DESIGN AND EXPERIMENTAL STUDY OF THE COMB-TYPE HARVESTING TEST BENCH FOR CERASUS HUMILIS
/
梳脱式钙果采收试验台设计与试验

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ABSTRACT
A comb-type harvesting test bench was designed to address low fruit collection rate and theoretical analysis and simulation analysis of the harvesting process were carried out in this work. Single factor simulation experiment and bench experiment were carried out, and fruit collection rate was used as the evaluation index. The motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement were selected as the experimental factors. Results showed that the collection rate decreased with the increase of motor speed; and increased with the increase of the bending angle of comb teeth or the radial diameter of comb teeth arrangement. The orthogonal experiment of three-factor and three-level quadratic rotation centre combination was performed. The results showed that motor speed had the largest effect on collection rate, followed by radial diameter of comb teeth arrangement and bending angle of comb teeth. The optimal parameter combination was predicted by the response surface model as follows: motor speed of 25 r/min, bending angle of comb teeth of 120°, radial diameter of comb teeth arrangement of 868.45 mm and correspondingly the collection rate reached 91.51%. Based on actual harvesting efficiency and the machining problems of the test bench, the bench experiment was performed with the motor speed of 25 r/min, the bending angle of comb teeth of 120°, the radial diameter of comb teeth arrangement of 900 mm, and the collection rate was 93.82%. The relative error with the predicted optimal result was 2.48%, achieving the purpose of improving the collection rate.

摘要
针对钙果采收要求，本文设计了梳脱式钙果采收试验台，并对采收过程进行了理论分析与仿真分析。以采收率为评价指标，以电机转速、梳齿弯曲角度和梳齿排布弧度的直径为影响因素，进行单因子仿真试验与台架试验，试验结果表明采收率随着电机转速的增大而逐渐降低，随着梳齿弯曲角度或梳齿排布弧度直径的增大而逐渐升高。进行了三因素三水平二次旋转中心组合正交试验，结果表明各因素对采收率影响的主次顺序是电机的转速、梳齿排布弧度和梳齿弯曲角度。由响应面模型预测最优梳脱参数组合为：电机转速 25 r/min、梳齿弯曲角度 120°、梳齿排布弧度直径 868.45 mm，在此参数下模型预测最大采收率为 91.51%。结合实际采收效率以及试验台加工等问题，用试验台以电机转速 25 r/min、梳齿弯曲角度 120°、梳齿排布弧度直径 900 mm 进行试验，得到采收率为 93.82%，与预测最优结果相对误差为 2.48%，达到了提升采收率的目的。

INTRODUCTION
In recent years, with the popularization and development of breeding experts on *Cerasus humilis*, the planting area of *C. humilis* in China has been increasing year by year. As *C. humilis* is gradually recognized by the Chinese market, people attach great importance to the development of *C. humilis* industry (*Wang et al., 2016*). *C. humilis* is soft and easy to be damaged, and artificial harvesting efficiency is low, which seriously harms the economic benefits for the *C. humilis* industry. Therefore, the realization of mechanized harvesting of *C. humilis* is an urgent problem to be solved in the development of *C. humilis* industry.

The performances of the air shaking, trunk shaking, limb shaking and canopy shaking mechanical harvesting systems are briefly summarized (*Sanders., 2004*). The traction force of the fruits, the percentage of fruit removed, the detachment point and the tree damage were evaluated (*Torregrosa et al., 2009*).

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A research aimed at assessing the effect of excitation position on fruit removal efficiency and fruit damage using a hand-held limb shaker for harvesting sweet cherry (*Zhou et al., 2014*). A study aimed to evaluate the feasibility of a mechanical-assist shake-and-catch system to harvest sweet cherries in a large range of commercial orchards (*Zhou et al., 2016*).

In China, some scholars have done the following relevant studies on the mechanized harvesting of *C. humilis*. A rotating wire collision *C. humilis* picking device was developed (*Liu et al., 2013*). The material properties and biomechanical properties of *C. humilis* were measured (*Sun et al., 2016*). An intermittent comb - brush *C. humilis* picking device was proposed and developed (*Zhang et al., 2018*).

The relationship between comb teeth of different shapes and the collision force of *C. humilis* was analysed based on the principle of comb brush (*Kang et al., 2017*). An eccentric swing combing device for *C. humilis* was designed aiming at the low removal rate of *C. humilis* (*Du et al., 2019; Du et al., 2020*). The finger-type lifter test bench, the continuous *C. humilis* picking test bench and a self-moving electric harvester for *C. humilis* were developed. (*He et al., 2018; He et al., 2019; Fang et al., 2019*), realizes the specific planting agronomic harvest of *C. humilis*, but the collection rate remains to be improved.

To improve the collection rate, a comb-type harvesting test bench for *C. humilis* was designed and the fruit shedding track was analysed in this paper. The experimental study was carried out with fruit collection rate being used as the evaluation index, the motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement were selected as the experimental factors, to explore the optimal parameter combination of test bench and improve collection rate.

MATERIALS AND METHODS

Experiment *C. humilis* variety: 'Nongda 4'. Sampling location: Juxin Modern Agriculture Base in Taigu County, Shanxi Province, China (E 112°29′, N 37°23′). Sampling time: September 7, 2019. The growth status of 'Nongda 4' as shown in Fig. 1a. Due to the different effects of field environmental differences on the growth status of fruit, 5 different sampling sites were set in the experimental field of 'Nongda 4' to sample the fruit， so as to minimize the influence of individual differences on the experimental results.
Fig. 1b shows the hanging fruit branches samples of 'Nongda 4' *C. humilis*.

'Nongda 4' Cerasus humilis sampling

a) Growth state of 'Nongda 4' *b) Sample of hanging fruit branches*

Fig. 1 - 'Nongda 4' Cerasus humilis branches

Design of comb-type test bench

The combing and stripping mechanism was the core component of the *C. humilis* harvester; the design must be optimized to improve the collection rate of *C. humilis* harvester. In this paper, a comb-type harvesting test bench for *C. humilis*, as shown in Fig. 2, was designed on the basis of the characteristics of *C. humilis* plants and previous studies. It was mainly composed of a frame, combing and stripping mechanism, baffle, clamping conveying mechanism, control system, fruit-collecting box and transmission system. The combing and stripping mechanism was composed of rotating disk, comb teeth carrier plate and comb teeth, which was mainly used to separate branches and fruits. Branches could pass through the comb teeth, and fruits were blocked by the comb teeth and took off. The comb teeth could be replaced to facilitate the experiment with different parameters of comb teeth (*Zhang et al., 2014*).

The clamping conveying mechanism and control system were composed of controller, guide rail and branch fixing clamp, it mainly transported the hanging fruit branches to the combing and stripping mechanism. The transmission system was composed of motor, synchronous pulley, belt and transmission shaft, which provided the turnover power for the test bench. Fruit-collecting box served as a fruit gatherer.

Before the experiment, the number of fruits on the hanging fruit branches was counted, and the hanging fruit branches was fixed on the branch fixing clamp of the clamping conveying mechanism. The electromagnetic speed-regulating motor was started to provide turnover speed for the combing and stripping mechanism by the transmission system.

The control system controlled the branch fixing clamp to feed the hanging fruit branches into the combing and stripping mechanism, under the action of the motor, the combing and stripping mechanism performed continuous rotation movement to remove the fruits. After, the fruit finally fell into the fruit-collecting box to complete the harvesting process under the joint action of the initial collision velocity, gravity, and the comb teeth back pull and baffle.

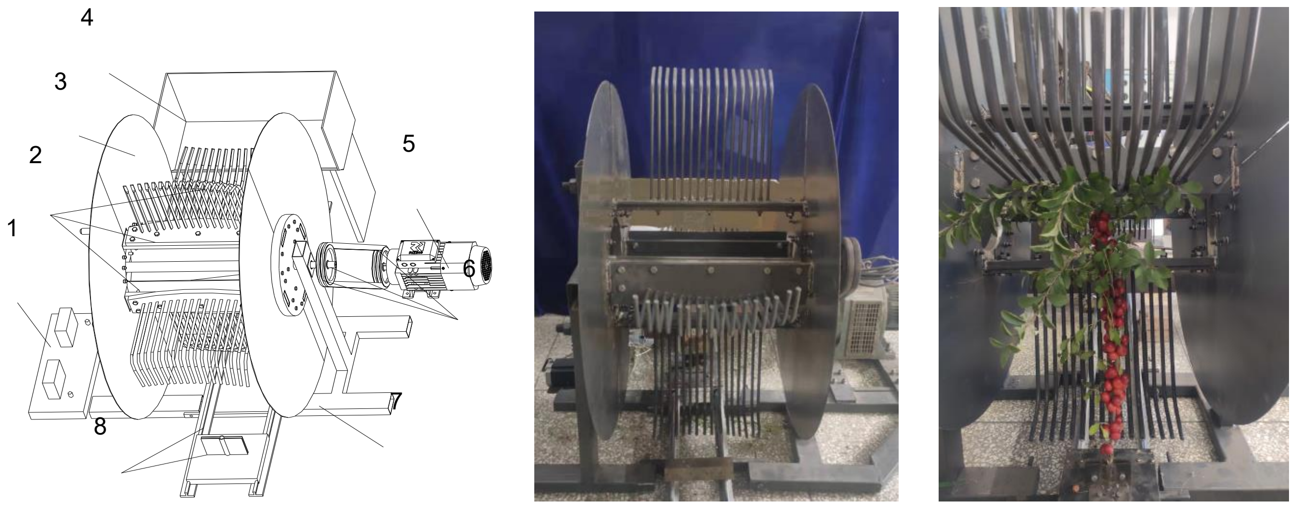


Fig. 2 - Comb-type harvesting test bench for Cerasus humilis

1- Control system；2- Combing and stripping mechanism；3- Baffle；4- Fruit-collecting box；5- Electromagnetic speed-regulating motor；6- Transmission system；7- Frame；8- Clamping conveying mechanism

Experiment factor analysis confirmed

Theoretical analysis of *Cerasus humilis* shedding track

The comb teeth would collide with the fruit when the Comb-type harvesting test bench for *C. humilis* is working, according to colliding situation in mechanics; the collision was accompanied by a change in energy from kinetic energy to potential energy to kinetic energy, so that after the collision, the speed of the test bench would give the fallen fruit an initial impact speed, the direction and size of this speed determined the range of fruit shedding, which would directly affect the fruit collection rate.

The previous experiment and research showed that the direction of fruit shedding was uncertain (*Liu et al., 2020*). If we assume that the fruit of shedding is a two-dimensional motion in a plane from which are detached, there would be two situations after shedding. When the position of *C. humilis* is lower than the rotating centre of the comb-type test bench, the *C. humilis* would finally fall to the front of the test bench. When the position of *C. humilis* is higher than the rotating centre of the comb-type test bench, the *C. humilis* would finally fell into the fruit-collecting box behind the test bench, as shown in Fig.3a. When the comb teeth were bent at a certain angle, some fruits below the rotating centre would be pushed back by the curved comb teeth, as shown in Fig.3b. With the constant turnover of the test bench, the fruit eventually fell into the fruit-collecting box under the action of comb teeth and baffle, and the proportion of fruit falling into the fruit-collecting box behind the test bench would increase, as shown in Fig. 3c.

Theoretically, the lower rotating centre of the test bench is the better, but if the centre is too low, it will limit the length of the comb teeth. If the length of the comb teeth is less than half of that of the branches, it is easy to cause branches winding. Therefore, bending the comb teeth angle was preferred to improve the collection rate.

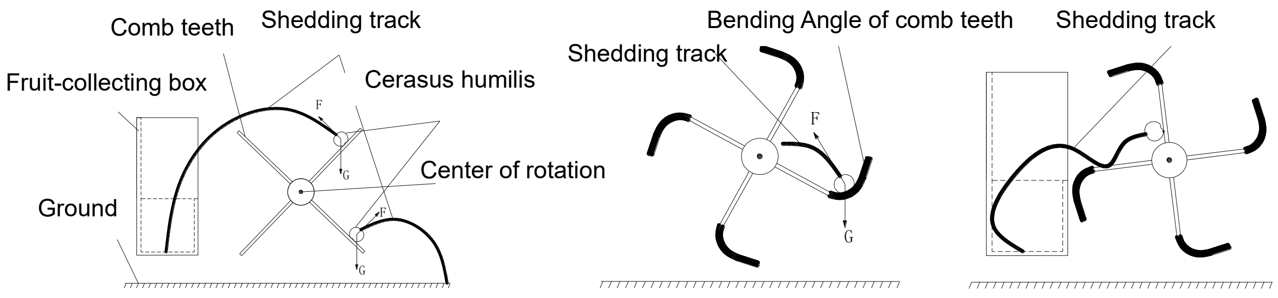


Fig. 3 - Fruit shedding track in two - dimensional plane

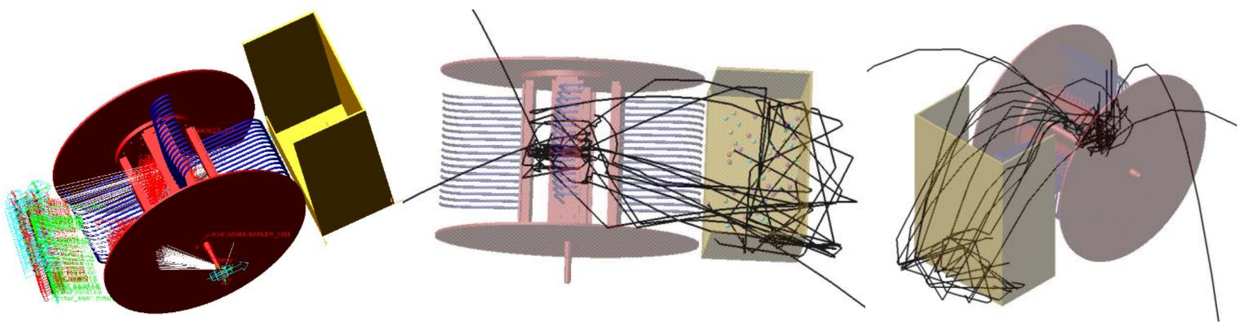
In fact, the branches of *C. humilis* are soft and pliable, and the fruit grows in different directions, hence some of the fruit bounce left or right after shedding off. In order to improve the collection rate, this paper combines the design of left and right baffles to arrange the comb teeth in a certain radian, which would give the fruit a left or right orienting force, so that fruit fell off in accordance with the predetermined direction, and the fruit fell into the fruit-collecting box under the action of baffle and comb teeth, which improved the collection rate of the test bench.

The above analysis showed that the motor speed determined the initial speed of the fruit after collision, which determined the range of the fruit falling off. The bending angle of comb teeth would increase the proportion of *C. humilis* falling into the fruit-collecting box. The comb teeth arrangement radian combined the design of baffle and test bench could improve the collection rate. These three factors would affect the collection rate of *C. humilis*.

Simulation analysis of *Cerasus humilis* shedding track

Based on PROE and ADAMS, this paper carried out dynamic simulation analysis on harvesting process of *C. humilis* (*He et al., 2020*). The 3D model of the test bench was established by PROE, and the simplified model was imported into ADAMS. The branch model of *C. humilis* hanging fruit was established in ADAMS, the number of *C. humilis* was set at 80, and the mechanical characteristics of *C. humilis* plant were simulated by flexible treatment of the branches. The harvesting of fruit was simulated by combining sensor and script simulation. The dynamic simulation model is shown in Fig. 4a. The shedding track diagram of No. 35～50 *C. humilis*, under the conditions of the motor speed 25 r/min, the bending angle of comb teeth 60°, and radial diameter of comb teeth arrangement 900 mm, is shown in Fig. 4b.

Fig. 4b shows that the direction of fruit shedding was random. Due to the blocking and combing effect of baffle and test bench, most fruits were collected in the fruit-collecting box with the movement of comb teeth, but some fruits still fell from the front, the left and right. The simulation result was basically consistent with the fruit shedding track results in the theoretical analysis, which further verified that the three experimental factors in the theoretical analysis, namely motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement, would have a certain influence on the collection rate of C. humilis.



a) three-dimensional model of test bench b) *Cerasus humilis* shedding track

Fig. 4 - Dynamic simulation model

Experiment design

To clarify the effects of motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement on the collection rate, this paper took the collection rate as the evaluation index and carried out single factor dynamic simulation experiment, single factor bench experiment and the orthogonal experiment of three-factor and three-level quadratic rotation center combination. The calculation formula of collection rate is shown in Equation (1). Three times tests were conducted for each group, and the results were averaged. The design of each experiment scheme was as follows:

$$Y = \frac{G_1}{G} \times 100\% \tag{1}$$

Where

Y is the fruit collection rate, [%];

G_1 is the total number of *Cerasus humilis* on the branches;

G is the number of *Cerasus humilis* in the fruit-collecting box.

Design of single factor simulation experiment

Taking motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement as experimental factors, a single-factor dynamics simulation experiment was designed, with five levels for each factor. The experiment design is shown in Table 1.

Table 1

Single factor simulation experiment scheme

Item	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Motor [r/min]	20	25	30	35	40	30					30				
Bending angle [°]	60					60	75	90	105	120	60				
Radial diameter [mm]	900					900					600	700	800	900	1000

Design of single factor bench experiment

The simulation experiment basically proved that the collection rate of *Cerasus humilis* was affected by the motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement. In order to further confirmed the accuracy of the simulation experiment results, the single factor bench experiment was used to verify the experiment results in this paper. Considering the machining problem of the test bench, each factor of the bench experiment was set at three levels, and the experiment scheme was consistent with the simulation experiment.

Design of orthogonal experiment

To study the influence of interactive factors on fruit collection rate, the orthogonal experiment of three-factor and three-level quadratic rotation center combination was designed in this paper. The experimental factors and levels are shown in Table 2.

Table 2

Coding schedule of experimental factors

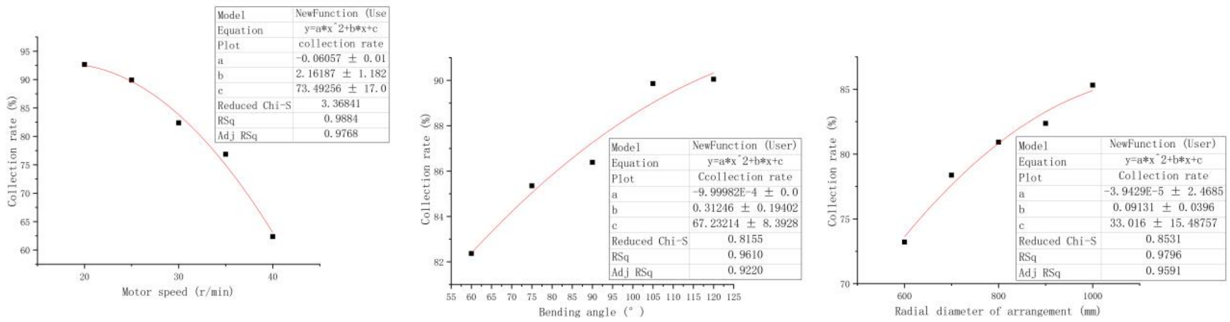
Coded value	Motor speed [r/min] A	Bending angle [°] B	Radial diameter [mm] C
Lower level（-1）	25	60	600
Middle level（0）	30	90	750
Upper level（1）	35	120	900

If all the experimental schemes of orthogonal experiment were conducted, it would be too complicated. In order to improve the experiment efficiency and ensure the accuracy, the experiment scheme was designed by box-Behnken module in the Design-Export, with a total of 17 experiment points. The Design does not require multiple consecutive experiments and could assess the nonlinear influence of factors.

RESULTS

Simulation experiment results and quadratic regression analysis

Origin 2018 was used for fitting analysis of single-factor simulation experiment data, and the results are shown in Fig. 5.



a) Motor speed fitting diagram b) Bending angle fitting diagram c) Radial diameter fitting diagram

Fig. 5 - The result of single factor simulation experiment

Fig. 5a shows the influence of motor speed on the collection rate, the quadratic polynomial parameters are shown in the figure, the determination coefficient (R^2) up to 0.9884, the adjusted determination coefficient (Adj R^2) up to 0.9768, it indicated that the predicted value of the regression model was well fitted to the actual value thus can be used in the prediction and analysis of the influences of the motor speed on the collection rate in the harvesting process. With the motor speed increased from 20 r/min to 40 r/min, the collection rate decreased from 92.65% to 62.37%.

Fig. 5b shows the influence of the bending angle of comb teeth on the collection rate, the quadratic polynomial parameters are shown in the figure, the determination coefficient (R^2) up to 0.9610, the adjusted determination coefficient (Adj R^2) up to 0.9220, it indicated that the predicted value of the regression model was well fitted to the actual value thus can be used in the prediction and analysis of the influences of the bending angle of comb teeth on the collection rate in the harvesting process. With the bending angle of comb teeth increased from 60° to 120°, the collection rate increased from 82.37% to 90.05%.

Fig. 5c shows the influence of the radial diameter of comb teeth arrangement on the collection rate, the quadratic polynomial parameters are shown in the figure, the determination coefficient (R^2) up to 0.9796, the adjusted determination coefficient (Adj R^2) up to 0.9591, it indicated that the predicted value of the regression model was well fitted to the actual value thus can be used in the prediction and analysis of the influences of the radial diameter of comb teeth arrangement on the collection rate in the harvesting process. With the radial diameter of comb teeth arrangement increased from 600 mm to 1000 mm, the collection rate increased from 73.18% to 85.32%.

Analysis of single factor bench verification experiment

Table 3 shows the comparison between the bench experiment and the simulation experiment, Table 3 showed that with the motor speed increased from 25 r/min to 35 r/min, the collection rate decreased from 88.65% to 78.86%; with the bending angle of comb teeth increased from 60° to 120°, the collection rate increased from 83.23% to 89.32%; with the radial diameter of comb teeth arrangement increased from 600 mm to 900 mm, the collection rate increased from 75.21% to 83.23%.

The maximum relative error between the bench and the simulation experiment is 3.09%, and the influence of the motor speed, the bending angle of the comb teeth and the radial diameter of the comb teeth arrangement on the collection rate are basically consistent with the conclusions from the simulation experiment. This shows that the simulation results are reliable, and the conclusion and regression model can be adopted.

Table 3

Comparison of experimental data

Item		**Motor speed [r/min]**			**Bending angle [°]**			**Radial diameter [mm]**		
		25	30	35	60	90	120	600	750	900
Collection rate [%]	**Bench experiment**	88.65	83.23	78.86	83.23	86.19	89.32	75.21	81.29	83.23
	Simulation experiment	89.92	82.37	76.42	82.37	86.39	90.05	73.18	79.32	82.37
Relative error [%]		1.43	1.03	3.09	1.03	0.23	0.82	2.70	2.42	1.03

Results of orthogonal experiment and ANOVA

The experiment points and experiment results designed by box-Behnken module in design-Export are shown in Table 4.

Table 4

Orthogonal experiment points and experiment results

No.	Motor speed A [r/min]	Bending angle B [°]	Radial diameter C [mm]	Collection rate Y [%]
1	-1	-1	0	87.30
2	1	-1	0	75.83
3	-1	1	0	94.78
4	1	1	0	81.66
5	-1	0	-1	85.32
6	1	0	-1	73.27
7	-1	0	1	92.25
8	1	0	1	81.02
9	0	-1	-1	75.21
10	0	1	-1	79.63
11	0	-1	1	83.23
12	0	1	1	89.32
13	0	0	0	85.38
14	0	0	0	85.12
15	0	0	0	86.09
16	0	0	0	84.96
17	0	0	0	85.89

The results of variance analysis are shown in Table 5.

Table 5

The results of ANOVA

Item	Degree of freedom	Mean square	*F Value*	*P Value*
Model 1	9	58.55	124.50	< 0.0001**
A	1	286.44	609.08	< 0.0001**
B	1	70.92	150.81	< 0.0001**
C	1	131.14	278.85	< 0.0001**
AB	1	0.68	1.45	0.2681
AC	1	0.17	0.36	0.5688
BC	1	0.70	1.48	0.2628
A^2	1	0.29	0.61	0.4604
B^2	1	3.09	6.57	0.0374*
C^2	1	32.63	69.39	< 0.0001**

Note: $P < 0.01$ (extremely significant, **), $P < 0.05$ (significant, *).

The regression equation as shown in Equation (2).

ANOVA in Table 4 showed that the motor speed, the bending angle of the comb tooth and the radial diameter of the comb tooth arrangement all have extremely significant impact on collection rate ($P<0.01$). The quadratic regression model of fruit collection rate Y was extremely significant ($P<0.01$), with determination coefficient (R^2) was 0.9938, the adjusted determination coefficient (Adj R^2) was 0.9858, and the predicted determination coefficient (Pred R^2) was 0.9265, the difference between adjusted determination coefficient and the predicted determination coefficient was not more than 0.2. These results indicated that the quadratic regression fitting model has a high fitting precision, which can be used to predict and analyze the influence of motor speed, the bending angle of comb teeth and the radial diameter of comb teeth arrangement on the collection rate.

$$Y = 85.49 - 5.98 \cdot A + 2.98 \cdot B + 4.05 \cdot C - 0.41 \cdot AB + 0.20 \cdot AC + 0.42 \cdot BC + 0.26 \cdot A^2 - 0.85 \cdot B^2 - 2.78 \cdot C^2 \quad (2)$$

Where:

A is the motor speed, [r/min];

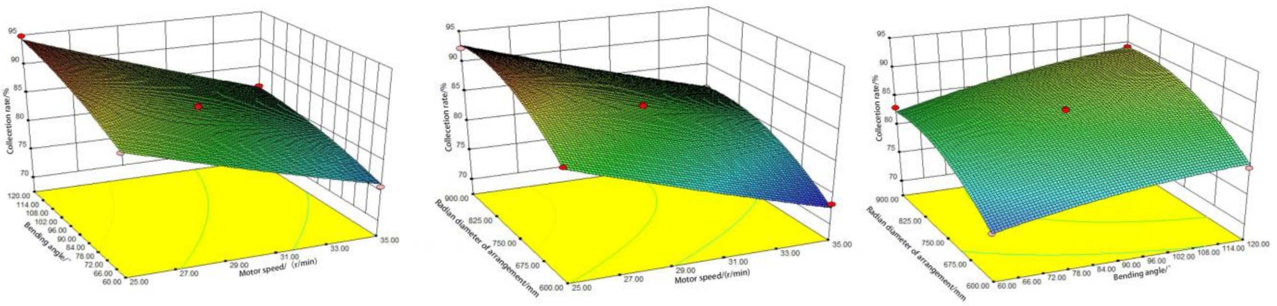
B is the bending angle of the comb teeth, [°];

C is the radial diameter of the comb teeth arrangement, [mm];

Y is the fruit collection rate, [%].

Analysis of the influence of interaction factors on the collection rate

In order to more visually see the interactive effect of motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement on collection rate, the 3D response surface was generated according to the Box-Behnken Centre combination method, as shown in Fig. 6a-6c.



a. Y (A, B, 750) b. Y (A, 90, C) c. Y (25, B, C)

Fig. 6 - Response surface of various factors on fruit collection rate

Fig. 6a shows the interaction of motor speed and bending angle of comb teeth on the collection rate. Under the condition that the radial diameter of comb teeth arrangement was 750 mm, the collection rate decreased with the increase of motor speed, and increased with the increase of the bending angle of comb tooth. But when both the motor speed and the bending angle of comb teeth increased, the collection rate decreased gradually. When the motor speed increased, and the bending angle of comb teeth decreased, the collection rate declined significantly, indicating that the influence of the motor speed on the collection rate is more significant.

Fig. 6b shows the interaction of motor speed and radial diameter of comb teeth arrangement on the collection rate. Under the condition that the bending angle of comb teeth was 90°, the collection rate decreased with the increase of motor speed, and increased with the increase of the radial diameter of comb teeth arrangement. But when both the motor speed and the radial diameter of comb teeth arrangement increased, the collection rate decreased gradually. When the motor speed increased and the radial diameter of comb teeth arrangement decreased, the collection rate declined significantly, indicating that the influence of the motor speed on the collection rate is more significant.

Fig. 6c shows the interaction of bending angle of comb teeth and radial diameter of comb teeth arrangement on the collection rate. Under the condition that the motor speed was 30 r/min, the collection rate increased with the bending angle of comb teeth, and increased with the increase of the radial diameter of comb teeth arrangement. But when the bending angle of comb teeth increased and the radial diameter of comb teeth arrangement increased, the collection rate increased significantly. When the bending angle of comb teeth increased and the radial diameter of comb teeth arrangement decreased, the collection rate decreased gradually, indicating that the influence of the radial diameter of comb teeth arrangement on the collection rate is more significant.

As indicated by above analysis of the response surface, the priority of motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement for the collection rate was motor speed A, radial diameter of comb teeth arrangement C and bending angle of comb teeth B in turn.

Selection of optimal combination parameters

By analyzing above experiments and data, we found that interaction among factors, including the motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement, has influence on the collection rate, and the influence from each factor varies. To obtain the best combination of parameters, the Optimization module in design-Export was used to predict the optimal value of response surface test.

Considering mechanical efficiency in field work, the optimal range of each factor were determined as follows: motor speed A: 25-35 r/min, bending angle of comb teeth B: 60-120°, radial diameter of comb teeth arrangement C: 600-900 mm, the fruit collection rate Y was set to its maximum value.

The optimal parameters were motor speed A: 25 r/min, bending angle of comb teeth B: 120°, radial diameter of comb teeth arrangement C: 868.45mm. The comprehensive response value of the model surface was optimal, and the collection rate was 91.51%.

The optimized parameters were applied in test bench. Due to the constraints of processing accuracy and experiment materials, the experimental parameters in this paper were as follows: motor speed: 25 r/min, bending angle of comb teeth: 120°, radial diameter of comb teeth arrangement 900 mm. The average collection rate taken from three experiments was 93.82%. The relative error between the experiment results and the model prediction is 2.48%, indicating that the model prediction is highly accurate and the prediction is reliable, thus, the goal of improving the collection rate is achieved.

CONCLUSIONS

1) To increase fruit collection rate, this paper offers a comb-type harvesting test bench. It is mainly composed of a frame, combing and stripping mechanism, baffle, clamping conveying mechanism, control system, fruit-collecting box and transmission system, among which the comb teeth parts in the combing and stripping mechanism can be replaced to conduct experiments with different parameters.

2) Through theoretical and simulation analysis of Cerasus humilis shedding track, it was determined that the main factors affecting the fruit collection rate were motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement. Single factor simulation experiment and bench experiment showed that the collection rate decreased gradually with the increase of motor speed, and increased gradually with the increase of the bending angle of comb teeth or the radial diameter of comb teeth arrangement. The orthogonal experiment showed that motor speed had the largest effect on collection rate, followed by radial diameter of comb teeth arrangement and bending angle of comb teeth.

3) Based on the quadratic response surface model，the optimal combined parameters of motor speed, bending angle of comb teeth and radial diameter of comb teeth arrangement were predicted, and the optimal parameters were motor speed: 25 r/min, bending angle of comb teeth: 120°, and radial diameter of comb teeth arrangement: 868.45mm, the corresponding maximum collection rate was 91.51%.

The bench experiment was carried out with parameters as follows motor speed: 25 r/min, bending angle of comb teeth: 120°, radial diameter of comb teeth arrangement 900 mm, and the collection rate was 93.82%. The relative error with the predicted values was 2.48%, and the goal of improving the collection rate is achieved.

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