DESIGN AND EXPERIMENT OF ECCENTRIC SWING COMBING DEVICE FOR *CERASUS HUMILIS*
/
钙果偏心摆动梳脱装置的设计与试验

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ABSTRACT
An eccentric swing combing device was designed on the basis of the growth characteristics of Cerasus humilis in mature stage in this work to improve the removal rate and reduce the damage rate. The device adopted a swing mechanism to realize comb rod entry from the roots of branches and an eccentric mechanism to realize horizontal combing. The kinematic equation and the main affecting factors of the combing effect were obtained through the kinematic and dynamic analyses of the combing device. Rotation speed, feeding speed, and comb swing angle were considered the influencing factors, and removal and damage rates were taken as the evaluation indexes. We conducted an experiment of quadratic orthogonal rotation centre combination with three factors and five levels on the combing device. Results showed that the contribution rate of each factor to the removal and damage rates was in the order of feeding speed, rotation speed and comb swing angle. The best combination of parameters was obtained as follows: rotating speed of 11.26 r/min, feeding speed of 0.227 m/s, and comb swing angle of 5°. The removal and damage rates were 95.21% and 4.56%, respectively, under this parameter combination. The relative error with the predicted result was less than 5%. This study can effectively improve the effect of C. humilis fruit removal and provide reference for further design of C. humilis harvesting machinery.

摘要
针对钙果机械化采收难以脱果的问题，本文为提高钙果脱净率，降低破损率，结合其生长特性，设计了钙果偏心摆动梳脱装置。该装置采用摆动机构实现枝条根部喂入，利用偏心机构实现水平梳脱，完成脱果作业。在钙果梳脱状态动力学分析的基础上，利用该装置选择以脱净率和破损率为评价指标，以梳齿轮转速、喂入速度和梳齿摆角为试验因素，实施三因素五水平二次正交旋转中心组合优化试验。结果表明，各因素对脱净率和破损率的贡献率由大到小依次是喂入速度、梳齿轮转速和梳齿摆角；得到最佳参数组合为梳齿轮转速 11.26 r/min，喂入速度0.227 m/s，梳齿摆角5°，在此参数组合下钙果偏心摆动梳脱装置的脱净率为95.21%，破损率为4.56%，与预测结果相对误差小于 5%。该研究有效提高钙果脱果效果，可为提高钙果机械化收获提供参考。

INTRODUCTION
Cerasus humilis pulp is rich in calcium citrate malate pentahydrate, which is easy to be absorbed (*Chang et al., 2011*). In recent years, the planting area has increased rapidly year by year with the promotion and recognition of the market. *C. humilis* species have a large number of fruits, which can be produced from the root to the top of the branch (*He et al., 2018; He et al., 2019*). *C. humilis* branches are soft, and they will lodge under the gravity of fruits when they are mature. Lodging is good for fruit to receive light and ensure good colour and quality (*Du et al., 1992*). However, the characteristics of dense fruit and lodging branches bring difficulty in harvesting the C. *humilis* near the root. At present, the mechanized harvesting equipment of *C. humilis* is yet to be perfected. Thus, the development of the *C. humilis* industry should be promoted to strengthen the research of *C. humilis* harvesting machinery.

Traditional *C. humilis* harvest mainly depends on manual picking, which has high labour intensity and cost (*Sanders., 2005*). Extensive research has been conducted on picking small berries. The use of high-power fan to produce intermittent air flow and make branches swing can achieve fruit removal (*Whitney et al., 1972*). Pneumatic harvester has no rigid connection with fruit trees and can thus reduce the mechanical damage of fruit trees (*Chen et al., 2011*).

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A close relationship exists between fruit removal rate and connection force (*Coppock et al., 1981*). *C. humilis* has a strong connection force, and the cost of air flow for fruit removal is high (*Sun et al., 2016*). Vibration harvester uses vibrating rods to knock fruits off or vibrate the trunk of the plant to cause fruit swing and fall-off (*Peterson et al., 1997*). However, *C. humilis* branches are soft, and the vibration transmission is difficult. Fruit removal equipment suitable for *C. humilis* growth characteristics should be developed. Our research group has performed a series of research on the way and equipment of *C. humilis* fruit removal. Double-roller stripping harvester simulates the mechanism of artificial harvesting and achieves staged harvesting (*Liu et al., 2013*). However, this harvester requires cutting off branches to reduce the yield in the next year. Comb-type *C. humilis* harvester can achieve high fruit removal rate and low damage rate but has difficulty harvesting the *C. humilis* near the root (*Zhang et al., 2018*).

On the basis of the feasibility of combing verified by previous research (*Du et al., 2019*), an eccentric swing combing device was designed in accordance with the growth characteristics of *C. humilis*. In this work, the key parameters of the device were studied by experiment of quadratic orthogonal rotation centre combination. The best working parameters were obtained using the removal and damage rates as evaluation indexes. This study can provide technical support for further research and development of *C. humilis* harvester.

MATERIALS AND METHODS

Materials and growth characteristics

Sampling was conducted in early September, 2018. The sampling site was Juxin Modern Agriculture Base in Taigu County, Shanxi Province, China (112°29'E, 37°23'N), and the variety was “Nongda 4.” The branches with uniform length and no damage were selected and cut from the place close to the ground. The number of fruits on each branch was 40–60, the moisture content of branch was 56.74%, and the moisture content of grape was 78.2%. The experiment was performed immediately after sampling.

C. humilis is an oblate fruit. Fig. 1 presents the mature *C. humilis* plants. These plants are characterized by a large and dense number of fruits. Table 1 exhibits the measurement data of shape parameters and connecting force of fruit stalk in the mature stage. The average diameter of *C. humilis* is 24.65 mm, the connection force is 8.20 N, the number of fruits is 48.84, and the root diameter is only 6.56 mm, which hardly supports its weight and upright position. Mechanical fruit removal requires overcoming the difficulty in fruit removal near the root caused by the lodging of branches and reducing the damage caused by the large connecting force of fruit stalk.

Fig. 1 – Growth characteristics of *C. humilis* at maturity

Table 1

Measured data of *C. humilis*

Parameters	Range	Average	Standard deviation
Fruit diameter/ mm	20.64~30.3	24.65	2.65
Connection force/ N	3.55~13.65	8.20	2.19
Branch length/ cm	24~80	46.72	10.35
Root diameter/ mm	4.60~8.28	6.56	1.00
Number of fruits	30~65	48.84	10.74
Fruit bearing interval length/ cm	18~61	39.24	11.09

Device and process

The fruit removing device was the key part of *C. humilis* harvester. In this work, an eccentric swing combing device was designed on the basis of the growth characteristics of *C. humilis*. The device was mainly composed of the gantry, swing mechanism, eccentric combing mechanism, and transmission system. The swinging mechanism was composed of a rocker, a rocker shaft, a connecting rod and a crankshaft to feed the comb rods from the root of the plant. The eccentric combing mechanism was composed of the comb wheel, comb rods, comb rack, comb wheel rocker, and eccentric wheel. Six rows of comb rods were present to realize the horizontal combing of the comb rods rotating with the comb wheel. The transmission system included motor and synchronous pulley and belt. Fig. 2 shows the system structure. The comb clearance was larger than the branch diameter but smaller than the fruit diameter. Thus, the fruits could be removed by combing (*Zhang et al., 2014*). With the advance of the device, the transmission system drove the combing device to rotate clockwise for realizing combing from bottom to top.

Before the experiment, the crankshaft was changed to adjust the swing angle, and the feeding speed control system was adjusted to set the feeding speed. The number of fruits on branches was counted, and then, the fruits were fixed in the branch fixture. During the experiment, the electromagnetic speed regulating motor was started, and the eccentric swing combing device was operated. Then, the electromagnetic speed regulating controller was adjusted. The digital tachometer was used to measure the speed of the combing wheel. When the device ran stably, the feeding speed control system was started. Branch feeding was realized by track traction. At the end of experiment, the abscission fruits were collected and counted.

Fig. 2 − Eccentric swing combing mechanism

1- Track; 2- Branch fixture; 3- Feeding speed control system; 4- Comb rods; 5- Gantry; 6- Synchronous belt; 7- Crank rocker mechanism; 8- Crankshaft; 9- Electromagnetic speed regulating motor; 10- Electromagnetic speed regulating controller

Design of key structural parameters

Design of the swing mechanism

The swing mechanism, which was actually a crank rocker mechanism, was designed to make the comb rods enter from the root of branches and increase the combing range. The mechanism was mainly composed of a crankshaft, a connecting rod, and a rocker. The comb wheel was connected to the rocker. As the rocker swung back and forth, the comb angle was changed to form elevation and depression angles. The average speed of the process and the return of the rocker should be close to reduce the impact damage caused by the swinging comb rods. Thus, the travel speed ratio coefficient k = 1.05. The polar angle θ was obtained from the polar angle formula. The dimension of each member was obtained from the limit position relationship, as shown in Fig. 3. The crank length was changed by changing the crankshaft to adjust the swing angle.

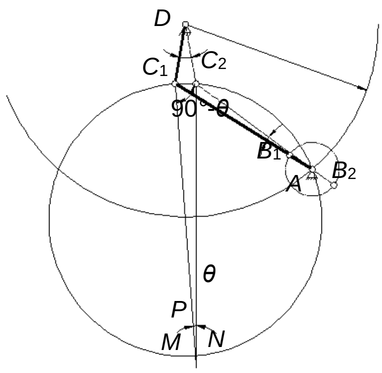


Fig. 3 − Design principle of the swing mechanism

Design of the eccentric mechanism

The eccentric mechanism was composed of the comb wheel *M*, comb rod *AK*, comb rack *A-A*, comb wheel rocker *O-O*1, and eccentric wheel *M*1. Fig. 4 shows the eccentric mechanism structure. Six rows of comb rod *AK* were present. The length of the comb wheel rocker and the other end of the comb rack was equal ($O-O_1=A-a$) because the outer diameters of the comb and eccentric wheels were equal ($A-O=a-O_1$). Thus, the whole eccentric comb wheel was composed of six groups of parallelogram mechanism OO_1aA. The maximum length of the branch was 800 mm, and the comb wheel radius *R* was 450 mm in design.

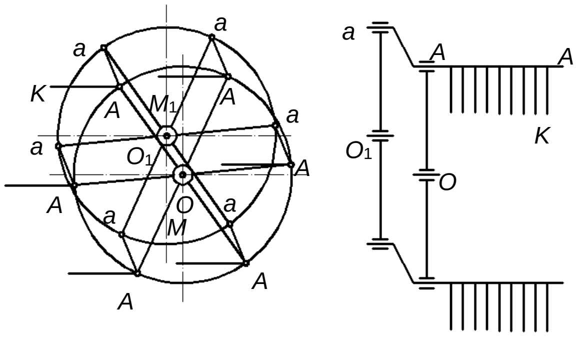


Fig. 4 – Schematic of the eccentric mechanism

Experimental factor analysis and simulation

Kinematic analysis of comb rods

During the device operation, the comb rods were involved in three movements. The comb rods moved along the straight-line direction with the device, the root of comb rods rotated around the comb wheel, and the comb swings up and down. Fig. 5 shows the movement principle.

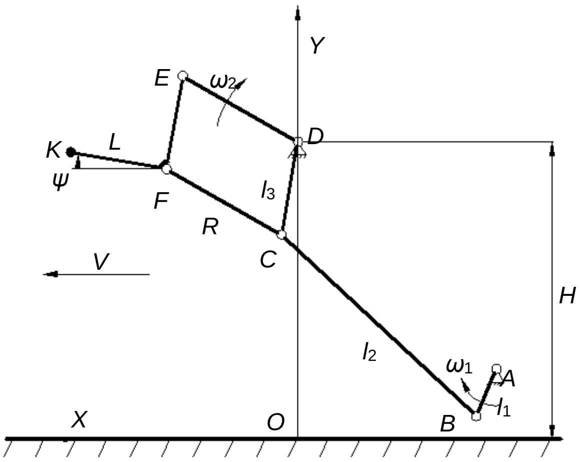


Fig. 5 – Motion principle

After time *t*, the motion equation of the comb tip (shown as point *K* in fig. 5) was

$$\begin{cases} x_1 = Vt + L\cos\psi + R\cos\omega_2 t + l_3\sin\psi \\ y_1 = H + L\sin\psi + R\sin\omega_2 t - l_3\cos\psi \end{cases} . \tag{1}$$

The motion equation of the root of comb rods (shown as point *F* in fig. 5) was

$$\begin{cases} x_2 = Vt + R\cos\omega_2 t + l_3\sin\psi \\ y_2 = H + R\sin\omega_2 t - l_3\cos\psi \end{cases} , \tag{2}$$

where *V* is the feeding speed, [mm/s];

t is the rotation time interval of comb wheel, [s];

L is the length of comb rod, [mm];

ψ is the swing angle, [°];

R is the radius of comb wheel, [mm];

ω_2 is the angular velocity of comb wheel, [rad/s];

l_3 is the length of rocker, [mm];

H is the height of eccentric from the ground, [mm].

A key factor affecting the combing effect was the number of times that the comb rods brush the branches. The more the branches were brushed, the more fruits were removed. However, the damage of comb rods to branches and leaves was great. The number of times of each branch was brushed was

$$Q = 6 \cdot \frac{n}{60} \cdot \frac{L+2R}{V} = \frac{n}{10V} \cdot (L+2R), \tag{3}$$

where Q is the number of times the branches were combed, [times];

n is the rotation speed, [r/min].

Therefore, feeding and rotation speeds were the two factors that must be considered in the combing of *C. humilis.*

Dynamics analysis of comb rods

In the process of combing, the collision and squeezing forces between fruits are mainly produced by the comb teeth. These forces simultaneously make the fruit fall off but cause different degrees of damage (*Li et al., 2017*). In this work, comb up and down were selected for analysis, as shown in Fig. 6.

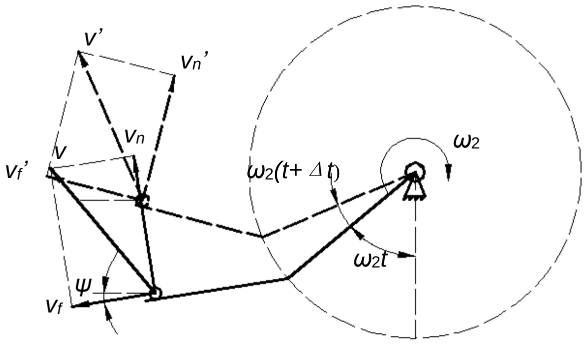


Fig. 6 – Sketches of combing *C. humilis*

Let the comb be located directly below the rotation centre of the comb wheel as the starting point. After time t, the rotation angle of the comb was $\omega_2 t$. At this time, the movement speed of the comb relative to the fruit was v, which can be divided into v_n and v_f, as shown in Fig. 6.

When the comb rods first contacted with the plant, the comb rods were in a downward state, and the comb started from the root of the plant. At this time,

$$\begin{cases} v_n = v\sin(\omega_2 t + \psi) \\ v_f = v\cos(\omega_2 t + \psi) \end{cases}. \tag{4}$$

The normal velocity v_n of the comb increased due to the swing angle ψ of the comb rods, and this condition improved the combing ability of the comb.

After time Δt, the comb went up. At this time,

$$\begin{cases} v_n' = v'\sin[\omega_2(t-\Delta t) - \psi] \\ v_f' = v'\cos[\omega_2(t-\Delta t) - \psi] \end{cases}. \tag{5}$$

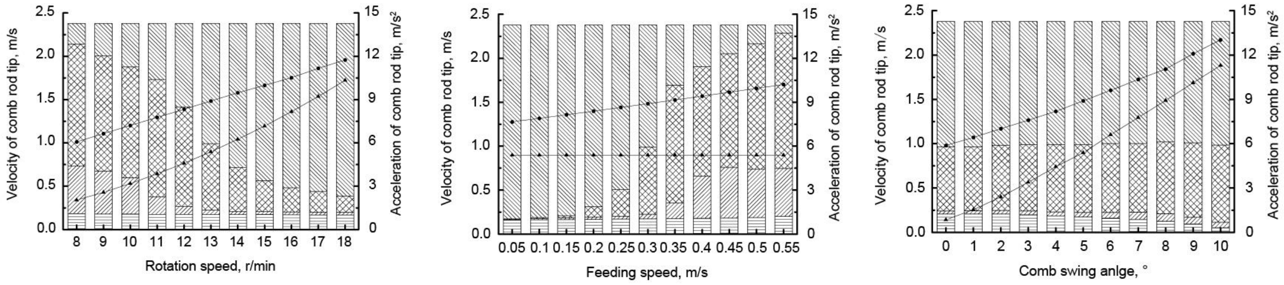
The comb swing angle ψ could reduce the normal velocity v_n, increase the tangential velocity v_f, improve the movement ability of fruits along the comb surface, reduce the accumulation above the comb surface, and decrease the extrusion and collision between fruits. Therefore, the proper comb swing angle was beneficial to increase the combing range and reduce the damage of *C. humilis.*

Combing simulation

The previous experiment and research manifested that the fruit removal result was related to the movement track of the comb rod, and the reasonable movement track could improve the removal rate (*Zhang et al., 2018*). Therefore, this work used rotation speed, feeding speed, and swing angle as factors to analyse the absolute movement track of the comb rod (*Xiang et al., 2015; Shi et al., 2017*). The motion trace of the comb tip and root and the velocity and acceleration of the comb tip were obtained using ADAMS simulation software. The area ratios of leakage under one-time combing, two-time combing, and multiple-time combing were calculated using the inclusion–exclusion principle. Fig. 7 shows the results.

Fig. 7(a) indicates that, as the rotation speed increased, the speed of combing off became fast, the area of multiple-time combing significantly increased, and the speed and acceleration of tooth tip rose. Fig. 7(b) reveals that the comb rods repeatedly brushed the same part when the feeding speed was small. As a result, the combing efficiency was low.

When the feeding speed was large, the area of multiple-time combing decreased. Fig. 7(c) shows that the leakage area decreased gradually with the increase in the swing angle, but the velocity and acceleration of tip increased.



(a) Influence of rotation speed on the combing effect ***(b) Influence of feeding speed on the combing effect*** ***(c) Influence of comb swing angle on the combing effect***

Leakage area; One-time comb area; Two-time comb area; Multiple-comb area; —●—Velocity of tip; —▲—Acceleration of tip

Note: In Fig. 7(a), the feeding speed was 0.3 m/s and the comb swing angle was 5°; in Fig. 7(b), the rotation speed was 13 rad/min and the comb swing angle was 5°; in Fig. 7(c), the rotation speed was 13 rad/min and the feeding speed was 0.3 m/s.

Fig. 7 − Simulation results of the influence of various factors on the combing effect

Experiment design

The theoretical analysis showed that the main affecting factors of the combing effect were rotation speed, feeding speed and comb swing angle. In this experiment, quadratic orthogonal rotation centre combination was designed to study the influence of rotation speed X_1, feeding speed X_2 and comb swing angle X_3 on the combing effect. The multi-objective parameter optimization was completed. The level range of each factor was determined by the simulation results and pre-experiments. The experiment had three factors and five levels. Table 2 presents the factor codes.

Table 2

Coding schedule of experimental factors

Coded	**Rotation speed [r/min]** X_1	**Feeding speed [m/s]** X_2	**Comb swing angle [°]** X_3
1.682	16.70	0.47	8.36
1	15.00	0.40	7.00
0	12.50	0.30	5.00
−1	10.00	0.20	3.00
−1.682	8.30	0.13	1.64

The combing effect was evaluated by fruit removal and damage rates. Fruit removal rate Y_1 was the percentage of the numbers of *C. humilis* to be combed off in the total number of *C. humilis* on branches. Damage rate Y_2 was the percentage of the number of *C. humilis* damaged in the number of *C. humilis* to be combed off. The drop damage can be ignored because of the low drop height (*He et al., 2019*).

$$Y_1 = \frac{N_1}{N}, \tag{6}$$

$$Y_2 = \frac{N_2}{N_1}, \tag{7}$$

where N is the total number of *C. humilis* on the branches before experiment;

N_1 is the number of *C. humilis* removed from experiment;

N_2 is the number of damaged *C. humilis* after experiment.

RESULTS

Experimental results and establishment of the regression model

The experiments of the quadratic orthogonal rotation centre combination were conducted in accordance with the code of the experimental factors. A total of 23 groups of experiment were considered, and each group was repeated five times. The results were taken as the average value. The experiment scheme design and result analysis were completed with Design Expert software, as shown in Table 3.

Table 3

Experimental results

No.	Comb distance X_1 [mm]	Combing speed X_2 [mm/s]	Comb rod radius X_3 [mm]	Fruit removal rate Y_1 [%]	Damage rate Y_2 [%]
1	−1	−1	−1	90.20	4.79
2	1	−1	−1	93.07	7.90
3	−1	1	−1	85.02	6.23
4	1	1	−1	91.42	8.61
5	−1	−1	1	95.28	5.45
6	1	−1	1	96.77	9.13
7	−1	1	1	87.60	6.52
8	1	1	1	92.62	8.12
9	−1.6818	0	0	88.57	3.97
10	1.6818	0	0	94.27	9.31
11	0	−1.6818	0	93.87	6.25
12	0	1.6818	0	87.65	7.81
13	0	0	−1.6818	89.57	5.81
14	0	0	1.6818	91.85	6.96
15	0	0	0	92.77	4.56
16	0	0	0	94.09	5.00
17	0	0	0	91.65	4.68
18	0	0	0	94.04	5.19
19	0	0	0	93.27	4.61
20	0	0	0	95.25	4.58
21	0	0	0	92.82	5.26
22	0	0	0	94.32	4.89
23	0	0	0	93.88	4.53

Table 4

ANOVA

Sources	SS	DF	*F* Value	*P* Value	Sources	SS	DF	*F* Value	*P* Value
Model 1	168.18	9	17.17	<0.0001**	Model 2	57.82	9	55.23	<0.0001**
X_1	47.12	1	43.29	<0.0001**	X_1	28.56	1	245.54	<0.0001**
X_2	62.09	1	57.05	<0.0001**	X_2	1.71	1	14.71	0.0021**
X_3	19.68	1	18.08	0.0009**	X_3	0.96	1	8.27	0.0130*
$X_1 X_2$	6.23	1	5.72	0.0325*	$X_1 X_2$	0.99	1	8.48	0.0121*
$X_1 X_3$	0.95	1	0.87	0.3667	$X_1 X_3$	0.01	1	0.05	0.8311
$X_2 X_3$	3.13	1	2.87	0.1140	$X_2 X_3$	0.55	1	4.69	0.0494*
X_1^2	6.01	1	5.52	0.0352*	X_1^2	7.96	1	68.43	<0.0001**
X_2^2	11.44	1	10.51	0.0064**	X_2^2	11.36	1	97.69	<0.0001**
X_3^2	11.92	1	10.95	0.0056**	X_3^2	6.06	1	52.11	<0.0001**
Residual	14.15	13			Residual	1.51	13		
Lack of Fit	5.20	5	0.93	0.5097	Lack of Fit	0.87	5	2.18	0.1564
Pure Error	8.95	8			Pure Error	0.64	8		
Total	182.33	22			Total	59.33	22		

*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.

Multiple regression analysis was performed on the test results in Table 3. The quadratic polynomial regression models among the rotation speed X_1, feeding speed X_2, comb swing angle X_3, fruit removal rate Y_1, and damage rate Y_2 were established. The following regression equations were obtained after the insignificant factors were eliminated:

$$Y_1 = 93.55 + 1.86X_1 - 2.13X_2 + 1.20X_3 + 0.88X_1X_2 - 0.62X_1^2 - 0.85X_2^2 - 0.87X_3^2 \tag{8}$$

$$Y_2 = 4.80 + 1.45X_1 + 0.35X_2 + 0.27X_3 - 0.35X_1X_2 - 0.26X_2X_3 + 0.71X_1^2 + 0.85X_2^2 + 0.62X_3^2 \tag{9}$$

where X_1, X_2, and X_3 were the coding values of rotation speed, feeding speed, and comb swing angle, respectively.

ANOVA was conducted to verify the applicability of the regression model, as shown in Table 4. The P values of the regression models of removal rate Y_1 and damage rate Y_2 were less than 0.0001, which indicates that the models were extremely significant. The P values of the regression models were larger than 0.05, which indicates that the regression models effectively fit with the actual situation within the scope of the experiment. The coefficient determination R^2 of regression models Y_1 and Y_2 were 0.8687 and 0.9569, respectively. A high correlation was observed between the predicted and actual values, and the experiment error was small. Therefore, the models could be used to analyse and predict the effect of fruit removal.

Analysis of influencing factors

Analysis of the effect of experimental factors on the performance indexes

By referring to the calculation method of the contribution rate of each factor to the index in multiple quadratic regression (*Zhou et al., 2009*), the influence degree of each factor on each index was determined. Table 5 shows the results.

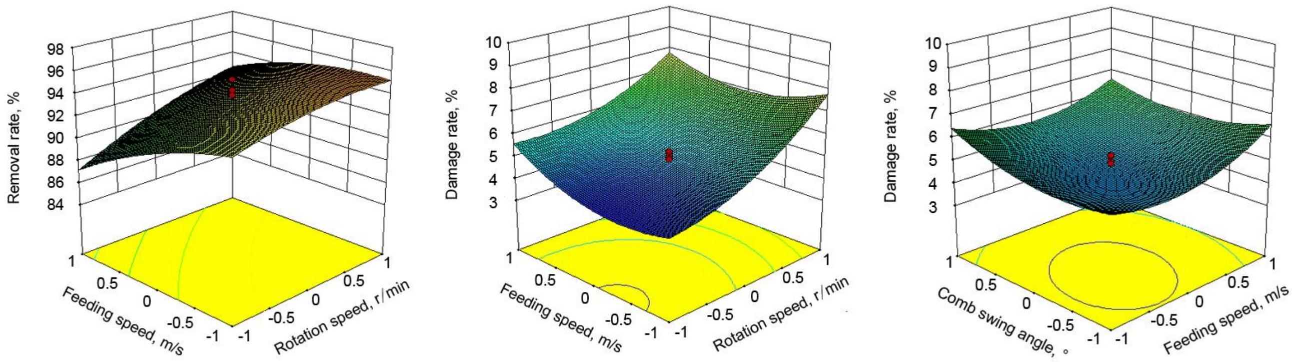
Table 5

Contribution rate of each factor

Factors	Contribution rate			Ranking contribution rate from large to small
	X_1	X_2	X_3	
Y_1	2.208	2.626	2.179	$X_2>X_1>X_3$
Y_2	2.422	2.756	2.253	$X_2>X_1>X_3$

Analysis of the effect of interaction of experimental factors on the performance indexes

This work studied the influence rule of interaction of factors on the performance indexes by using ANOVA. The interaction of rotation and feeding speeds significantly affected the fruit removal rate (P<0.05). The fruit removal rate increased with the increase in rotation speed and decreased with the increase in feeding speed when the comb swing angle was at 0 level (X_3=5°), as shown in Fig. 8a. The branches were combed frequently when the feeding speed was low. The fruits that were not combed off in the previous row or leaked from the comb clearance were combed again by the next row of comb rods. As a result, the fruit removal rate was high. At least one row of comb rods could not be guaranteed to enter from the root of branches when the feeding speed was large. The branches were partially combed. Consequently, the fruit removal rate was low.



a. Y_1=f(X_1,X_2,0) **b. Y_2=f(X_1,X_2,0)** **c. Y_2=f(0,X_2,X_3)**

Fig. 8 − Response surfaces of the interaction of test factors on the performance indexes

The interaction of rotation and feeding speeds significantly affected the damage rate (P<0.05). When the comb swing angle was at the 0 level (X_3=5°), the damage rate increased with the increase in rotation speed and initially decreased before increasing with the increase in the feeding speed, as shown in Fig. 8b. When the rotation speed increased, the velocity and acceleration of comb rods increased, and the collision effect between fruits increased. This phenomenon resulted in the increase in damage rate. When the feeding speed was increased properly, the fruit accumulation on the comb rod surface, the extrusion effect between fruits, and the damage of fruits could be reduced. However, if the feeding speed was too high, then the feeding amount would be large. The fruits would also accumulate at the joint of the root of comb rods and would thus block the comb rods. Ultimately, the damage rate would increase.

The interaction of feeding speed and comb swing angle significantly affected the damage rate ($P<0.05$). When the rotation speed was at 0 level (X_1=12.5 r/min), the damage rate initially decreased before increasing with the increase in feeding speed and comb swing angle, as shown in Fig. 8C. The swing of the comb surface caused by the swing angle was conducive to the fruit movement.

This situation decreased the accumulation of fruits on the comb surface and avoided the damage of fruits stuck in the clearance of comb rods. Accordingly, the damage rate decreased. However, the excessive comb swing angle increased the velocity and acceleration of comb rods simultaneously. The collision effect of the comb rods on the fruits increased, which resulted in the increase in the damage rate. This finding was consistent with the results of the dynamic analysis and simulation.

Parameter optimization and validation

This work aimed to achieve high fruit removal and low damage rates to ensure enhanced performance of the eccentric swing combing device. The numerical optimization module in Design Expert software was used to solve the optimization problem. The objective function and constraints were as follows:

$$\begin{cases} X_1 \in [-1,1] \\ X_2 \in [-1,1] \\ X_3 \in [-1,1] \\ \max Y_1 \\ \min Y_2 \end{cases} \tag{10}$$

After optimization, the optimum combination of parameters was obtained as follows: rotation speed of 11.26 r/min, feeding speed of 0.227 mm/s, and comb swing angle of 5.185°. The predicted value of the fruit removal rate was 94.01%, and the damage rate was 4.38%.

The validation test was performed on the eccentric swing combing device with the following parameter combination: rotation speed of 11.26 r/min, feeding speed of 0.227 mm/s and comb swing angle of 5°. The experiment was repeated five times to obtain the average value, as shown in Table 6. The results showed that the fruit removal rate was 95.21%, and the relative error with the predicted result was 1.28%. The damage rate was 4.56%, and the relative error with the predicted result was 4.20%. These values were consistent with the result of optimization parameters and meet the operation requirements of *C. humilis* combing.

Verification result **Table 6**

Test number	Rotation speed ($r \cdot min^{-1}$)	Feeding speed ($m \cdot s^{-1}$)	Comb swing angle / (°)	Fruit removal rate / %			Damage rate / %		
				Predictive value/ %	Actual value/ %	Relative error/ %	Predictive value/ %	Actual value/ %	Relative error/ %
1	11.26	0.227	5	94.01	96.28	1.28	4.38	4.73	4.20
2					96.53			3.98	
3					93.76			4.91	
4					95.45			4.77	
5					94.04			4.43	

CONCLUSIONS

(1) An eccentric swing combing device of *C. humilis* was designed. This device adopted a swing mechanism to feed the comb rods from the root of *C. humilis* plant and an eccentric mechanism to realize horizontal combing of *C. humilis* for improving the combing effect.

(2) The kinematic equation of the combing device and the main affecting factors of the combing effect were obtained through the kinematic and dynamic analyses of the combing device. The times that the *C. humilis* plants were combed was calculated by simulation analysis of the absolute movement track of the comb rod combined with the inclusion–exclusion principle, and the influence rule of each factor on the combing effect was obtained.

(3) The bench tests showed that the contribution rate of the test factors to the fruit removal and damage rates was in the order of feeding speed, rotation speed, and comb swing angle. The best working parameter combination of the device was as follows: rotation speed of 11.26 r/min, feeding speed of 0.227 m/s, and comb swing angle of 5°. Under this condition, the fruit removal rate was 95.21%, and the damage rate was 4.56%. These findings were consistent with the results of the optimized parameters and meet the operation requirement of the *C. humilis* combing. This work provides a reference for the further design of *C. humilis* harvesting machinery.

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