STUDY ON SINGLE-BRANCH COMBING OF *Cerasus humilis*
/
钙果单枝梳脱试验研究

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ABSTRACT

In this study, a central unloading reel structure was proposed to achieve continuous harvest of Cerasus humilis, and an indoor test bench was constructed to carry out the combing test of branches. The cross-section of the comb was made of an isosceles triangle, and an orthogonal test was carried out with tooth gap, winch rotational velocity and cross-section base angle as test factors, and fruit breakage rate and leakage rate as test indicators. The results show that the tooth gap and winch rotational velocity have a significant influence on the breakage rate, and the tooth gap and section bottom angle have a significant influence on the fruit leakage rate. Considering the comprehensive loss rate, the appropriate deformation of the comb teeth and the manufacturing difficulty, the optimal values of the three test factors are 10 mm, 130 r/min, and 45°, respectively. At the same time, the maximum combing force of a single branch through the comb is 240 N through the pressure sensor of the test bench. The experimental results can be used as the basis for the structural design of continuous harvesting head.

摘要

本研究设想了一种滚筒中心卸载果实的结构以实现钙果的连续采收，制作了一个室内试验台进行整枝的梳脱试验。梳齿截面采用等腰三角形，以齿间隙、绞盘转速和截面底角为试验因素，以果实破损率和泄露率为试验指标，进行了正交试验，分析了各试验因素对各个指标的影响机制。结果表明，齿间隙和绞盘转速对破损率有着显著的影响，齿间隙和截面底角对漏果率有着显著的影响，考虑综合损失率、梳齿的适当变形和制造难度，三个试验因素的最佳值分别为：10 mm、130 r/min、45°。同时，通过试验台的压力传感器得到单个枝条通过梳齿的最大梳脱力为240 N。试验结果可以作为连续收获采摘头的结构设计依据。

INTRODUCTION

The *Cerasus humilis* tree is a tufted shrub with dense fruits at maturity, and its branches spread out and fall in all directions *(He et al., 2018)*. Its fruit is rich in calcium, which is easily absorbed by the human body, and has gradually been recognized by the market, and the planting area has expanded year by year, facing the problem of harvesting difficulties *(Chang et al., 2011)*. Vibration harvester is widely used in small fruits, such as in high-bush blueberry harvesting *(DeVetter et al., 2019; Yu et al., 2012)*. However, the research object in this paper is unable to transmit high-frequency vibration due to weak branches, and it is difficult to collect fruits. In mechanical harvesting practice, previous researchers have verified the effectiveness of combing fruit *(Du et al., 2019)*. Branches go through the comb gap, the fruit is removed, while gaining kinetic energy, and there is a tendency to splash away from the picking mechanism *(Liu et al., 2021)*. Through the analysis of the previous study, it was found that the *Cerasus humilis* could not withstand the high-speed impact, and would reach a relative static with the comb teeth in a short time after gentle combing, so the fruit could not be unloaded by backward throwing. The unloading device in this study refers to the design of a wild blueberry picking head and is arranged inside the picking head *(Farooque et al., 2014)*. In contrast, in the combing of chrysanthemums and rare Soybean pods, a higher rotation speed is required to obtain enough centrifugal force to leave the combing teeth *(Ehlert et al., 2014; Zhao et al., 2023)*, because they have different mechanical properties from *Cerasus humilis*.

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When the branches pass through the comb tooth gap, the comb teeth have a complex interaction relationship with the branches and fruits. During this process, the fruit may be cracked and scratched by branches *(Du et al., 2020)*. As a cantilever structure, comb teeth may be deformed and lose their working ability under the reaction of branches *(Zhao et al., 2023)*. It is of great significance to study the combing process of a single fruit-bearing branch to understand the harvest of the whole fruit tree. Therefore, a comb stripping test bench is designed to conduct physical tests on the operation effect of a single branch through comb teeth, to obtain the optimal comb structure and operating parameters, as well as the impact force of branches on comb teeth. The research results can guide the design of the structure and operation parameters of the picking head.

MATERIALS AND METHODS

Cerasus humilis combing is a group behaviour, and the time is very short, the combing process is less than 1 s, and the branches with good growth have factors that are not conducive to combing, so the stress of single fruit during combing is difficult to obtain in physical tests, and the theoretical calculation of the stress of single fruit has little significance for the group picking behaviour of *Cerasus humilis*. The performance of the population can only be known through statistics. At the same time, the impact force of the comb teeth is also an important parameter in the design of the picking device, which needs to be tested. Therefore, an indoor test bench was designed that could fully control variables. The comb teeth were still and the pruned branches were pulled through the teeth gap to observe the combing effect of the fruit, make statistics on the leakage rate and breakage rate, and study the statistical effect of fruit picking from a macro perspective. At the same time, the impact force was calculated.

Structure of the test bench

The schematic diagram of the simple comb teeth made in this study to experience the comb stripping process in the field and the envisaged continuous picking head are shown in Fig. 1. As the picking head advances with the machine, the comb teeth rotate backward around its pivot to comb the branches, and the picked fruit slides down into the device located in the centre of the reel after the comb teeth are raised higher than the pivot. The cross-section shape of comb teeth was all circular in previous studies *(Du et al., 2019; Liu et al., 2021)*, to make the simple comb easily in the Fig.1, a circular cross-section is also used. However, if from the contact point of view, under the same external force, the contact area between the fruit of the approximate sphere and the cylindrical surface is smaller than that of the triangular comb tooth, the corresponding contact stress is larger, and theoretically, greater fruit damage will be caused *(Kang et al., 2017)*. Based on the above considerations, a triangular-section comb was used in this study.

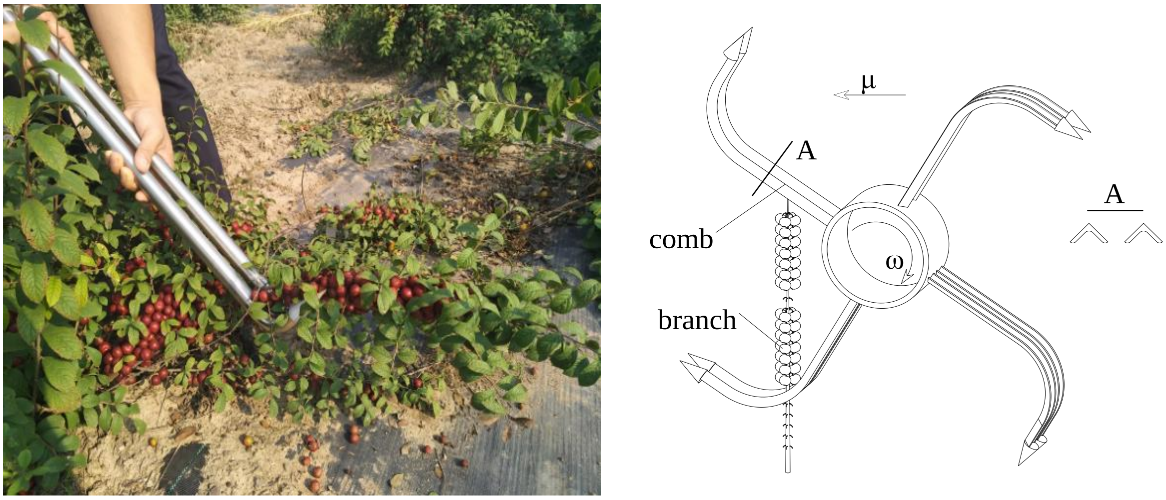

Fig. 1 - Schematic diagram of simple combing and continuous harvesting of *Cerasus humilis*

The structure of the test bench is shown in Fig 2. A winch *13* with a decelerating motor is fixed on the ground, and a speed governor *12* is provided. Two supporting platforms *1* with a height of nearly 1 m are placed, and a rectangular frame *10* is arranged between the two platforms. A pressure sensor *9* is connected to each longitudinal side of the frame. The other end of the sensor has two isosceles triangular sections of comb *8* mounted through a transverse support plate with long holes for adjusting the comb gap. The edge that forms the gap has as large a rounded corner as possible near the tooth surface to prevent scratching the fruit.

One transparent acrylic baffle *7* is placed on each side of the comb teeth to prevent the fruit from falling after the fruits are stripped, to avoid affecting fruit injury, and to facilitate subsequent statistical work. Also, some supporting sensor power supply, transmitter, and other electrical appliances are included.

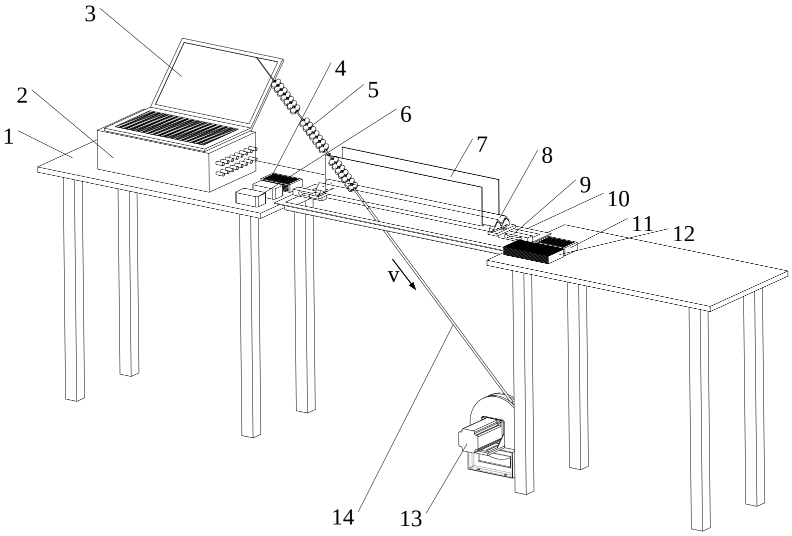

Fig. 2 - Combing test bench

1. Platform; 2. Data acquisition system; 3. Data processing software; 4. Sensor power; 5. Branch; 6. Transmitter; 7. Baffle; 8. Comb; 9. Sensor; 10. Frame; 11. Motor power; 12. Governor; 13. Gear motor and winch; 14. Rope

According to the previous combing experience of the hand-held tool, the quality of the parts above the sensor, and the peak tension of 300 N on the branch, the two pressure sensors adopted the ZEMIC L6D sensor with a measuring range of 0 ~ 200 N and a comprehensive error of ±0.02%. The transmitter is equipped with the same brand, the accuracy is 0.1%, and the output is a 0-5 V standard voltage signal. Before the test bench is installed, an electronic scale is used to test the quality of the accessories above the sensor. After the installation, the transmitter needs to be adjusted to a certain extent, so that the gravity corresponding to the mass can display the correct static voltage signal on the software. One end of the rope is connected to the root of the branch, and the other end is wound around the winch, and the tension and speed of the passing - tooth are provided by the adjustable motor to drive the winch. A nylon winch with a radius of 0.065 m is selected according to the size of the test bench.

Maximum torque required for winch

$$T_{max} = F \times r = 300 \times 0.065\ N \cdot m = 19.5\ N \cdot m \qquad (1)$$

Where: F–estimated maximum tension of branch, 300 N

r–winch radius, 0.065 m

Du et al., (2019), found that the maximum speed of *Cerasus humilis* branches passing vertically through the circular-section of the comb was 0.4 m/s, which had a good effect. Through the observation of his test bench, it is found that the lack of a collecting device causes the fruit to fall after combing, so the statistical damage rate is related to the landing impact. In the continuous picking envisaged in this paper, branches and comb teeth are mostly oblique, which has better fruiting conditions. In the pre-test, it is found that the fruit spread along the comb surface and the accumulation phenomenon is not as serious as the vertical combing, so the passing-teeth speed can be faster, and good results can be obtained even when the value is lower than 1.35 m/s, which is set as the maximum linear speed at the bottom of the winch groove v.

The maximum rotational speed of the gear motor is:

$$\omega_{max} = \frac{v}{r} = \frac{1.35}{0.065} rad = 20.8\ rad/s = 198\ r/min \qquad (2)$$

The maximum power of the gear motor is:

$$\mathrm{P}_{max} = \frac{T_{max} \times \omega_{max}}{9550} = \frac{19.5 \times 198}{9550} = 0.4\ kW \qquad (3)$$

The motor model 6DC400-24GU is selected according to the above calculation. The maximum rotational speed is 200 r/min and the maximum torque is 19.12 N.m. Since the estimated maximum combing force is sufficient, this type of motor meets the requirements.

The gear motor spins the winch, and after the winch wraps the rope, the branch is dragged through the gap between the comb teeth.

The branch movement direction denoted by v shown in Fig.2 is pulled by the winch over the comb teeth, and the fruit is stripped by the comb teeth. The fruit has some damage phenomena, such as leakage, stuck loss, fracturing, and scratching during this process. The combing effect of the test bench is evaluated by statistics of the above loss and damage. At the same time, the comb is also affected by the impact force of the fruit, the impact force is transmitted to the two pressure sensors below. The transmitter converts the sensor signal into a standard voltage signal and then passes it into the signal collector. The signal collector and supporting software analyse the voltage signal and obtain the dynamic data of the impact force of the branch on the comb tooth.

Test materials, methods and indexes

"Nongda No. 4" *Cerasus humilis* branches were regarded as experimental materials in Juxin Modern Agriculture Demonstration Park, Taigu District, Jinzhong City, Shanxi Province, which were cut off and brought back to the laboratory on the morning of September 5, 2022. The third-year basal branches were cut from the root, the branches of this year are moderate in flexibility, dense in fruit, and many fruits seamlessly close together being the most adverse to comb and the extreme material for testing. To make the test results only affected by experimental factors, try to eliminate the difference between the test materials, the selected branches are as close as possible in terms of length, fruit number and compactness. A small number of stunted and damaged fruits were manually removed to facilitate the correct evaluation of the effect of the operation at a later stage. The fruits within 100 mm of the root were removed to facilitate the connection of the rope and eliminate the influence of the motor starting instantaneous speed instability on the test. When removing the fruit, the arrangement of the sparse fruit is not deliberate, because the sparse fruit is easy to pick, has small combing resistance, and it is not easy to leak and damage, which is not conducive to testing the effectiveness of the combing method.

Before each test, the branches were numbered, a number tag was affixed to the root, and the fruit was counted. The branch is placed on the test guide plate at the end of the comb teeth, so that it can enter the teeth smoothly when the rope pulls the root, rather than falling to the side and breaking the branch due to abnormal force. Fig. 3a and b are the images before the test. Fig. 3c and d show the distribution of fruits and branches and leaves on the surface of comb teeth after combing. It can be seen that many leaves and secondary branches with low lignification degrees were combed, and the number of leaves and secondary branches may be related to the space between comb teeth. 3e and f are the retention of leaves and secondary branches and the damage of fruits after combing.


（a） （b） （c）

（d） （e） （f）

Fig. 3 - Before and after the operation of combing

Breakage rate refers to the percentage of the number of fruits with epidermal rupture in the combing process to all fruits in the whole branch, see Equation 4. Statistics were taken immediately after every test, the fallen fruits were not considered, only the damaged fruits on the tooth surface were considered, and the internal injury was not considered.

Leakage rate refers to the percentage of the fruit that is not trapped on the tooth surface as a percentage of all the fruit in the whole branch, see Equation 5. The stiffness of *Cerasus humilis* is low, a large deformation will occur when even a small force is applied, and some smaller fruits will be squeezed through the gap, more likely to occur when the gap is larger. Fruit stuck in the middle of the combs should also be regarded as lost because it is unlikely to enter the fruit-collecting device, such fruit may be crushed by subsequent branches and cause damage, and fruit that falls through the gap is lost regardless of whether it is broken or not.

$$Y_1 = \frac{N_1}{N} \times 100\% \tag{4}$$

$$Y_2 = \frac{N_2}{N} \times 100\% \tag{5}$$

Where: Y_1–breakage rate, [%];

Y_2–leakage rate, [%];

N–number of fruit before combing;

N_1–number of broken fruit;

N_2–the number of leaked fruit.

Orthogonal test

Test factor selection

It is found that the comb gap will affect the success rate of picking from the preliminary test, too big a gap will lead to more leakage, and too small a gap will cause the gap congestion and cause more serious damage to the branch. The gap of comb teeth is regarded as an important parameter of comb tooth structure, which is worth studying. According to the previous size survey of the fruit-bearing branches, the maximum diameter is about 7 mm. The secondary branches and leaves will lean on the primary branches when passing the comb gap, which increases the difficulty of passing. The comb gap is larger than the diameter of the branch, but also less than the minimum diameter of the fruit, the minimum diameter of "Nongda No. 4" *Cerasus humilis* is as low as 15 mm, 10 ~ 14 mm is considered the ideal gap range when considering a certain fruit deformation, and three levels of 10, 12, 14 mm are set.

Comb teeth with isosceles triangle section were used to replace the previous circular section in the study, and the contact between two convex curved surfaces was changed into the contact between convex and plane, and the contact area was increased theoretically *(Johnson et al., 1987)*. They are usually carried out one by one when picking large-size fruits and vegetables, a concave manipulator is used to increase the contact area *(Zhi-Guo et al., 2009)*. *Cerasus humilis* is too small to be picked one by one, and the contact area also cannot be further increased. At the same time, it also has the problem of contact angle in the triangular comb tooth, and the base angle of the isosceles triangle is specified here as the characteristic angle of the comb tooth. Different angles and different forces will cause different working effects, then the comb angle is also regarded as a factor affecting the comb effect, and 3 levels are set, respectively, 30°, 45° and 60°.

According to the author's previous research, the contact velocity of 1.18 m/s (corresponding to the drop height of 70 mm) is the critical height for yielding inside the fruit *(Kang et al., 2023)*. The contact force is complicated when the branch is combed off, it is found that the damage caused is within the acceptable range of mechanical harvest in the pre-test when the winch rotation speed does not exceed 200 r/min. At the same time, the efficiency of the operation is affected by too low speed. The speed of the branches passing through the comb was also regarded as an influencing factor, and three levels of 130, 160 and 190 r/min were set. Equation 2 was used to calculate the corresponding branch velocities, which were 0.9, 1.1 and 1.3 m/s respectively. The no-load speed was adjusted to the target value before the test.

Test method

It can be seen that the winch rotational speed, comb gap and tooth angle are the main factors affecting the operation effect from the above analysis, In order to reduce the number of test, a three-factor and three-level orthogonal test is conducted to find the optimal values of the factors, and the zero-level test is repeated five times (*Klauss et al., 2008*). The influence rule of three factors on the operation effect is studied through the analysis of variance of the test results. Data analysis software Design-Expert 12 was used to design the test, and variance analysis, model construction, and related graph drawing were performed on the test results.

RESULTS

The orthogonal test design and its physical test results data are shown in Table 1. Statistical work was carried out immediately at the end of each test, and the indicators of the last two columns were calculated.

Table 1

Test design and results

Run	Rotational speed (A) （r/min）	Comb gap (B) (mm)	Comb angle (C) (°)	Damage rate (Y_1) （%）	Leakage rate (Y_2) （%）
1	160	12	45	4.3	4.1
2	190	10	45	7.4	0
3	160	10	30	4.6	0
4	160	12	45	4.1	4.3
5	130	10	45	1.1	0
6	160	12	45	4.3	5.9
7	190	12	30	4.9	3.4
8	160	10	60	8.6	1.9
9	130	14	45	2.9	11.3
10	190	12	60	7.3	5.4
11	160	14	30	1.4	10.6
12	130	12	30	1.4	3.3
13	160	12	45	2.9	2.4
14	160	14	60	1.4	11.4
15	160	12	45	4.9	2.8
16	190	14	45	6.9	11.4
17	130	12	60	1.7	10

Linear variance analysis was performed on the damage rate, without considering the interaction between factors and the higher-order terms. The results are shown in Table 2, and the model is extremely significant (P<0.01), indicating that the influence of each test factor on the results can be analysed within the range of test values (*Zhang et al., 2018*). The change in winch rotation speed has a significant effect on the breakage rate (P<0.01), it can also be seen in Fig. 4 that the breakage rate increases from 2% to 6% as the rotation speed increases from 130 r/min to 190 r/min. The faster the relative speed, the greater the impact force must be, and the greater the possibility of breakage. So, the winch rotation speed, that is, the speed of the branches relative to the comb teeth, needs to be controlled at a low level from the point of view of the breakage rate. The change of comb gap has a significant influence on the breakage rate (P<0.01), it can also be seen in Fig. 4 that with the widening of the comb gap from 10 mm to 14 mm, the breakage rate decreases from 5% to 3%. The reason may be that the wider gap allows the branches and leaves to pass more smoothly, the crowding phenomenon is reduced, and the bearing condition of the fruit is improved. The influence of the change of comb angle on the breakage rate is not significant. As can be seen from Fig. 4, the breakage rate is slightly increased when the angle changes from 30° to 60°.

Table 2

Analysis of variance of breakage rate

Source	DF	SS	F-value	P-value	Sig
Model	3	57.22	10.97	0.0007	**
Rotational speed (A)	1	33.15	19.07	0.0008	**
Comb gap (B)	1	18.43	10.6	0.0063	**
Comb angle (C)	1	5.64	3.24	0.095	
Residual	13	20.42			
Total	16	79.82			

Notes: SS is the sum of squares, DF is degrees of freedom, Sig is significance, ** means P < 0.01, $F_{0.01}(1,13)=9.07$, $F_{0.01}(3,13)=5.74$.

The image of fruit breakage is shown in Fig. 3f. Observing the morphology of wounds, it can be found that they are not caused by tooth surface extrusion, but are scratched by lateral buds of branches. The lateral bud exerts a tangential force on the fruit when the branch passes against the fruit. The greater the pressure of the fruit, the greater the tangential force if the fruit is restricted in space at some time. The smaller the comb gap means the greater the extrusion pressure and the higher the breakage rate. When the side bud contacts the fruit at a very low speed, the fruit will be pushed away, speeding up the speed, the side bud will cut through the fruit, the faster the relative speed, the easier to cut in, and the higher the breakage rate.

The change of tooth angle can affect the compression force of fruit, but the influence of this factor on the breakage rate is not significant, which is evidence that the wound is not caused by tooth surface compression.

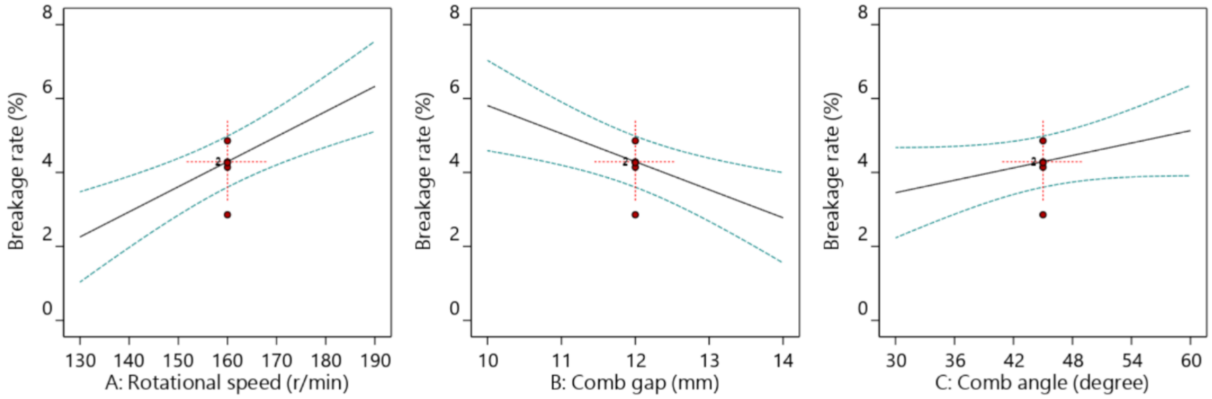

Fig. 4 - Influence of various test factors on breakage rate

Linear regression analysis was performed on the orthogonal test results of the breakage rate, and the model was obtained as shown in equation 6.

$$Y_1 = 0.068A - 0.759B + 0.056C + 0.025 \quad (6)$$

Where：A–Rotational speed of winch, [r/min];

B–Comb gap, [mm];

C–Comb angle, [°].

The coefficient of determination R^2 of the regression model is 0.77, which is not too high, probably because the consistency of agricultural materials is poor, and the number of fruits closes together on the branches and the degree of closeness are not small differences.

Linear ANOVA was performed on the leakage rate, and the results are shown in Table 3. The model was extremely significant ($P<0.01$). The change in winch rotational speed has no significant effect on the leakage rate. It can also be seen from Fig. 5 that the change in leakage rate is very small when the rotational speed increases from 130 r/min to 190 r/min. The change of the comb tooth gap has a significant effect on the leakage rate ($P<0.01$), it can also be seen in Fig. 5 that with the widening of the comb gap from 10 mm to 14 mm, the fruit leakage rate increases from 0% to 10%. The reason must be that the wider gap makes it difficult to intercept the fruit, allowing more fruit to squeeze through the gap. From the point of view of the leakage rate, the comb gap needs to be controlled at a low level. The comb angle has a significant impact on the leakage rate. It can also be seen from Fig. 5 that when the comb angle changes from 30° to 60°, the leakage rate also increases greatly. This is because the fruit wedged into the comb is also regarded as a leaked fruit, and the larger angle produces greater lateral extrusion pressure, resulting in some of the fruit getting stuck.

Table 3

Analysis of variance of leakage rate

Source	DF	SS	F-value	P-value	Sig
Model	3	248.25	32.21	<0.0001	**
Rotational speed (A)	1	2.27	0.8848	0.3640	
Comb gap (B)	1	229.59	89.39	<0.0001	**
Comb angle (C)	1	16.39	6.38	0.0253	*
Residual	13	33.4			
Total	16	281.65			

Notes: SS is the sum of squares, DF is degrees of freedom, Sig is significance, ** means P < 0.01, * means P < 0.05, $F_{0.01}(1,13)=9.07$, $F_{0.01}(3,13)=5.74$, $F_{0.05}(1,13)=4.67$, $F_{0.05}(3,13)=3.41$.

Linear regression analysis was carried out on the orthogonal test results of the leakage rate, and the model was obtained as shown in equation 7.

$$Y_2 = -0.018A + 2.679B + 0.095C - 28.406 \quad (7)$$

The coefficient of determination R^2 of the regression model is 0.85, which is slightly higher than that of the damage rate above.

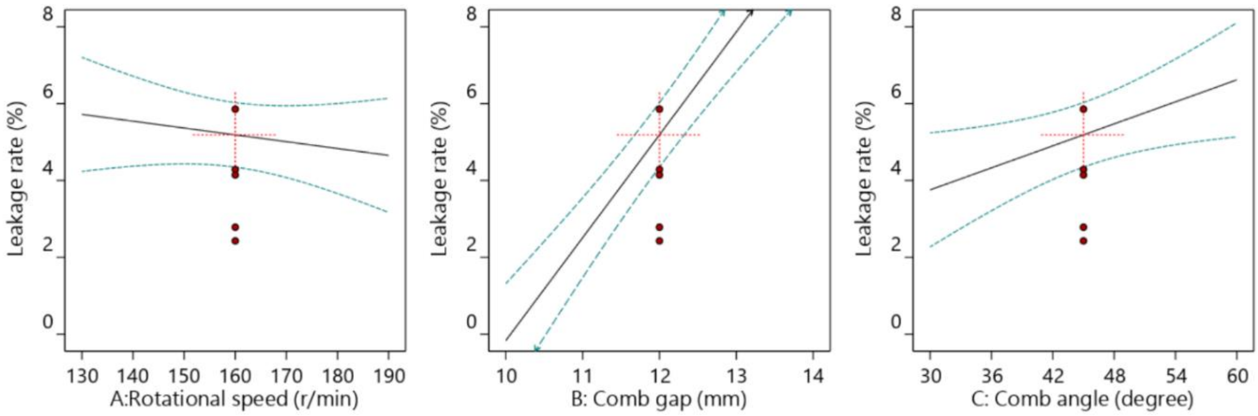

Fig. 5 Influence of each test factor on leakage rate

The reason for examining the models of breakage rate and leakage rate separately is to understand the mechanism by which each of them is affected by factors. It can be seen from the above that factors that have the greatest influence on the breakage rate are the winch rotational speed and the comb gap, while factor that has the greatest influence on the fruit leakage rate is the comb gap, and the bottom angle of the comb teeth only has a certain influence on the leakage rate. Then the combined loss rate is obtained by adding the last two columns in Table 3. The 5th test point with the smallest value is selected, with winch rotational speed of 130 r/min, comb gap of 10 mm, and bottom angle of 45°.

The selection of the results of the comb gap is in line with *Du's* mechanical theory analysis results; he believes that a smaller comb gap has smaller comb withdrawal force and fruit damage *(Du et al., 2019)*. In practice, the comb teeth should be made of materials with high stiffness, which will be subjected to horizontal and vertical impact forces when the branch is pulled off, which will widen the gap, making the actual gap greater than the ideal set value *(Arak et al., 2021)*. The base angle of 45° is selected because its fruit leakage rate is medium, and it can also be made of ready-made angle steel.

The peak value of combing force is the maximum force of branches on combing teeth during combing, which is related to the closeness of the sample fruits. This force is the key load parameter for selecting the tooth material and designing the tooth structure *(Du et al., 2021)*. Although the force–time history data corresponding to each sample is obtained in the orthogonal test, no correlation is found between several test factors, even if the correlation is not of practical significance, only the maximum value has application value. When harvesting, different measures will not be taken according to the closeness of fruits, and the closeness of fruits could not be identified, and the comb structure designed according to the maximum comb force can adapt to the different closeness of fruits. The distribution of the maximum contact force of each test is shown in Fig.6.

The average value is not used here, because the value higher than this index is ignored, and the safety and reliability of picking comb teeth designed according to this index cannot be guaranteed. The maximum comb contact force of all tests is 240 N, which has reference significance for the subsequent design.

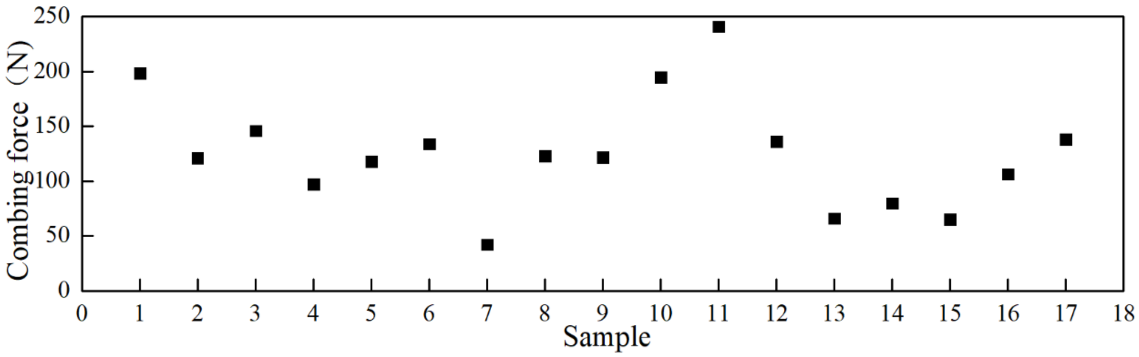

Fig. 6 - Maximum combing force of each sample

CONCLUSIONS

(1) Aiming at the assumed picking principle, a single branch combing test bench based on triangular section combs was designed. Orthogonal tests were carried out with tooth gap, tooth angle and winch speed (passing speed) as test factors, and breakage rate and leakage rate as test indexes. The influence mechanism of the test factors on each index is analysed. The factors that have a significant influence on the breakage rate are the passing speed and the gap of the comb teeth, and the gap of the comb teeth and the angle of the comb teeth have a significant influence on the leakage rate. By synthesizing the two test indexes, the optimal values of the test factors are as follows: comb gap is 10 mm; comb angle 45°; winch rotational speed 130 r/min.

(2) In the test, it was also obtained that the maximum combing force of the branches through the combing teeth was 240 N, which was much larger than the separation force of a single fruit and related to the closeness of fruits. The force is the load condition for the design of comb structure and the selection of power.

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