# Design and parameters optimization of the curved sieve for an air suction jujube harvester

Shenghe Bai[1,2], Yanwei Yuan[1,2*], Kang Niu[2], Liming Zhou[2], Bo Zhao[2], Liguo Wei[2], Lijing Liu[1,2], Xuejun Zhang[3]

(1. *College of Engineering, China Agricultural University, Beijing 100083, China*;
2. *National Key Laboratory of Agricultural Equipment Technology, Chinese Academy of Agricultural Mechanization Sciences Group Co., Ltd., Beijing 100083, China*;
3. *College of Mechanical and Electrical Engineering, Xinjiang Agricultural University, Urumqi 830052, China*)

**Abstract:** In order to improve the screening performance and cleaning effect of the jujube harvesting machinery cleaning device, a vibrating curved screen device was designed in this study. By analyzing the structure mechanism of the curved sieve body, it was obtained that the arc-shaped mesh hole spacing *S* was 15-25 mm and the curved mesh hole curvature *U* was 90°-150°. By exploring the movement state and stress of jujube and impurities on the curved sieve body, it was determined that the horizontal spacing *L* of the curved layer sieve was 30 mm and the vertical spacing *H* was 45-65 mm. Taking the vertical spacing *H* of the curved layer sieve, the curvature *U* of the curved mesh hole, and the spacing *S* of the curved mesh hole as the experimental factors, considering the screening efficiency *α* and the impurity content *β* of the jujube as the response values, the three-factor three-level quadratic regression orthogonal experiment was designed, establishing the regression mathematical model of each factor and response value, and the multiple target optimization algorithm of Design-expert software was used to optimize various factors. The results showed that the influence factors on the screening efficiency were in the descending order as: the arc screen spacing, the vertical spacing of the curved layer screen, and the curved screen hole curvature; The significant factors affecting the impurity content of jujube were in the descending order as: the arc screen spacing, the curved screen hole curvature, and the vertical spacing of the curved layer screen. The experimental results were verified by the optimized combination of parameters: when the vertical spacing *H* of the curved layer screen was 65 mm, the curved screen hole curvature *U* was 110°, and the arc screen spacing *S* was 23 mm, the average screening efficiency *α* in the test was 91.09%. The relative error between the experimental verification value and the theoretical optimization value was 1.36%, which was less than 5%. The impurity content of jujube *β* in the test was 1.02%. The relative error between the experimental verification value and the theoretical optimization value was 2.00%, which was also less than 5%. The test results can provide a reference for the research and optimization of the subsequent air-suction-type jujube harvester cleaning device.

**Keywords:** jujube harvesting, cleaning device, curved sieve, sieve structure, conveying pipe, mathematical model
**DOI:** 10.25165/j.ijabe.20241702.7818

**Citation:** Bai S H, Yuan Y W, Niu K, Zhou L M, Zhao B, Wei L G, et al. Design and parameters optimization of the curved sieve for an air suction jujube harvester. Int J Agric & Biol Eng, 2024; 17(2): 132–139.

## 1 Introduction

At present, the cleaning method of jujube harvesting machinery is mainly airflow type and vibrating screen type[1-4], and the cleaning device is one of the important components of the air suction jujube harvester, which working performance has a direct and inevitable relationship with many indicators such as loss rate and impurity of the jujube[5-12].

For different types of sieves, previous researchers have conducted a lot of research on mesh size, screen inclination, distribution law and optimization configuration[13-16]. Dong et al.[17] used discrete element method to explore the law between vibrating screen frequency, amplitude and screen inclination angle in order to obtain the best screening efficiency; Fernandez et al. Revealed the flow characteristics of particles through a double-layer banana sieve[18]; Jiao et al.[19,20] studied the optimal configuration relationship between the mesh diameter and the screen inclination angle, revealing the influence of the mesh diameter and the screen inclination on the screening efficiency; Wang et al.[21] proposed a shell sieve body. In order to obtain the best screen efficiency, the combination of simulation and experiment was used to obtain the optimal combination of shell sieve size and distribution; Jiang et al.[22] used DEM simulation software to study the relationship between the effect of circular sieve of circular sieve and square sieve on the screening efficiency of vibrating screen by changing the length of the sieve surface; Yang[23] discussed the problem of tandem grading of curved screens. According to the above

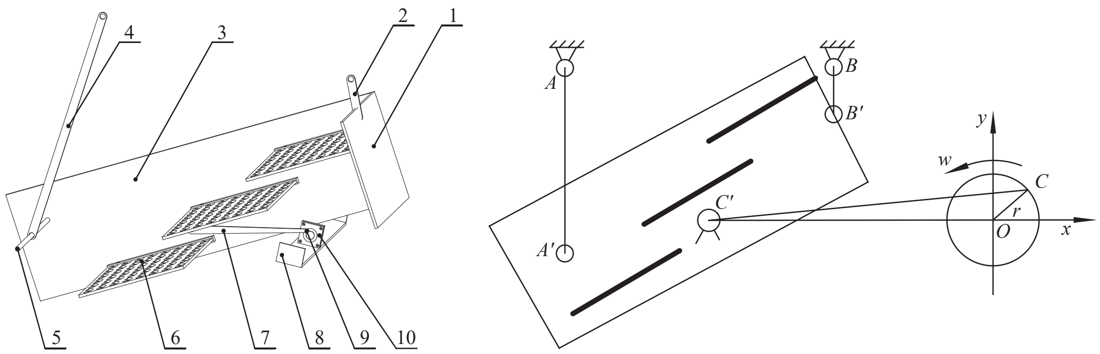
**Received date:** 2022-07-24 **Accepted date:** 2024-02-07
**Biographies: Shenghe Bai**, Engineer, research interest: agricultural machinery and intelligent equipment, Email: 1114963067@qq.com; **Kang Niu**, Professor, research interest: agricultural machinery and intelligent equipment, Email: niukag@163.com; **Liming Zhou**, Professor, research interest: agricultural machinery and intelligent technology, Email: haibo1129@163.com; **Bo Zhao**, Professor, research interest: agricultural machinery and intelligent technology, Email: zhaoboshi@126.com; **Liguo Wei**, Professor, research interest: agricultural machinery and intelligent technology, Email: weilg78@126.com; **Lijing Liu**, Professor, research interest: agricultural machinery and intelligent equipment, Email: xyliulj@sina.com; **Xuejun Zhang**, Professor, research interest: agricultural machinery and equipment, Email: tuec@163.com.
***Corresponding author: Yanwei Yuan**, Professor, research interest: agricultural machinery and intelligent technology. National Key Laboratory of Agricultural Equipment Technology, Chinese Academy of Agricultural Mechanization Sciences Group Co., Ltd., Beijing 100083, China. Tel: +86-13522326652, Email: yyw215@163.com.

references, factors such as mesh size, screen inclination and distribution law have an important influence on the screening efficiency. At present, there is no report on the influence of the jujube clearing sieve device on the cleaning performance at home and abroad. Therefore, the effects of mesh size, distribution law and optimal configuration on the screen effect of jujube are still unclear.

Based on the previous research on vibrating screen, through the previous research on the woven sieve, round sieve, round sieve, rod sieve and shell sieve, this paper found: Although the woven sieve has good permeable performance, the sieve hole is easy to be deformed, which is not conducive to continuous sieving of the jujubes and impurities; The sieving effect of the round hole sieve is good, but it is easy to cause clogging problem; Although the sifting sieve has better cleaning ability, the jujube loss rate is low, causing local accumulation problems; Shell sieve push ability is relatively strong, but it will cause the jujube damage. Therefore, combining the advantages of the above four sieves and aimed at the problems, a three-layer curved sieve body was designed, analyzing the movement state of the jujubes and impurities on the curved sieve body, and studying the degree of influence of various parameters of curved sieve on the cleaning performance of jujube[24-26]. By analyzing the influence of various parameters on the screening performance, the optimal parameter combination was obtained, which provided reference for subsequent research and optimization of curved sieve structure.

## 2 Vibration curved screen structure and parameter design

The vibrating curved screen is composed of arc-shaped screen body, crank, baffle, DC motor, boom and rocker. The structure and working diagram are shown in Figure 1. The mechanism mainly screens out the crushed stone and clods mixed in the jujubes, enhances the sorting ability and the permeable performance. The materials of the connecting rod components are selected from high-quality carbon steel (quenching treatment). According to the previous research theory[27,28], the paper determines that the $L_{OC}$ is 20 mm, the $L_{AA'}$ is 425 mm, the $L_{BB'}$ is 70 mm, and the $L_{CC'}$ is 210 mm. The initial angle of the vibrating curved screen to the ground is 5°.




a. Vibrating curved screen structure b. Vibrating curved screen working diagram

1. Horizontal baffle 2. Left boom 3. Side baffle 4. Right boom 5. Right boom support 6. Curved screen 7. Rocker 8. DC motor frame 9. Crank 10. DC motor. $O$ point is the coordinate origin; $x$, $y$ is the coordinate axis; $L_{OC}$, $L_{AA'}$, $L_{BB'}$, $L_{CC'}$ are the crank length, left boom length, right boom length, rocker length, mm; $\omega$ is the crank speed, r/min; $r$ is the eccentricity of the vibrating curved screen distance, mm.

Figure 1 Vibrating curved screen structure and working diagram

## 3 Design and work analysis of curved screen structure

### 3.1 Structural design

The curved screen structure is shown in Figure 2. The curved screen body is mounted on the side fence by rails and then fixed by bolts and nuts for easily disassembling, repair and replacement. The paper adopts a 3-layer curved sieve from to better sift the jujubes and impurities, and improve the cleaning performance. According to the preliminary investigation and preliminary tests, the longitudinal diameter of jujube is 48.06-55.54 mm, and the two waist diameters (front and rear transverse diameter, left and right transverse diameter) are 28.03-35.23 mm and 35.65-39.98 mm, respectively. Therefore, in order to ensure that the jujubes does not accumulate on the curved sieve body, reduce the missing rate of the jujube, and improve the screening performance of the jujube, it is determined that the spacing of the unit curved screen holes of the curved sieve body $S$ ($r_2$-$r_1$) is 15-25 mm, $r_1$ is 5 mm, curved screen hole curvature $U$ is 90°-150°, curved screen body length $J$ is 350 mm, width $K$ is 230 mm, the horizontal spacing $M$ between the unit curved screen holes is 65 mm, and the longitudinal spacing $N$ is 35 mm. Its material is nylon (PA).

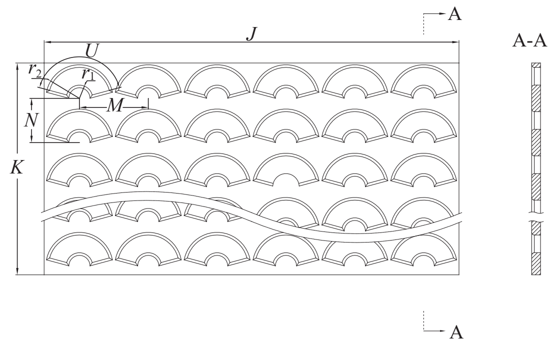



Figure 2 Curved screen structure

### 3.2 Work analysis

When the jujubes and impurities (mainly gravel and clods) are thrown obliquely from the airlock to the vibrating curved screen, through the vibration and swing of the screen surface, the jujube can be separated from the crushed stone and the soil block three times. The vibrating curved screen is moved in a straight harmonic mode, as shown in Figure 3, which is a motion and force analysis diagram of jujubes and impurities.

As shown in Figure 3a, the motion analysis equation for the jujubes and impurities is listed:

$$\begin{cases} v_{m+1}\cos\theta_{m+1} = v_0\cos\theta_0 + \sum_{m=0}^{2、4、6} g t_m + \sum_{m=1}^{3、5} a_1 t_m \\ v_{m+1}\sin\theta_{m+1} = v_0\sin\theta_0 + \sum_{m=1}^{3、5} a_2 t_m \end{cases} \quad (1)$$

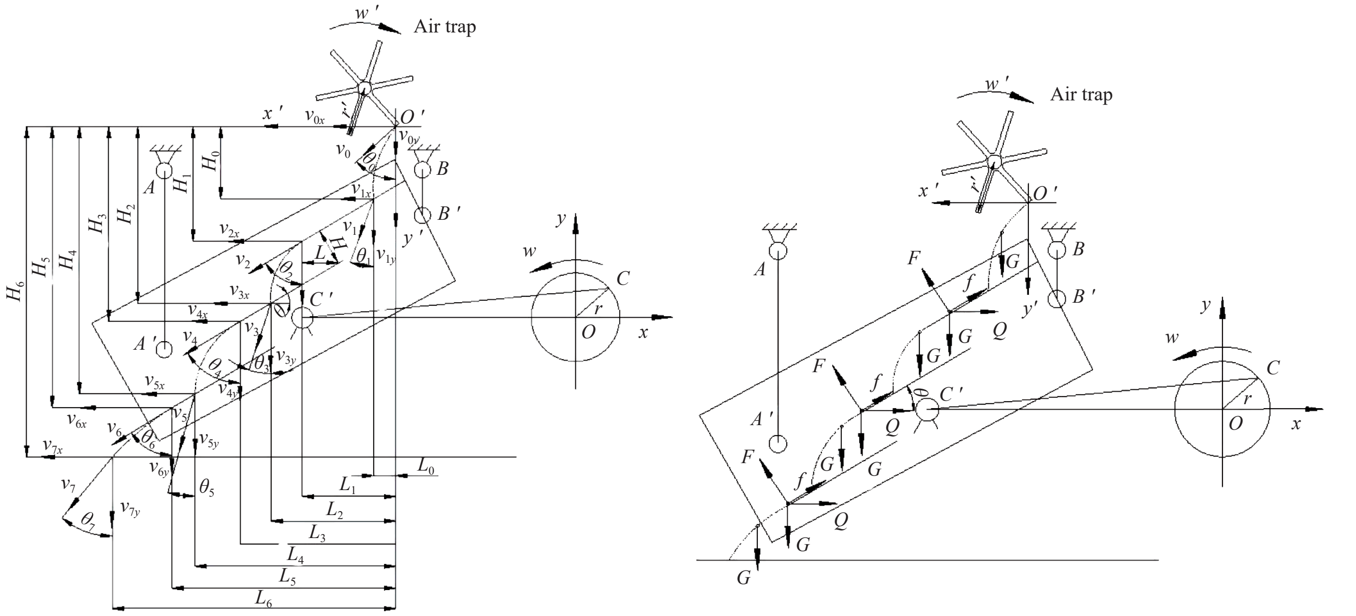
Analyze and calculate equation (1) to obtain equation (2):

$$\begin{cases} H_m = \sum_{m=0}^{2、4、6}\left(v_m\cos\theta_m t_m + \frac{1}{2}g t_m^2\right) + \sum_{m=1}^{3、5}\left(v_m\cos\theta_m t_m + \frac{1}{2}a_1 t_m^2\right) \\ L_m = \sum_{m=0}^{2、4、6} v_m\sin\theta_m t_m + \sum_{m=1}^{3、5}\left(v_m\sin\theta_m t_m + \frac{1}{2}a_2 t_m^2\right) \end{cases} \quad (2)$$

When the jujubes and impurities are thrown out from the airlocker, they are dropped onto the vibrating curved screen after the oblique throwing motion. At this time, the stress analysis of the jujubes and impurities during the movement is shown in Figure 3b.

$$\begin{cases} f = \mu m g\cos\theta \\ Q = m\omega^2 r\sin\omega t \\ a_1 = \dfrac{mg - f\sin\theta}{m} = (1-\mu\sin\theta\cos\theta)g \\ a_2 = \dfrac{Q - f\cos\theta}{m} = \omega^2 r\sin\omega t - \mu g\cos^2\theta \end{cases} \quad (3)$$

Analyzing Equations (1)-(3) to obtain Equations (4)-(6):




a Motion analysis of the jujube and impurity

b Stress analysis chart of the jujube and impurity

Note: In Figure 3a, the $O$, $O'$ point are the coordinate origin; $x$, $y$, $x'$, $y'$ are the coordinate axes; $\omega$, $\omega'$ are the crank speed and the damper speed respectively, r/min; $r$, $r'$ are the crank radius and the wind deflector radius respectively, m; $\theta$ is the angle between the curved screen and the horizontal direction, (°); $H$ is the vertical spacing of the curved layer sieve, m; $L$ is the curved layer sieve horizontal spacing, m; $v_0$ is the initial velocity of the jujubes and impurities, m/s; $v_{0x}$ is the velocity of $v_0$ in the horizontal direction, m/s; $v_{0y}$ is the velocity of $v_0$ in the vertical direction, m/s; $\theta_0$ is the angle between $v_0$ and the vertical direction, (°); $v_1$ is the velocity of the jujubes and impurities thrown to the upper sieve, m/s; $v_{1x}$ is the velocity of $v_1$ in the horizontal direction, m/s; $v_{1y}$ is $v_1$ divides the velocity vertical direction, m/s; $\theta_1$ is the angle between $v_1$ and the vertical direction, (°); $v_2$ is the speed at which the jujubes and impurities are thrown out from the upper sieve, m/s; $v_{2x}$ is $v_2$ dividing speed in the horizontal direction, m/s; $v_{2y}$ is $v_2$ dividing speed in the vertical direction, m/s; $\theta_2$ is the angle between $v_2$ and the vertical direction, (°); $v_3$ is the jujubes and impurities throwing medium screen speed, m/s; $v_{3x}$ is $v_3$ in the horizontal direction, m/s; $v_{3y}$ is $v_3$ in the vertical direction, m/s; $\theta_3$ is $v_3$ and vertical angle, (°); $v_4$ is the speed at which the jujubes and impurities are thrown out from the sieve, m/s; $v_{4x}$ is $v_4$ in the horizontal direction, m/s; $v_{4y}$ is $v_4$ in the vertical direction, m/s; $\theta_4$ is the angle between $v_4$ and the vertical direction, (°); $v_5$ is the speed at which the jujubes and impurities are thrown to the lower sieve, m/s; $v_{5x}$ is the velocity of $v_5$ in the horizontal direction, m/s; $v_{5y}$ is $v_5$ divides the velocity in the vertical direction, m/s; $\theta_5$ is the angle between $v_5$ and the vertical direction, (°); $v_6$ is the speed at which the jujubes and impurities are thrown out from the lower sieve, m/s; $v_{6x}$ is the velocity of $v_6$ in the horizontal direction, m/s; $v_{6y}$ is $v_6$ divides the velocity in the vertical direction, m/s; $\theta_6$ is the angle between $v_6$ and the vertical direction, (°); $v_7$ is the velocity when the jujubes and impurities are thrown to the ground, m/s; $v_{7x}$ is the velocity of $v_7$ in the horizontal direction, m/s; $v_{7y}$ is the velocity of $v_7$ in the vertical direction, m/s; $\theta_7$ is the angle between $v_7$ and the vertical direction, (°); $H_0$ is the vertical height of the jujubes and impurities thrown to the upper sieve, m; $L_0$ is the horizontal distance between the jujubes and impurities thrown to the upper sieve, m; $H_1$ is the vertical height of the jujubes and impurities from the initial point to the end of the upper sieve, m; $L_1$ is the horizontal distance between the jujubes and impurities from the initial point the end of the sieve, m; $H_2$ is the vertical height of the jujubes and impurities from the initial point to the middle sieve, m; $L_2$ is the horizontal distance between the jujubes and impurities thrown from the initial point to the middle sieve, m; $H_3$ is the vertical height of the jujubes and impurities from the initial point to the end of the middle sieve, m; $L_3$ is the horizontal distance between the jujubes and impurities from the initial point to the end of the middle sieve, m; $H_4$ is the vertical height of the jujubes and impurities thrown from the initial point to the lower sieve, m; $L_4$ is the horizontal distance between the jujubes and impurities from the initial point to the lower sieve, m; $H_5$ is the vertical height of the jujubes and impurities from the initial point to the end of the lower sieve, m; $L_5$ is the horizontal height of the jujubes and impurities from the initial point to the end of the lower sieve, m; $H_6$ is the vertical height of the jujubes and impurities from the initial point to the end of the ground, m; $L_6$ is the horizontal height of the jujubes and impurities from the initial point to the end of the ground, m. In Figure 3b, the $O$, $O'$ point is the coordinate origin, $x$, $y$, $x'$, $y'$ are the coordinate axes; $\omega$, $\omega'$ are the crank speed and the damper speed respectively, r/min; $r$, $r'$ are the crank radius and the wind deflector radius respectively, m; $\theta$ is the angle between the curved screen and the horizontal direction, (°); $F$ is the support force of the jujubes and impurities, N; $f$ is the friction force of the jujubes and impurities on the curved sieve body, N; $G$ is the gravity of the jujubes and impurities, N; $Q$ is the inertia force of the curved sieve against the jujubes and impurities, N.

Figure 3 Stress analysis of the jujubes and impurities

$$H_6 = v_0\cos\theta_0\sum_{m=1}^{6}(t_m) + g\left[\left[\sum_{m=0}^{2,4,6}\left(\frac{t_m^2}{2}\right) + t_0\sum_{m=1}^{6}(t_m) + t_2\sum_{m=3}^{6}(t_m) + t_4\sum_{m=5}^{6}(t_m)\right] + (1-\mu\sin\theta\cos\theta)\left[\sum_{m=1}^{3,5}\left(\frac{t_m^2}{2}\right) + t_1\sum_{m=1}^{6}(t_m) + t_3\sum_{m=4}^{6}(t_m) + t_5 t_6\right]\right] \quad (4)$$

$$L_6 = v_0\sin\theta_0\sum_{m=1}^{6}(t_m) + \left(\omega^2 r\sin\omega t - \mu g\cos^2\theta\right)\left[\sum_{m=1}^{3,5}\left(\frac{t_m^2}{2}\right) + t_1\sum_{m=2}^{6}(t_m) + t_3\sum_{m=4}^{6}(t_m) + t_5 t_6\right] \quad (5)$$

$$\begin{cases} v_7\cos\theta_7 = v_0\cos\theta_0 + (t_0+t_2+t_4+t_6)g + \\ \qquad (1-\mu\sin\theta\cos\theta)(t_1+t_3+t_5)g \\ v_7\sin\theta_7 = v_0\sin\theta_0 + \left(\omega^2 r\sin\omega t - \mu g\cos^2\theta\right)(t_1+t_3+t_5)g \end{cases} \quad (6)$$

As shown in Figure 3a, the vertical spacing $H$ and the horizontal spacing $L$ of the curved layer sieve are analyzed and calculated to obtain Equation (7):

$$\begin{cases} H = [(H_2-H_1)-(L_2-L_1)\sin\theta]\cos\theta \\ L = [J-(L_2-L_1)]\cos\theta \end{cases} \quad (7)$$

Equation (8) is obtained by arranging Equation (2):

$$\begin{cases} H_2-H_1 = (v_0\cos\theta_0 + gt_0 + (1-\mu\sin\theta\cos\theta)gt_1) \\ L_2-L_1 = \left[v_0\sin\theta_0 + \left(\omega^2 r\sin\omega t - \mu g\cos^2\theta\right)t_1\right] \end{cases} \quad (8)$$

Comprehensive analysis Equations (7) and (8) to obtain the vertical spacing $H$ of the curved layer sieve, and the horizontal spacing $L$ calculation Equation (9):

$$\begin{cases} H = [(H_2-H_1)-(L_2-L_1)\sin\theta]\cos\theta = [(v_0\cos\theta_0 + gt_0 + \\ \quad (1-\mu\sin\theta\cos\theta)gt_1) - (v_0\sin\theta_0 + (\omega^2 r\sin\omega t - \\ \quad \mu g\cos^2\theta)t_1)\sin\theta]\cos\theta \\ L = [J-(L_2-L_1)]\cos\theta = [J-(v_0\sin\theta_0 + \\ \quad (\omega^2 r\sin\omega t - \mu g\cos^2\theta)t_1]\cos\theta \end{cases} \quad (9)$$

where, $m$ is the jujube and impurity mass, kg; $g$ is a gravitational acceleration, 9.8 m/s$^2$; $a_1$ is the horizontal acceleration of the jujubes and impurities, m/s$^2$; $a_2$ is the vertical acceleration of the jujubes and impurities, m/s$^2$; $t_0$ is the time used for jujubes and impurities to be sent to the upper sieve, s; $t_1$ is the time taken for the jujubes and impurities from the initial point to the end of the upper sieve, s; $t_2$ is the time taken for the jujubes and impurities to be thrown from the initial point to the middle sieve, s; $t_3$ is the time taken for the jujubes and impurities from the initial point to the end of the middle sieve, s; $t_4$ is the time taken for the jujubes and impurities to be thrown from the initial point to the lower sieve, s; $t_5$ is the time taken for the jujubes and impurities from the initial point to the end of the lower sieve, s; $t_6$ is the time taken for the jujubes and impurities to be thrown from the initial point to the ground, s.

According to the previous device design, taking $\omega'$=200 r/min, $r'$=135 mm, the initial velocity of the jujubes and impurities is $v_0$= $\omega' r'$=0.45 m/s. Substituting $\mu$=0.58, $\theta$=5°, $\omega$=140 r/min, $r$=20 mm into the above equations, $H_6$ is 0.88 m, $L_6$ is 1.01 m, and $v_7$ is 2.97 m/s. The height of the impurity movement is 0.88 m, the horizontal distance is 1.01 m, and the speed at the time of landing is 2.91 m/s. Since the weight of the jujube is small, the force received when landing will not cause loss to the jujube. According to the above and preliminary tests, it is determined that $L$ is 30 mm and $H$ is 45-65 mm. If $H$ is greater than 65 mm, shortening the movement time of jujubes and impurities in the curved sieve body is not completely separated, less than 45 mm, which is not conducive to realization the screening of the jujubes and impurities.

## 4 Field performance test

### 4.1 Experiment conditions and equipment

The test site was selected in the Seventh Regiment of the First Division of the Xinjiang Production and Construction Crops. The jujube planting in this area was planted in a dwarf and dense planting pattern (The plant spacing was 4 m×1.5 m, the age of the tree was 5a, and the number is about 1650 plants/hm$^2$). The soil moisture content of the test site was 13.95%, and the firmness was 0.68 MPa.

The main equipment of the test was an air suction type jujube harvester vibrating curved screen device, a quartz electronic stopwatch, a soil firmness meter, a soil moisture meter, steel tape measure, and sample bag, etc. The field work of the machine is shown in Figure 4.

Figure 4 Field test

### 4.2 Experiment factors and indicators

Through theoretical analysis and preliminary tests, it was shown that the vertical spacing $H$ of the curved layer sieve, the curvature $U$ of the curved screen hole, and the spacing $S$ of the curved screen hole were selected as test factors, and the design level of the test factors is shown in Table 1. The vertical spacing of the curved layer screen was more than 65 mm, which shortened the movement time the jujubes and impurities in the curved sieve body, and could not fully exert the screening effect. Less than 45 mm, the vibration amplitude of the jujubes and impurities was not large, which was not conducive to the screening of the jujubes and impurities; The curvature of the curved screen hole was greater than 150°, which was not easy to be sieved by the jujubes and impurities, resulting in the omission of the jujubes. Less than 90°, the screening efficiency was low, which affected the performance of cleaning performance; The spacing of the curved screen holes was larger than 25 mm, which increased the amount of the jujube leakage, and it was difficult to screen impurities. If it was less than 15 mm, impurities such as gravel and clods were difficult to be screened, resulting in a large inclusion ratio.

According to the GB/T 5667-2008 (Agricultural Machinery Production Test Method) and GB/T 5262-2008 (General Rules for Measuring Methods of Agricultural Machinery Test Conditions) standard design test[29-30], the vibrating curved sieve screening efficiency $\alpha$ and the jujube impurity content $\beta$ were used as test indicators, and the test indicators were calculated as follows:

**Table 1 Factors and levels of the test**

| No. | The vertical spacing of the curved layer screen $X_1$/mm | The curved screen hole curvature $X_2$/(°) | The arc screen spacing $X_3$/mm |
|---|---|---|---|
| –1 | 45 | 90 | 15 |
| 0 | 55 | 120 | 20 |
| 1 | 65 | 150 | 25 |

$$\begin{cases} \alpha = \dfrac{k_1}{k_1 + k_2} \\ \beta = \dfrac{p_1}{p_1 + p_2} \end{cases} \tag{10}$$

where, $\alpha$ is the screening efficiency, %; $k_1$ is the mass of the vibrating curved sieve, g; $k_2$ is the mass of the sieve box less than the vibrating curved sieve, g; $\beta$ is the jujube impurity, %; $p_1$ is the mass of the impurities in the jujube box, g; $p_2$ is the mass of the jujube in the jujube box, g.

### 4.3 Test results and analysis

4.3.1 Establishment and saliency analysis of regression models

Three-factor and three-level tests were designed according to the Box-Benhnken test principle. The test design and test response values are listed in Table 2.

According to the data samples in Table 2, the data was subjected to multiple regression fitting analysis using Design-expert 8.0.6 software[31-32], the targets of the screening efficiency and the impurity content of jujube were established, and the vertical spacing of the curved layer screen, the curved screen hole curvature and the arc screen spacing were a quadratic polynomial response surface regression model of three independent variables[36-38], as shown in Equations (11) and (12). The results of the analysis of variance are listed in Table 3.

$$Y_1 = 93.92 + 1.59X_1 + 0.91X_2 + 1.87X_3 + 0.062X_1X_2 - 0.63X_1X_3 - 1.43X_2X_3 + 2.81X_1^2 + 0.22X_2^2 - 4.24X_3^2 \tag{11}$$

$$Y_2 = 1.60 - 0.10X_1 - 0.25X_2 - 0.34X_3 + 0.27X_1X_2 + 0.11X_1X_3 - 0.055X_2X_3 - 0.28X_1^2 - 0.087X_2^2 + 0.099X_3^2 \tag{12}$$

**Table 2 Test design scheme and response value results**

| No. | The vertical spacing of the curved layer screen $X_1$ | The curved screen hole curvature $X_2$ | The arc screen spacing $X_3$ | The screening efficiency $\alpha$/% | The impurity content of jujube $\beta$/% |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 94.27 | 1.08 |
| 2 | 1 | 0 | –1 | 86.57 | 1.59 |
| 3 | 1 | –1 | 0 | 91.95 | 1.09 |
| 4 | 0 | 1 | –1 | 90.63 | 1.78 |
| 5 | 0 | 0 | 0 | 94.49 | 1.50 |
| 6 | –1 | 1 | 0 | 90.58 | 0.82 |
| 7 | 0 | 0 | 0 | 93.48 | 1.63 |
| 8 | 0 | 0 | 0 | 92.99 | 1.70 |
| 9 | –1 | 0 | 1 | 88.42 | 1.02 |
| 10 | 0 | 1 | 1 | 90.63 | 1.01 |
| 11 | –1 | 0 | –1 | 82.53 | 1.94 |
| 12 | 1 | 0 | 1 | 89.95 | 1.10 |
| 13 | 0 | –1 | 1 | 92.03 | 1.55 |
| 14 | 0 | 0 | 0 | 94.38 | 1.68 |
| 15 | –1 | –1 | 0 | 88.51 | 1.92 |
| 16 | 0 | –1 | –1 | 86.31 | 2.10 |
| 17 | 0 | 0 | 0 | 94.28 | 1.48 |

**Table 3 Test design scheme and response value results**

| Source | The screening efficiency | | | | The impurity content of jujube | | | |
|---|---|---|---|---|---|---|---|---|
| | Sum of squares | Degree of freedom | $F$ | $p$ | Sum of squares | Degree of freedom | $F$ | $p$ |
| Model | 179.56 | 9 | 36.05 | <0.0001 | 2.27 | 9 | 28.58 | 0.0001 |
| $X_1$ | 20.16 | 1 | 36.43 | 0.0005 | 0.088 | 1 | 10.00 | 0.0159 |
| $X_2$ | 6.68 | 1 | 12.07 | 0.0103 | 0.49 | 1 | 54.99 | 0.0001 |
| $X_3$ | 28.09 | 1 | 50.75 | 0.0002 | 0.93 | 1 | 105.60 | <0.0001 |
| $X_1X_2$ | 0.016 | 1 | 0.028 | 0.8713 | 0.30 | 1 | 33.67 | 0.0007 |
| $X_1X_3$ | 1.58 | 1 | 2.85 | 0.1355 | 0.046 | 1 | 5.24 | 0.0559 |
| $X_2X_3$ | 8.18 | 1 | 14.78 | 0.0063 | 0.013 | 1 | 1.37 | 0.2799 |
| $X_1^2$ | 33.35 | 1 | 60.26 | 0.0001 | 0.34 | 1 | 38.49 | 0.0004 |
| $X_2^2$ | 0.20 | 1 | 0.36 | 0.5666 | 0.032 | 1 | 3.57 | 0.1007 |
| $X_3^2$ | 75.77 | 1 | 136.90 | <0.0001 | 0.041 | 1 | 4.63 | 0.0684 |
| Residual | 3.87 | 7 | | | 0.062 | 7 | | |
| Lack of fit | 2.15 | 3 | 1.66 | 0.3107 | 0.020 | 3 | 0.64 | 0.6270 |
| Pure error | 1.72 | 4 | | | 0.042 | 4 | | |
| Total | 183.43 | 16 | | | 2.33 | 16 | | |

It could be seen from the analysis in Table 3 that the screening efficiency in the response surface regression model was $p$<0.0001<0.01, indicating that the model was extremely significant, and the lack of fit $p$=1.66>0.05, indicating that the regression model had a high degree of fit. The model's coefficient of determination $R^2$ was 0.9789, indicating that the screening efficiency model could explain more than 97.89% of the evaluation indicators; The impurity content of jujube was $p$=0.0001<0.01, indicating that the model was extremely significant, and the lack of fit $p$=0.6270>0.05, indicating that the regression model had a high degree of fit. The model's coefficient of determination $R^2$ was 0.9735, indicating that the impurity content of jujube model could explain more than 97.35% of the evaluation indicators. Therefore, the operating parameters of the device could be optimized by using the model.

For the screening efficiency model, factors $X_1$, $X_3$, $X_2X_3$, $X_1^2$ and $X_3^2$ were extremely significant ($p$<0.01), factors $X_2$ was significant ($p$<0.05), and the other factors $X_1X_2$, $X_1X_3$, and $X_2^2$ were not significant ($p$>0.05). For the impurity content of jujube, Factors $X_2$, $X_3$, $X_1X_2$, and $X_1^2$ had significant effects on the impurity content of jujube ($p$<0.01). Factor $X_1$ had a significant effect on the impurity content of jujube ($p$<0.05), and the other factors $X_1X_3$, $X_2X_3$, $X_2^2$ and $X_3^2$ were not significant ($p$<0.05). If the insignificant factors are removed, the optimized equations are:

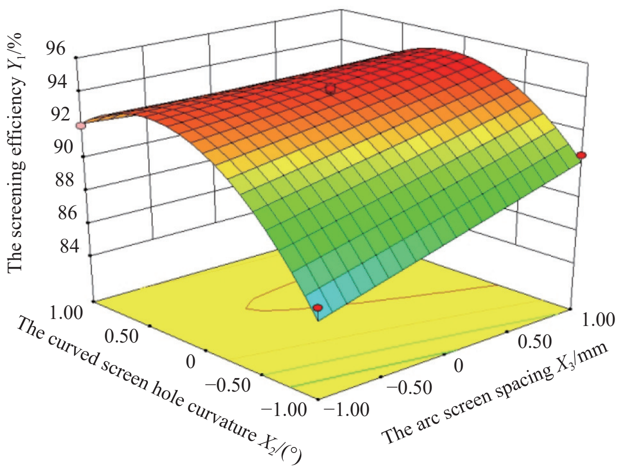
$$Y_1 = 94.02 + 1.59X_1 + 0.91X_2 + 1.87X_3 - 1.43X_2X_3 - 2.80X_1^2 - 4.23X_3^2 \tag{13}$$

$$Y_2 = 1.60 - 0.10X_1 - 0.25X_2 - 0.34X_3 + 0.27X_1X_2 - 0.28X_1^2 \tag{14}$$

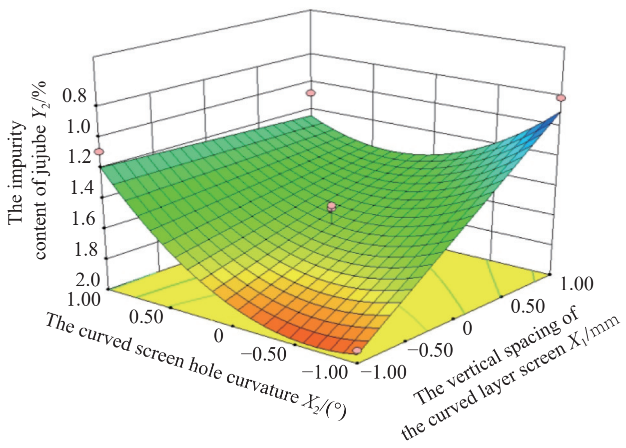
4.3.2 Analysis of the influence of interaction factors on the performance of machine tools

Through the Design-Expert 8.0.06 software, remove the non-significant items to generate 3D Surface optimization response surface, and the response surface of the screening efficiency and impurity content of jujube were shown in Figure 6 with the vertical spacing of the curved layer screen, the curved screen hole curvature, and the arc screen spacing.

The significance order of the three factors that affected the screening efficiency was: the arc screen spacing > the vertical spacing of the curved layer screen > the curved screen hole curvature. The overall trend of various factors was that when the vertical spacing of the vertical spacing of the curved layer screen was moderate, the curved screen hole curvature was relatively high, the arc screen spacing was large, and the screening efficiency was higher. The main reason: When the arc screen spacing was high, it was beneficial to realize the screening work of the jujubes and impurities; When the curved screen hole curvature was large, the effect of cleaning performance was enhanced; The vertical spacing of the curved layer screen was moderate, which increased the movement time of the jujubes and impurities in the curved sieve, which was beneficial to fully exert the screening effect; When it was small, the vibration amplitude of the jujubes and impurities was not large, which was not conducive to the screening of the jujubes and impurities.




a. Effect of $X_2X_3$ on $Y_1$




b. Effect of $X_1X_2$ on $Y_2$

Figure 6 Effect of the test factors on the screening efficiency and impurity content of jujube

The significance order of the three factors that affected the impurity content of jujube was: the arc screen spacing > the curved screen hole curvature > the vertical spacing of the curved layer screen. The overall trend of various factors was that when the vertical spacing of the curved layer screen was low, the curved screen hole curvature was small, the arc screen spacing was moderate, and the impurity content of jujube was lower. The main reason was: when he vertical spacing of the curved layer screen was low, it was beneficial to screen the impurities such as gravel and clod; When he curved screen hole curvature was low, it was beneficial to reduce the omission of the jujubes; The curved screen hole curvature was moderate, and the spacing was large, which may increase the amount of the jujubes leakage and reduce the sorting ability. The impurities such as small gravel and clods were difficult to be screened, resulting in a large inclusion ratio.

4.3.3 Parameter optimization and experimental verification

In order to improve the cleaning performance of the vibrating curved screen, under the condition that the factors satisfy the test range, the optimal mathematical model of the parameter optimization was established by using Optimization in Design-expert:

$$\begin{cases} \max\ Y_1 \\ \min\ Y_2 \\ \text{s.t.} \begin{cases} 45\ \text{mm} \le X_1 \le 60\ \text{mm} \\ 90^\circ \le X_2 \le 150^\circ \\ 15\ \text{mm} \le X_3 \le 25\ \text{mm} \end{cases} \end{cases} \tag{15}$$

The optimization result was as follow: when the vertical spacing of the curved layer screen was 65 mm, the curved screen hole curvature was 112.24°, and the arc screen spacing was 23.06 mm, the screening efficiency of the response value was 92.35% and the impurity content of jujube was 1.00%.

To verify the accuracy of the optimization results, the above parameters were used to perform three repetitive tests in the Seventh Regiment of the First Division of the Xinjiang Production and Construction Crops (The plant spacing was 4 m×1.5 m, the age of the tree was 5a, and the number is about 1650 plants/hm$^2$). The average value was the test verification value. Considering the feasibility of the field test, the vertical spacing of the curved layer screen was 65 mm, the curved screen hole curvature was 110°, and the arc screen spacing was 23 mm. The results are listed in Table 4.

**Table 4 Comparison between model optimization and field experiment**

| Item | The screening efficiency/% | The impurity content of jujube/% |
|---|---|---|
| Average | 91.09 | 1.02 |
| Optimal value | 92.35 | 1.00 |
| Relative error | 1.36 | 2.00 |

According to the analysis of the orthogonal test results, the vertical spacing of the curved layer screen was 65 mm, the curved screen hole curvature was 110°, and the arc screen spacing was 23 mm, the average screening efficiency in the test was 91.09 kg/h, and the relative error between the test verification value and the theoretical optimization value was 1.36%, which is less than 5%. The impurity content of jujube in the test was 1.02%, and the relative error with the theoretical optimization value was 2.00%, which is less than 5%.

## 5 Conclusions

1) In order to improve the screening performance of jujube cleaning device, based on the previous research, combined with the advantages of round hole sieve, woven sieve, rod sieve and shell sieve and in response to its problem, a 3-layer vibrating curved screen device was designed. Then through the kinematic analysis and the preliminary pre-test, is was determined that the length $J$ of the curved screen was 350 mm, the width $K$ was 230 mm, the lateral spacing $M$ between the curved holes of the unit was 65 mm, and the longitudinal spacing $N$ was 35 mm. The spacing $S$ of the unit-shaped screen mesh of the sieve body was 15-20 mm, the curvature $U$ of the curved screen hole was 90°-150°, the vertical spacing $H$ of the curved layer sieve was 45-65 mm, and the horizontal spacing $L$ was 30 mm.

2) The Box-Benhnken center combination test method in Design-expert software was used to analyze the variance of the vertical spacing of the curved layer screen, the curved screen hole curvature, and the arc screen spacing was 23 mm to analyze the screening efficiency and the impurity content of the jujube. The significance order of the three factors that affect the screening efficiency was: the arc screen spacing > the vertical spacing of the curved layer screen > the curved screen hole curvature. The significance order of the three factors that affect the impurity content of the jujube was: the arc screen spacing > the curved screen hole curvature > the vertical spacing of the curved layer screen.

3) According to the analysis of the orthogonal test results, the vertical spacing of the curved layer screen was 65 mm, the curved screen hole curvature was 110°, and the arc screen spacing was 23 mm, the average screening efficiency in the test was 91.09 kg/h, and the relative error between the test verification value and the theoretical optimization value was 1.36%, which is less than 5%. The impurity content of jujube in the test was 1.02%, and the relative error with the theoretical optimization value was 2.00%, which is less than 5%. As a result, the parameter-optimized model was realizable.

4) Theoretical analysis and experimental verification showed that compared with woven sieve, round sieve, rod sieve and shell sieve, the vibration curved sieve could enhance the permeability of impurities and the ability of jujube to migrate, and could solve the clogging and partial accumulation of sieve holes. The problem was to effectively reduce or even avoid the jujube damage, ensure the quality of jujube, effectively enhance the cleaning ability and improve the screening performance.

## Acknowledgements

The authors acknowledge that this work was financially supported by the Scientific Research Project of Chongqing Ecological Environment Bureau (Grant No. 2023-002).

## [References]

[1] Meng X J. The design of portable red Chinese-dates vibration harvester. Shihezi: Shihezi University, 2014; pp.22–28. (in Chinese)

[2] Pan J B. The design and experimental research of air blow type ground jujube picking device. Shihezi: Shihezi University, 2018; pp.22–33. (in Chinese)

[3] Wang Z Q, Xu L Y, Zhou H P, Cui Y M, Cui H. Development and experiment of eccentric-type vibratory harvester for forest-fruits. Transactions of the CSAE, 2012; 28(16): 10–16. (in Chinese)

[4] Shi G K. Design and experiment study of pneumatic red dates harvesting machinery. Aksu: Tariml University, 2014; pp.9–13. (in Chinese)

[5] He R. Design and Experimental study of excitation device of self-propelled dwarf and close planting jujube harvester. Shihezi: Shihezi University, 2014; pp.39–45. (in Chinese)

[6] Wang L J, Zhang C G, Ding Z J. Structure optimization of cleaning screen for maize harvester. Transactions of the CSAM, 2016; 47(9): 108–114. (in Chinese)

[7] Li Y M, Tang Z, Li H C, Zhao Z, Xu L Z. Experiment on the flow field of the air-and-screen cleaning device. Transactions of the CSAM, 2009; 40(12): 80–83. (in Chinese)

[8] Li Y M, Zhao Z, Chen J, Xu L Z. Nonlinear motion law of material on air-and-screen cleaning mechanism. Transactions of the CSAE, 2007; 23(11): 142–147. (in Chinese)

[9] Wang L J, Feng X, Zheng Z H, Yu Y T, Liu T H, Ma Y. Design and test of combined sieve of maize screening. Transactions of the CSAM, 2019; 50(5): 104–113. (in Chinese)

[10] Wang L J, Wu Z C, Feng X, Li R, Yu Y T. Design and experiment of curved screen for maize grain harvester. Transactions of the CSAM, 2019; 50(2): 90–101. (in Chinese)

[11] Fu W, Zhang Z Y, Ding K, Cao W B, Kan Z, Pan J B, et al. Design and test of 4ZZ-4A2 full-hydraulic self-propelled jujube harvester. Int J Agric & Biol Eng, 2018; 11(4): 104–110.

[12] Zhang X C, Chen B Q, Li J B, Fang X, Zhang C L, Peng S B, et al. Novel method for the visual navigation path detection of jujube harvester autopilot based on image processing. Int J Agric & Biol Eng, 2023; 16(5): 189–197.

[13] Bing X, Zheng D C, Cui Q L. Experimental research on three-level vibrating screening of buckwheat based on discrete element method. INMATEH Agricultural Engineering, 2022; 68(3): 191–200.

[14] Fan R X, Cui Q L, Lu Q, Hou H, Zheng D C. Experimental study on non-planar screening device for buckwheat threshing material. INMATEH Agricultural Engineering, 2022; 66(1): 73–80.

[15] Pu Y J, Wang S M, Yang F Z, Ehsani R, Zhao L J, Li C S, Xie S Y, Yang M J. Recent progress and future prospects for mechanized harvesting of fruit crops with shaking systems. Int J Agric & Biol Eng, 2023; 16(1): 1–13.

[16] Wang L J, Yu Y T, Zhang S, Feng X, Song L L. Bionic design and performance test of maize grain cleaning screen through earthworm motion characteristics. Int J Agric & Biol Eng, 2021; 14(3): 12–21.

[17] Dong K J, Yu A B. Numerical simulation of the particle flow and sieving behaviour on sieve bend / low head screen combination. Minerals Engineering, 2012; 31: 2–9.

[18] Fernandez J W, Cleary P W, Sinnott M D, Morrison R D. Using SPH one-way coupled to DEM to model wet industrial banana screens. Miner Eng, 2011; 34(8): 741–753.

[19] Jiao H G, Zhao Y M, Luo Z F, Wang Q Q, Tie Z X. Parameters optimization of probability screen plane. Journal of China University of Mining & Technology, 2006; 35(3): 384–388. (in Chinese)

[20] Jiao H G, Li J R, Zhao Y M. Test and research on optimum configuration of diameter of screen aperture and incline of screen deck. Coal Preparation Technology, 2007; 72(2): 1–4. (in Chinese)

[21] Wang L J, Zhang C G, Ding Z J. Structure optimization of cleaning screen for maize harvester. Transactions of the CSAM, 2016; 47(9): 108–114. (in Chinese)

[22] Jiang H S, Zhao Y M, Zhang B, Wang K, Song S L. Study on cooperative effects of screening surface and material characteristics during screening process based on DEM. Mining and Processing Equipment, 2014; 42(1): 83–87. (in Chinese)

[23] Yang Z G. Research on classification theory and parameters of curved sieve. Journal of Beijing Iron and Steel University, 1981; 3: 9–17. (in Chinese)

[24] Li H. Research of modern design method for air-and-screen cleaning device. Nanjing: Nanjing Agricultural University, 2012; pp.21–31. (in Chinese)

[25] Su T S, Han Z D, Cui J W, Wang G X, Hao X M, Hao F P, et al. Research status and development trend of cleaning unit of cereal combine harvesters. Journal of Agricultural Mechanization Research, 2016; 38(2): 6–11. (in Chinese)

[26] Li H C, Li Y M, Tang Z. Test study on cleaning performance of air-and-screen cleaning mechanism. Chinese Agricultural Mechanization, 2010; 6: 54–57. (in Chinese)

[27] Luo K, Yuan P P, Jin W, Yan J S, Bai S H, Zhang Z S, et al. Design of chain-sieve type residual film recovery machine in plough layer and optimization of its working parameters. Transactions of the CSAE, 2018; 34(19): 19–27. (in Chinese)

[28] Zhang X J, Bai S H, Jin W, Yuan P P, Yu M J, Yan J S, et al. Development of pneumatic collecting machine of red jujube in dwarfing and closer cultivation. Transactions of the CSAE, 2019; 35(12): 1–9. (in Chinese)

[29] Ma S H, Zhang, X J. Test and analysis of the air flow field in the wind-screen soil residue separation unit. Journal of Agricultural Mechanization Research, 2014; 36(7): 199–203. (in Chinese)

[30] He R, Kan Z, Fu W, Wang L H, Yang H Y, Sun Y, et al. Design and kinematic analysis of excitation device of dwarf and close planting jujube harvest machine. Journal of Agricultural Mechanization Research, 2014; 36(2): 64–67. (in Chinese)

[31] Dai F, Guo X H, Zhao W Y, Xin S L, Liu X L, Wu Z W. Design and test of canvas belt potato dredge-residual film recovery combined operation machine. Transactions of the CSAM, 2018; 49(3): 104–113. (in Chinese)

[32] Jin W, Zhang X J, Yan J S, Yuan P P, Bai S H, Fang X. Analysis based on pickup film characteristics and working parameters optimization for film recycling machine of crankshaft in cotton field. Transactions of the CSAE,

2018; 34(16): 10–18. (in Chinese)

[33] Yan W, Hu Z C, Wu N, Xu H B, You Z Y, Zhou X X. Optimization and test of parameters of membrane transport mechanism of shovel-screen residual film recovery machine. Transactions of the CSAE, 2017; 33(1): 17–24. (in Chinese)

[34] Jiang D L, Yan L M, Chen X G, Mo Y S, Yang J C. Design and experiment of nail tooth picking up device for striptype residual film recycling and baling machine. Int J Agric & Biol Eng, 2023; 16(6): 85–96.

[35] Hu K, Wang J K, Li B, Jiang B, Ding S S, Li T W. Development and test of combined operation machine of cotton stalk crushing returning to field and residual film recovery. Transactions of the CSAE, 2013; 29(19): 24–32. (in Chinese)

[36] Zhang X J, Bai S H, Jin W, Yan J S, Shi Z L, Yu M J, et al. Design and parameter optimization of an air-suction jujube picking and conveying device. Transactions of the ASABE, 2020; 63(4): 943–954

[37] Wang X F, Hu C, Lu B, Ge X K, Hou S L. Design and test of conveying residual film recovery machine with casting chain teeth. Transactions of the CSAM, 2018; 49(3): 122–129. (in Chinese)

[38] Zhang X J, Liu J Q, Shi Z L, Jin W, Yan J S, Yu M J. Design and parameter optimization test of reverse membrane and soil separation device for residual film recovery machine. Transactions of the CSAE, 2019; 35(4): 46–55. (in Chinese)