and biomechanical properties of Cerasus humilis 5. *Agricultural Engineering*, Vol.6, Issue 2, pp. 1-4, Beijing/P.R.C.

[14] Wang Y.C., (2009). Optimization of parameters of blackcurrant harvesting mechanism. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol. 25, Issue 3, pp.79-83, Beijing/P.R.C;

[15] Xu L.M., (2018). Design and operating parameter optimization of comb brush vibratory harvesting device for wolfberry. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol. 34, Issue 9, pp. 75-82, Beijing/P.R.C;

[16] Yuan J.N., (1998). Researches of the theory for stripping harvester design. *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 29, Issue 2, pp. 37-43, Beijing/P.R.C;

[17] Zhang W., (2018). Simulation analysis and experiment of combing pluck of Cerasus humilis. *Agricultural Engineering*, Vol.8, Issue 5, pp.89-94, Beijing/P.R.C;

[18] Zhang Z.L., (2014). Design and experiment of corn stripping monomer mechanism. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, Vol. 30, Issue 20, pp. 1-9, Beijing/P.R.C;