Design and experiment of nail tooth picking up device for strip type residual film recycling and baling machine

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Abstract: In order to solve the problem of residual film pollution caused by large area of cotton mulched planting in Xinjiang, a strip type residual film recycling and baling machine was designed, which can complete mulching film picking up, impurities separation, baling and other operations. The picking up device, as the key part of residual film recycling machine, was designed and analyzed. The kinematics of the pick-up nail tooth was analyzed, and its motion equation, motion trajectory and the conditions for completing the film pick-up were determined. And the key parameters were determined by analyzing the conditions of no missing picking and the stress of the residual film. According to the Box-Benhnken test design principle, field experiments were carried out with the forward speed of machine, the pickup speed ratio and the number of auxiliary film removing mechanisms as the key experimental factors, and the residual film pickup rate, the cotton stalk content and the residual film winding rate as the operation performance indexes of the picking up device. The mathematical models between the experimental factors and indexes were established, and the effect of each factor was analyzed. Through multi-objective parameter optimization and field experiment, the optimal combination of operation parameters was obtained as follows: the forward speed of machine of 1.67 m/s, the pickup speed ratio of 1.13, and the number of auxiliary film removing mechanisms of 6. Under this parameter combination, the pickup rate of residual film was 88.9%, the cotton stalk content in recycled residual film of 3.9%, and the residual film winding rate of 1.5%. The absolute error with the theoretical value was less than 0.6%. The research results show that the picking up device has stable operation performance and good residual film recycling effect, which meets the design and practical operation requirements.

Keywords: strip mulching film, recycle, pick-up nail tooth, motion analysis, parameter optimization, film removing mechanism

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1 Introduction

Cotton is an important cash crop in the world. China is one of the major cotton producing countries in the world, and the cotton output accounts for more than 50% of China's cash crop[1]. Xinjiang, with its unique natural conditions, is very suitable for cotton planting. Cotton area and yield are increasing year by year, accounting for an increasing proportion of the whole country. In 2020, the total cotton planting area in Xinjiang reached 2501.9×10^3 hm^2, accounting for 78.92% of the national cotton planting area, and the output reached 5.161 Mt, accounting for 87.3% of the national total[2,3]. Cotton planting in Xinjiang adopts film mulching cultivation technology, with the rate of cotton mulching reaching almost 100% and the annual use of mulching film exceeding 180 kt. With the extensive use of mulching film, the problem of mulching film residue appears. Mulching film residual pollution is a new and unique type of pollution in China[4,5].

Mechanical recycling is a large-area and efficient residual film recycling, which has become an effective means of residual film recycling. Many scientific researchers have developed a variety of mulching film recycling machines, including nail-tooth type, tooth-chain type, rake-tooth type and other models. The research focus includes film lifting, picking up, conveying, removing, rolling and unloading[6-9]. In foreign countries, thick film is generally used for planting. The residual film is basically complete and can be directly rolled and recycled[10,11]. The cotton planting mode in Xinjiang is generally 2 films and 12 rows, and the wide and narrow rows are used. The row spacing of cotton is 660 mm+100 mm, the width of mulching film is 2050 mm, and the width after mulching film laying is 1800-1900 mm[12]. Aiming at the recycling of plastic film in cotton fields in Xinjiang, Xie et al.[13] designed a rake type surface residual film recycling machine with guide chain to solve the problems of missing pick up, incomplete mulching film removal and rake tooth bringing back residual film in the working process, and carried out field tests with a residual film pickup rate of 88.73% and residual film winding rate of 1.91%. Kang et al.[14] improved the structure of residual mulching film pickup device by using additional releasing film part and rearranged film-retrieving spring teeth to solve the problem of insufficient contact between ground and pickup attachment of spring-tooth topsoil residual mulching film collector. Liu et al.[15] designed a roller type residual film

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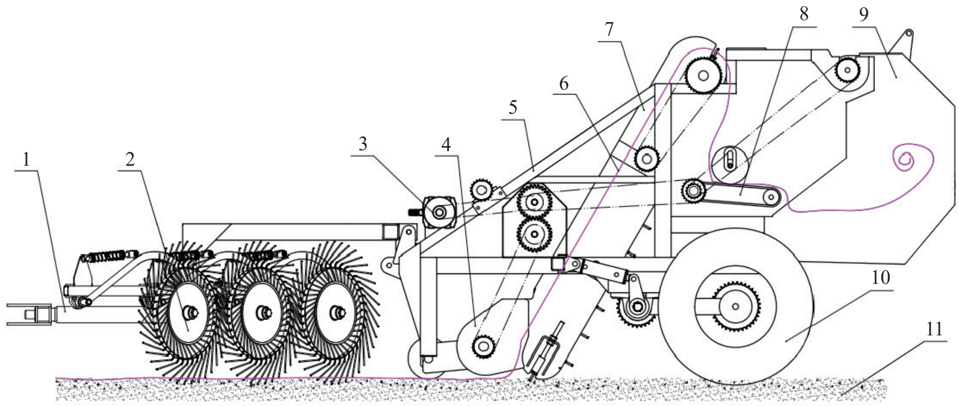
recycling machine and conducted field tests with orthogonal experimental analysis method to analyze the effects of different parameter ratios on the residue film pickup rate and obtain the optimal working parameters of the machine. By consulting References [14-18], according to the cotton planting mode in Xinjiang, the existing residual film recycling machine recycles one film per operation (the film width of 2050 mm), so the designed picking up device is about 2000 mm wide. The best operating speed of the machine obtained in the field test is 4-5 km/h. There are some problems such as large width of picking up device large power consumption and low operation speed.

In view of the appeal problem, this paper designed a strip type residual film recycling and baling machine, which used three groups of mulching film collecting disc devices to gather the 2050 mm wide mulching film to the middle to form 500-700 mm film strips. The picking up device completed the operations of residual film pickup, transportation and separation of residual film and impurities, and the packaging device bundled the mulching film into rolls. The width of the mulching film picking up device is about 1000 mm, which is significantly smaller, reduces the power consumption of the whole machine and improves the efficiency of operation. At the same time, the vibration mechanism and auxiliary film removing mechanisms were designed to improve the separation rate of residual film and impurities and removing film rate.

2 Structure and working principles

2.1 Machine structure and working principles

The strip type residual film recycling and baling machine can pick up one mulching film (film width 2050 mm) in one operation. Its structure is shown in Figure 1, which is mainly composed of traction frame, mulching film collecting discs, impurity conveying device, mulching film picking up device, film pressing device, packaging device, walking wheel and drive system, etc. The main technical parameters are listed in Table 1.



1. Traction frame 2. Mulching film collecting discs 3. Drive system 4. Impurity conveying device 5. Rack 6. Mulching film 7. Mulching film picking up device 8. Film pressing device 9. Packaging device 10. Walking wheel 11. Field

Figure 1 Structure of the strip type residual film recycling and baling machine

Table 1 Technical parameters of strip type residual film recycling and baling machine

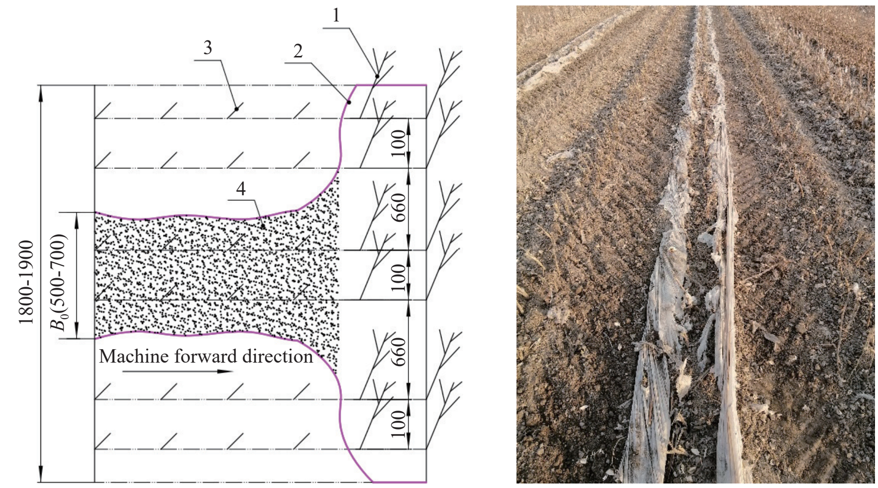
Parameter	Values
Connection mode	Traction type
Machine dimensions (L×W×H)/(m×m×m)	5.65×2.25×2.03
Matching power/kW	≥66
Working width/m	2.28
Recycled plastic film width/m	2.05
Working speed/(km·h^{-1})	5-8
Residual film picking rate/%	≥85%
Cotton stalk content in recycled residual film	≤5%
Residual film winding rate	≤2%

During the operation, the cotton stalks are first crushed by the straw crusher, and the side film is scooped up. The crushed cotton stalks are thrown to the outside of the width of the mulching film through the conveyor mechanism. Then the strip type residual film recycling and baling machine works. The mulching film laid in the field is cuddled and collected in the middle by the mulching film collecting discs, forming a film strip with width B_0 of 500-700 mm. The mulching film picking up device picks up the strip film and transports it upward. After the film reaches the end of the picking up device, it turns down and enters the film pressing and packaging device to complete the winding operation. After the residual film is integrated into strips, they are the operation objects of the picking up device. Compared with the uncollected residual film, there is a significant difference. The picking width decreases and the impurities on the film surface accumulate In the middle, as shown in Figure 2.

2.2 Structure and working principle of mulching film picking up device

The mulching film picking up device is an important part of the strip type residual film recycling and baling machine, which is used to complete the picking and transportation of residual film. It is mainly composed of mulching film pickup mechanism, auxiliary film removing mechanism, vibration mechanism, driving mechanism, passive mechanism and side plate, as shown in Figure 3a.

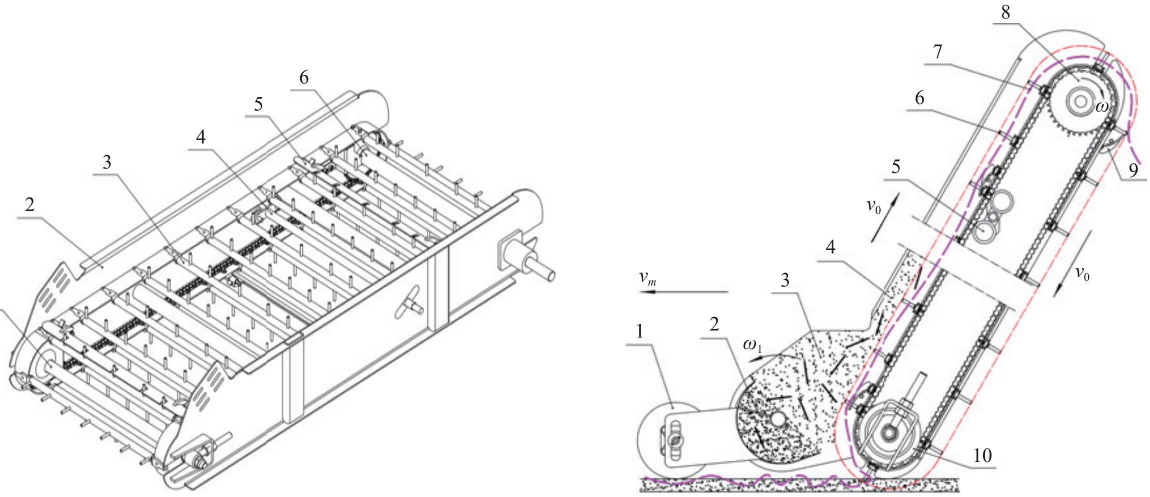
Figure 3b shows the operation of the mulching film pickup device. The height of the overall picking up device is controlled by adjusting the height of the depth limiting device to ensure that the lowest point of the mulching film pickup mechanism is buried to a certain depth during the rotation process. With the advance of the machine, mulching film pickup mechanism extends into the soil, picks up the residual film and transported film upward and backward. When the residual film is transported to the other rotating end of the picking up device, it is transported downward. Under the action of gravity and auxiliary film removing mechanism, the residual film slides from the mulching film pickup mechanism to complete the film removal. In the process of picking up and conveying the residual film, the vibrating mechanism intermittently strikes the mulching film pickup mechanism. The impurities on the film fall off and are conveyed by the screw conveyor to the outside. In order to improve the separation effect of recycled residual film and impurities, the designed plastic film pickup device has a large inclination angle of 60° and a long conveying distance of 1950 mm.



a. Schematic diagram of strip type residual film recycling (mm) b. Residual film strip collection effect

1. Cotton plant 2. Mulching film 3. Shredded cotton stalk stubble 4. Impurities on mulching film surface

Figure 2 Schematic diagram of strip type residual film recycling



1. Passive mechanism 2. Side plate 3. Mulching film pickup mechanism 4. Vibration mechanism 5. Auxiliary film removing mechanism 6. Driving mechanism

a. Structure of mulching film picking up device

1. Depth limiting device 2. Screw conveyor 3. Impurities 4. Side plate 5. Vibration mechanism 6. Mulching film pickup mechanism 7. Mulching film 8. Drive sprocket 9. Auxiliary film removing mechanism 10. Passive wheel

b. Schematic diagram of the operation of the plastic film pickup device

Note: v_m is the forward speed of the machine; ω is the angular velocity of film pickup mechanism; v_0 is the linear speed of pick-up nail tooth endpoint; ω_1 is the angular velocity of screw conveyor.

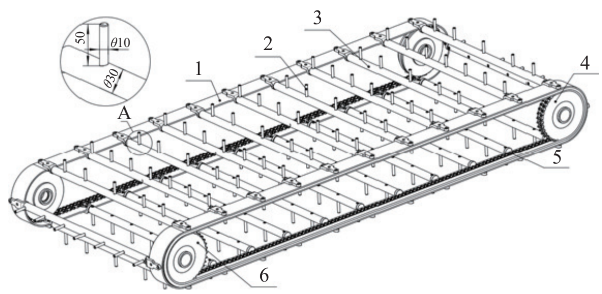
Figure 3 Schematic diagram of the structure and operation of mulching film picking up device

3 Design and analysis of key components

3.1 Mulching film pickup mechanism

Mulching film picking is the core technology of the residual film recycling machine. During the process of film picking, it is required to keep the integrity of residual film, prevent mulching film breaking, reduce missing picking and facilitate the separation of film impurities. The effect of picking up film directly affects the quality of residual film recycling. The mulching film pickup mechanism is mainly composed of pick-up nail tooth, nail tooth fixed tube, driving wheel, driven wheel, transmission chain and anti-winding film guard plate, as shown in Figure 4.

The pick-up nail teeth are fixed on the nail tooth fixed pipe according to a certain spacing. The nail tooth fixed pipes are connected with the anti-winding film guard plate, which is fixed on the transmission chain. During operation, driven by the driving wheel, the transmission chain moves to drive the nail tooth fixed

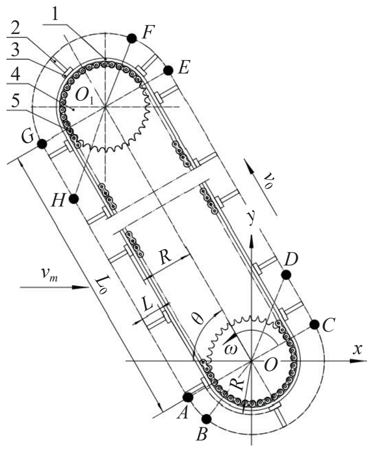


1. Anti-winding film guard plate 2. Pick-up nail tooth 3. Nail tooth fixed pipe 4. Driving wheel 5. Transmission chain 6. Driven wheel

Figure 4 Structure diagram of mulching film pickup mechanism pipe to move. The pick-up nail teeth form a rotary motion track to complete the operations of extending into the soil, picking up and transporting the residual film. According to the previous test, the diameter of the pick-up nail teeth was 10 mm, the length was 50 mm, and the diameter of the nail teeth fixed pipe was 30 mm[19].

3.1.1 Movement analysis of pick-up nail tooth

The rotary movement of pick-up nail tooth and the forward movement of machine form a composite motion track. Take the center O of the driven wheel as the origin, the horizontal forward direction of machine as the positive direction of the x axis, and the vertical upward direction as the positive direction of the y axis to establish the coordinate system, as shown in Figure 5.



1. Anti-winding film guard plate 2. Pick-up nail tooth 3. Nail tooth fixed pipe 4. Driving wheel 5. Transmission chain 6. Driven wheel

Figure 5 Motion analysis diagram of mulching film pickup mechanism

The residual film recycling machine moves forward at a constant speed of v_m, and the mulching film pickup mechanism rotates at a uniform speed of ω. The depth after the pick-up nail tooth extends into the collection strip of residual film is h.

Take the intersection point of the rotary motion and linear motion of the mulching film pickup mechanism as the starting point. After time t s, the displacement equations of the end of the pick-up nail tooth at each motion point are as follows:

$$B\text{point}:\begin{cases} x_B = v_m t-(R+L)\cos\left(\dfrac{\pi}{2}-\theta+\omega t\right) \\ y_B = -(R+L)\sin\left(\dfrac{\pi}{2}-\theta+\omega t\right) \end{cases} \tag{1}$$

$$\omega = \frac{v_0}{R+L} \tag{2}$$

where, x_B is the horizontal displacement of the pick-up nail tooth moving to point B, m; y_B is the vertical displacement of the pick-up nail tooth moving to point B, m; v_m is the forward speed of the machine, m/s; t is the operation time, s; R is the radius of nail tooth fixed pipe, m; L is the pick-up nail tooth length, m; θ is the picking up device and horizontal plane inclination angle, rad; ω is the angular velocity of film pickup mechanism, rad/s; v_0 is the linear speed of pick-up nail tooth endpoint, m/s.

$$D\text{point}:\begin{cases} x_D = v_m t+(R+L)\sin\theta - L_{CD}\cos\theta \\ y_D = (R+L)\cos\theta + L_{CD}\sin\theta \end{cases} \tag{3}$$

$$L_{CD} = v_0(t-t_0) \tag{4}$$

$$t_0 = \frac{\pi}{\omega} \tag{5}$$

where, x_D is the horizontal displacement of the pick-up nail tooth moving to point D, m; y_D is the vertical displacement of the pick-up nail tooth moving to point D, m; L_{CD} is the distance from point C to point D of the pick-up nail tooth, m; t_0 is the movement time of pick-up nail tooth from point A to point C, s.

F point:

$$\begin{cases} x_F = v_m t+(R+L)\cos\left[\dfrac{\pi}{2}-\theta+\omega(t-t_0'-t_0)\right] - L_0\cos\theta \\ y_F = L_0\sin\theta+(R+L)\sin\left[\dfrac{\pi}{2}-\theta+\omega(t-t_0'-t_0)\right] \end{cases} \tag{6}$$

$$t_0' = \frac{L_0}{v_0} \tag{7}$$

where, x_F is the horizontal displacement of the pick-up nail tooth moving to point F, m; y_F is the vertical displacement of the pick-up nail tooth moving to point F, m; t_0' is the movement time of pick-up nail tooth from point C to point E, s; L_0 is the center distance between driving wheel and driven wheel, m.

H point:

$$\begin{cases} x_H = v_m t - L_0\cos\theta-(R+L)\sin\theta + L_{GH}\cos\theta \\ y_H = L_0\sin\theta - L_{GH}\sin\theta-(R+L)\cos\theta \end{cases} \tag{8}$$

$$L_{GH} = v_0[t-(2t_0+t_0')] \tag{9}$$

where, x_H is the horizontal displacement of the pick-up nail tooth moving to point H, m; y_H is the vertical displacement of the pick-up nail tooth moving to point H, m; L_{GH} is the distance from point G to point H of the pick-up nail tooth, m.

According to Figure 5, the pick-up nail tooth completes the mulching film picking in the ABC arc section, and conveying in the straight section and removing in the $EFGH$ section. By deriving Equations (1) and (6) from time, the motion speed of pick-up nail tooth in ABC and EFG arc segment can be obtained respectively.

Speed of pick-up nail tooth in ABC arc section:

$$\begin{cases} v_{Bx} = v_m+\omega(R+L)\sin\left(\dfrac{\pi}{2}-\theta+\omega t\right) \\ v_{By} = -\omega(R+L)\cos\left(\dfrac{\pi}{2}-\theta+\omega t\right) \end{cases} \tag{10}$$

Speed of pick-up nail tooth in EFG arc section:

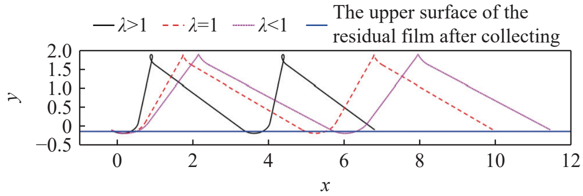
$$\begin{cases} v_{Fx} = v_m+\omega(R+L)\sin\left[\dfrac{\pi}{2}-\theta+\omega(t-t_0'-t_0)\right] \\ v_{Fy} = \omega(R+L)\cos\left[\dfrac{\pi}{2}-\theta+\omega(t-t_0'-t_0)\right] \end{cases} \tag{11}$$

where, v_{Bx} and v_{Fx} are respectively the horizontal motion speed of pick-up nail tooth in ABC and EFG arc segment, m/s; v_{By} and v_{Fy} are respectively the vertical motion speed of pick-up nail tooth in ABC and EFG arc segment, m/s.

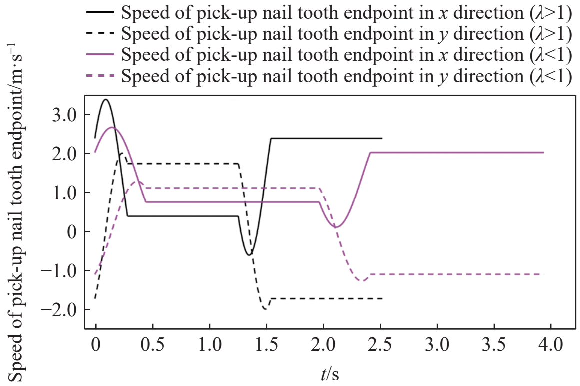
Take the ratio of the circumferential speed of the pick-up nail tooth endpoint v_0 to the forward speed of the machine v_m (hereinafter referred to as the pickup speed ratio) as λ.

$$\lambda = \frac{v_0}{v_m} \tag{12}$$

When λ is set to different values, different pick-up nail tooth movement tracks can be obtained, as shown in Figure 6a. The speed curves of the pick-up nail tooth endpoint in one cycle are shown in Figure 6b. According to Figures 6a and 6b, when $\lambda<1$, the speed of the pick-up nail tooth in the EFG arc section in the x direction is greater than 0. That is, there is no backward component velocity, and the mulching film cannot be removed. But when $\lambda>1$, the speed is less than 0, that is, there is a backward component velocity relative to the ground. Under the action of this movement, the mulching film can be removed.



a. Movement tracks of pick-up nail tooth endpoint under different pickup speed ratios



b. Speed curves of pick-up nail tooth endpoint in one cycle

Figure 6　Tracks and speed curves of pick-up nail tooth endpoint

When the forward speed of the machine v_m is higher than the average speed of the pick-up nail tooth v_0 (λ<1), that is, the length of the residual film to be picked up is greater than the transported by the mulching film picking mechanism. Then the residual film accumulation occurs in the process of picking and transportation, the impurities such as stalks and soil on the film surface are wrapped, and separating the residual film from impurities is difficult. Conversely, when the forward speed of the machine v_m is less than or equal to the average speed of the pick-up nail tooth v_0 ($\lambda\geq1$), the residual film is stretched or flattened during the picking and conveying operation. Proper stretching will make the residual film flat, increase the extension area, and effectively separate the impurities such as cotton stalk, cotton shell and soil. Therefore, the circumferential speed at the endpoint of the pick-up nail tooth v_0 is greater than or equal to the forward speed of the machine v_m ($\lambda\geq1$).

3.1.2　Conditions for no missing picking of residual film

During the residual film recycling operation of the machine, the pick-up nail teeth, arranged on the mulching film picking mechanism, pick up the residual film on the ground in turn. The motion tracks of the pick-up nail teeth on the adjacent two rows of nail tooth fixed pipes are shown in Figure 7.

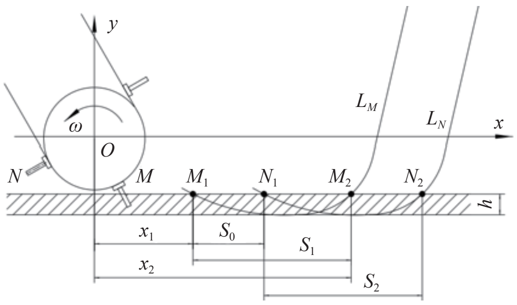


Figure 7　Motion tracks of two adjacent pick-up nail teeth on the film picking mechanism

The motion tracks of adjacent pick-up nail teeth M and N are L_M and L_N, respectively. The film pickup mechanism moves forward with the whole machine. At t_1 s and t_2 s (t_2>t_1), the nail tooth M intersects with the surface of the residual film area after strip collection at M_1 and M_2 points respectively. At t_3 s and t_4 s (t_4>t_3), the nail tooth N intersects at points N_1 and N_2 respectively. It can be seen from Figure 7 that in order to ensure no missing film picking, the motion trajectories of two adjacent pick-up nail teeth need to form an overlapping area on the surface of the film picking area. The condition for no missing film picking is as follows:

$$S_1 = S_2 \geq S_0 \tag{13}$$

where, S_1 and S_2 are the distance of pick-up nail teeth M and N into and out of the residual film respectively, m; S_0 is the distance between the entry point N_1 of pick up nail teeth N and the entry point M_1 of the previous pick up nail teeth M, m.

Substitute $y = -(R + L) + h$ into Equation (1),

$$\sin\left(\frac{\pi}{2} - \theta + \omega t\right) = \frac{R+L-h}{R+L} \tag{14}$$

$$\cos\left(\frac{\pi}{2} - \theta + \omega t\right) = \pm\sqrt{1-\left(\frac{R+L-h}{R+L}\right)^2} = \pm\frac{\sqrt{2(R+L)h-h^2}}{R+L} \tag{15}$$

Substitute Equations (14) and (15) into (1), then

$$x_1 = v_m t_1 - \sqrt{2(R+L)h-h^2} \tag{16}$$

$$x_2 = v_m t_2 + \sqrt{2(R+L)h-h^2} \tag{17}$$

where, x_1 and x_2 are the horizontal displacement of the pick-up nail teeth M and N at t_1 s and t_3 s respectively, m.

It can be seen from Figure 7,

$$S_1 = S_2 = x_2 - x_1 \tag{18}$$

Substitute Equations (16) and (17) into Equation (18), then

$$S_1 = v_m(t_2 - t_1) + 2\sqrt{2(R+L)h-h^2} \tag{19}$$

$$t_2 - t_1 = \frac{2\arccos\dfrac{R+L-h}{R+L}}{\omega} \tag{20}$$

Similarly,

$$t_3 - t_1 = \frac{L_1}{r\omega} \tag{21}$$

where, L_1 is the Longitudinal arrangement spacing of pick-up nail teeth, m; r is the drive roll diameter, m.

Substitute Equation (20) into Equation (19),

$$S_1 = v_m\frac{2\arccos\dfrac{R+L-h}{R+L}}{\omega} + 2\sqrt{2(R+L)h-h^2} \tag{22}$$

$$S_0 = v_m(t_3 - t_1) = \frac{L_1 v_m}{r\omega} \tag{23}$$

To make S_1–S_2≥0, i.e.,

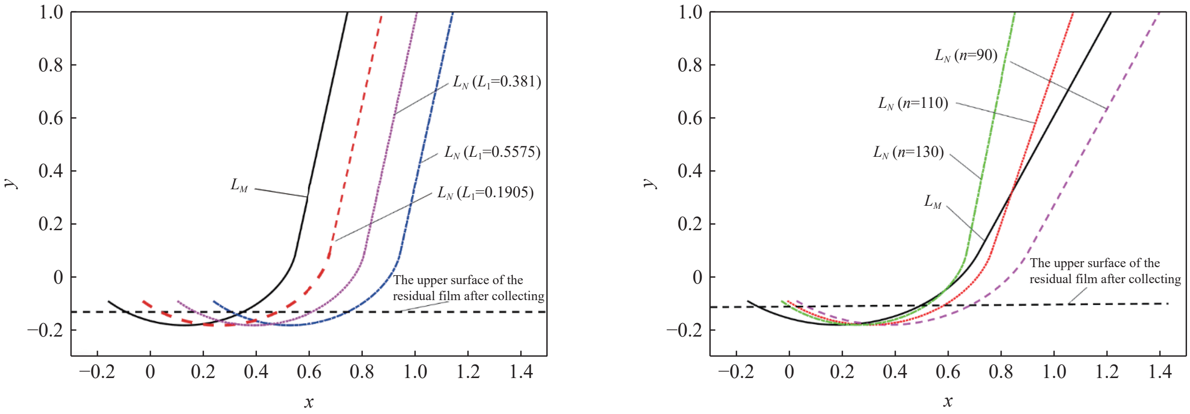
$$v_m\frac{2\arccos\dfrac{R+L-h}{R+L}}{\omega} + 2\sqrt{2(R+L)h-h^2} - \frac{L_1 v_m}{r\omega} \geq 0 \tag{24}$$

$$\omega \geq \frac{v_m\left(L_1 - 2r\arccos\dfrac{R+L-h}{R+L}\right)}{2r\sqrt{2(R+L)h-h^2}} \tag{25}$$

$$n = \frac{30\omega}{\pi} \geq \frac{15v_m\left(L_1 - 2r\arccos\dfrac{R+L-h}{R+L}\right)}{\pi r\sqrt{2(R+L)h-h^2}} \tag{26}$$

where, n is the rotational speed of film pickup mechanism, r/min.

Analysis shows that the condition for the residual film not to be missed is that the entry point N_1 of the pick-up nail tooth N is between the entry point M_1 and the exit point M_2 of the previous nail tooth M. According to the trajectory equation in the motion analysis of pick-up nail tooth in 3.1.1, the motion trajectories L_N of nail tooth N under different speed of film pickup mechanism n and different longitudinal arrangement spacing of pick-up nail teeth L_1 are drawn by using MATLAB software, as shown in Figure 8.



a. Motion trajectories L_N under different longitudinal arrangement spacing of pick-up nail teeth L_1

b. Motion trajectories L_N under different rotational speed of the pickup film mechanism n

Figure 8 Analysis of the movement trajectory of the pick-up nail tooth

As can be seen from Figures 8a and 8b, with the increase of the longitudinal arrangement spacing of the pick-up nail teeth L_1 or the decrease of the rotational speed of the pickup film mechanism n, the entry point N_1 of the nail tooth N gradually approaches the exit point M_2 of the nail tooth M, that is, the overlapping area of the motion trajectories of the two adjacent pick-up nail teeth in the pick-up film area gradually decreases. When the L_1 increases or the n decreases to a certain value, there will be no overlapping area between the motion trajectories of the two adjacent pick-up nail teeth. That is, the residual film is missed.

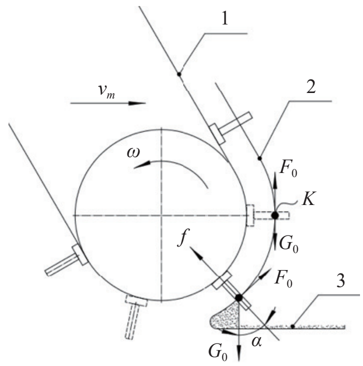
The smaller the longitudinal arrangement spacing of the pick-up nail teeth L_1 or the greater the rotational speed of the film pickup mechanism n, the less likely the residual film picking up device is to miss picking. However, according to the analysis of Equation (26), the condition that the residual film is not missed is the rotational speed n needs to be greater than a certain value, which increases with the increase of the longitudinal arrangement spacing L_1. According to the transmission performance, the selected chain type is 12A with a pitch p of 19.05 mm. At the same time, according to the preliminary test, it is determined the L_1 is 8 to 12 times the chain pitch p. Therefore, the longitudinal arrangement spacing of the pick-up nail teeth L_1 is 152.4 -228.6 mm.

3.1.3 Force analysis of residual film

When the residual film is recycled, there are a small amount of impurities such as cotton stalks and soil covered on the film. The mulching film is deformed under the action of the pulling force of the pick-up nail teeth and the impurities. The successful pick-up of the residual film must meet the following conditions: the residual film adheres to the pick-up nail teeth and does not fall off, and the tensile force of the residual film is less than its breaking force. The force analysis of the residual film picked up and conveyed by the film pickup mechanism is shown in Figure 9. It can be seen that the condition for the residual film to be picked up without slipping off is:

$$\begin{cases} G_0 \cdot \cos\alpha \le f = \mu F_0 \\ F_0 = G_0 \cdot \sin\alpha + F_1 \end{cases} \tag{27}$$

where, G_0 is the weight of impurities contained in the residual film picked up by adjacent pick-up nail teeth, N; α is the included angle between pick-up nail tooth and vertical direction, rad; f is the friction force of pick-up nail tooth on residual film, N; μ is the friction coefficient between film residue and pick-up nail tooth; F_0 is the tensile force on residual membrane, N; F_1 is the residual film elasticity, N.



1. Film pickup mechanism 2. Residual film 3. Impurities

Figure 9 Force analysis of residual film

According to Equation (27),

$$G_0 \cdot \cos\alpha \le \mu(G_0 \cdot \sin\alpha + F_1) \tag{28}$$

Equation (28) shows that the weight of impurities on the mulch film surface is an uncontrollable factor. After the structure and material of the devices are determined, their angle and friction factor have been determined. In order to ensure that the residual film is picked up smoothly and does not fall off from the nail teeth, F_1 should be increased. Analysis of Figure 9 shows that the residual film is subjected to the largest tensile force at point K. In order to prevent the residual film from being pulled off, the tensile force is smaller than the breaking force. According to the previous test[19], the longitudinal tensile breaking force of the weather resistant residual film is 2.4 N, so

$$F_0 = G_0 + F_1 \le 2.4 \tag{29}$$

The amount of impurities (W) on the film measured was 1.269 kg/m[20]. Then the weight of impurities in the length of the two pick-up nail teeth in a single seedling row is

$$G_0 = \frac{W \cdot L_1}{1000} \times 9.8 \tag{30}$$

where, W is the amount of impurities on the film surface, kg/m.

Combining Equations (28) and (29), the following results can be obtained:

$$L_1 \leq \frac{(2.4 - F_1) \times 1000}{9.8W} \tag{31}$$

The maximum value of the longitudinal arrangement spacing of the pick-up nail teeth L_1 is 192.98 mm through the calculation. Combined with the analysis in Section 3.1.2, the L_1 can be 152.4 mm (8p), 171.45 mm (9p), and 190.5 mm (10p). Assuming that G_0 only acts on the residual film with a width of 10 mm, the calculation can be obtained:

$$F_1 \leq 2.4 - G_0 \tag{32}$$

The deformation degree of residual film determines the value of F_1. According to the tensile property test of weather resistant mulching film, when the strain of residual film sample is 0-30 mm, the residual film is in the stage of elastic deformation, and the nominal fracture strain is 0-60%. When the strain is 30-110 mm, the nominal fracture strain is 60%-220%. At this time, the residual film is in plastic deformation state and there is no rebound force[21].

According to Equations (30) and (31) and the tensile properties of the residual film, the larger the longitudinal arrangement spacing of the pick-up nail teeth L_1, the greater the impurities weight in the length of two pick-up nail teeth in a single seedling row G_0, the smaller the elasticity of the corresponding residual film and the smaller the corresponding nominal fracture strain. According to the three values of the L_1, the residual film elastic force F_1 is respectively less than or equal to 0.50 N, 0.27 N, and 0.03 N. The residual film hung on the pick-up nail teeth has resilience and exerts pressure on the nail teeth. The existence of this pressure improves the friction between the nail teeth and the residual film, which is conducive to the picking up. Therefore, the longitudinal arrangement spacing of the pick-up nail teeth L_1 is 152.4 mm (8p). Residual film elastic force can be calculated:

$$F_1 \leq 0.50 \text{ N} \tag{33}$$

When the tensile force of the residual film is 0.50 N, the corresponding average elastic deformation is 10 mm, and the corresponding nominal fracture strain ε_{tB} can be calculated to be 20%[16]. So it can be seen from Equation (33) and the definition of fracture nominal strain of residual film:

$$\varepsilon_{tB} = \frac{S - S'}{S'} \times 100\% \leq 20\% \tag{34}$$

where, ε_{tB} is the film breaking nominal strain, %; S is the length of residual film picked up by pickup, m; S' is the forward distance of residual film machine, m.

In the mulching film pickup stage, the residual film moves in a circular motion with the film pickup mechanism, so

$$\varepsilon_{tB} = \frac{\omega(R+L)t - v_m \cdot t}{v_m \cdot t} \leq 20\% \tag{35}$$

Arranging Equation (35), combining Equation (12) and the analysis in Section 3.1.1, it can be obtained:

$$1 \leq \lambda = \frac{v_0}{v_m} \leq 1.2 \tag{36}$$

At this time, the tensile force of the residual film in the picking process is less than its longitudinal breaking force, and the strength of the residual film meets the picking requirements of the device. The film pickup mechanism makes a circular motion in the film picking stage, then,

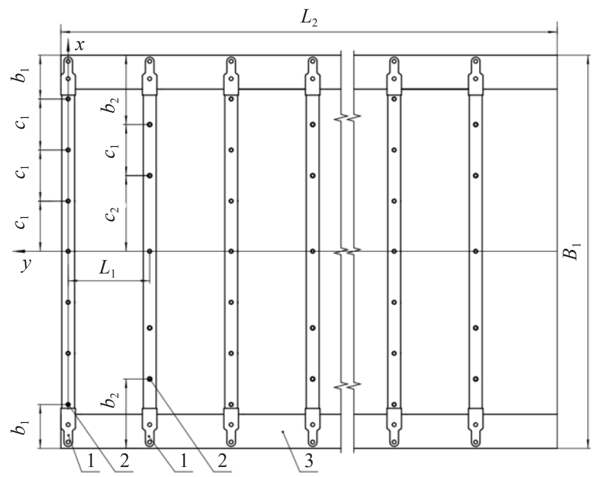
$$\begin{cases} v_0 = (R+L)\omega \\ \omega = \dfrac{n\pi}{30} \end{cases} \tag{37}$$

Bringing Equation (37) into Equation (36), the speed of the film pick-up mechanism n can be obtained:

$$n = \frac{30\lambda \cdot v_m}{\pi (R+L)} \tag{38}$$

3.1.4 Arrangement of pick-up nail teeth

The effect of picking up residual film is closely related to the spacing of pick-up nail teeth. If the spacing is too small, the recycling rate of residual film is high, but impurities such as cotton peach shell, leaves, stalks and soil block mixed with the residual film during the picking process are not easily separated from the residual film. The recycled residual film has a high impurity rate, which also makes it difficult to separate the residual film from impurities when reusing the residual film. If the spacing between the pick-up nail teeth is too large, it is easy to miss picking up small pieces of residual film, and the recycling rate of residual film is reduced. In order to solve this contradiction, the pick-up nail teeth on each adjacent nail tooth fixed pipes are arranged in a staggered manner, and the following principles are followed: make the nail teeth evenly contact and pick up the film impurity mixture to prevent missing pickup and ensure the smooth passage of impurities. Preliminary experiments have studied the relationship between the axial spacing of the pick-up nail teeth, the film pick up rate and the impurity removal rate[19]. Unfold the film pickup mechanism, and the arrangement of pick-up nail teeth is shown in Figure 10. The width of mulching film pickup mechanism B_1 is 920 mm, the length of which L_2 is 4420 mm. The axial distance of pick-up nail teeth c_1 is 120 mm and b_1 is 180 mm. The longitudinal arrangement spacing of pick-up nail teeth L_1 is 152.4 mm. The distance between pick-up nail teeth and inner edge of anti-winding film guard plate c_2 is 25 mm and b_2 is 85 mm.

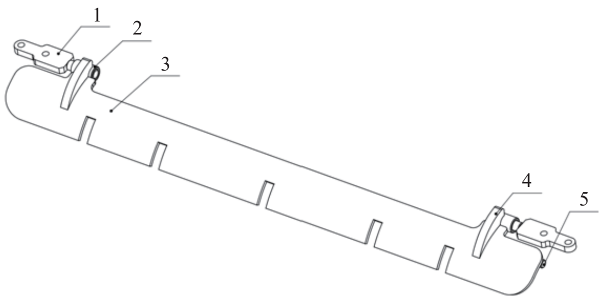


1. Nail tooth fixed pipe 2. Pick-up nail tooth 3. Anti-winding film guard plate

Figure 10 Schematic diagram of the arrangement of pick-up nail teeth

3.2 Auxiliary film removing mechanism

The auxiliary film removing mechanism is mainly composed of film removing plate, base plate, shaft sleeve, reinforcing plate and support rod, as shown in Figure 11. The film removing plate is an arc-shaped plate, one end of which is connected with the shaft sleeve, and the other end is provided with a number of tooth slots to pass through the pick-up nail teeth. One end of the base plate is connected with the film pickup mechanism, and the other end is hinged with the bearing. The reinforcing plate is preferably in the shape of a plane scimitar, and is installed on the outer convex surface of the film removing plate. The support rod is installed on the inner concave surface of the film removing plate. Due to the hinged structure, the film removing plate can be expanded under the action of its own weight to push the film on the pick-up nail teeth to the outside of the top, so as to improve the film removing rate. On the contrary, the film removing plate is closed by its contact with the ground. The designed film removal mechanism pushes the film to move outward along the direction of the pick-up nail teeth extending from the inside to the outside through the film removal plate, which assists the film removing.

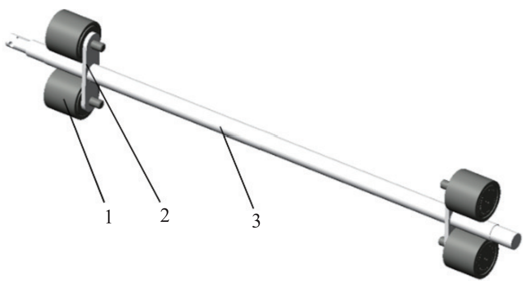


1. Base plate 2. Shaft sleeve 3. Film removing plate 4. Reinforcing plate 5. Support rod

Figure 11 Structural diagram of auxiliary film removal mechanism

3.3 Vibration mechanism

The vibrating mechanism is mainly composed of vibrating wheel, connecting plate and vibrating shaft, as shown in Figure 12. The middle of the connecting plate is connected with the vibration shaft, and the two ends are connected with the vibration wheels. The vibration shaft is connected with the side plate of the mulching film picking up device through a bearing, which is located inside the anti-winding film guard plate. The transmission mechanism transmits the power to the vibration shaft, which drives the vibration wheel to rotate, then the vibration wheel intermittently hits the film pickup mechanism. In the process of picking up residual film, the residual film is further separated from impurities under the action of vibration. Through the preliminary test, it was determined that when the ratio of the rotational speed of the vibration mechanism to the film pickup mechanism was 3, the separation effect of the residual film and impurity was better.



1. Vibrating wheel 2. Connecting plate 3. Vibrating shaft

Figure 12 Structural diagram of vibration mechanism

4 Field experiment

4.1 Experiment design and method

In order to test the field operation performance of the nail tooth picking up device, a field experiment was carried out in Manasi County, Changji Hui Autonomous Prefecture, Xinjiang in May 2021 (Figure 13). The operation plot was a cotton field after the cotton harvest, the ground was flat, and the drip irrigation belt had been pulled out. The average soil hardness was 2.4 MPa and the soil moisture content was 15.7%. The experiment area was about 30 hm^2. The supporting power tool was John Deere 904 wheeled tractor, and the residual film recycling machine was in good condition. The experiment shall be conducted according to the test method specified in the national standard GB/T 25412-2010 “Residual Film Recycling Machine”. The main test instruments were: electronic scale (range 7000 g, accuracy 1 g), electronic scale (range 500 g, accuracy 0.001 g), intelligent digital tachometer (99 999 r/min, accuracy ± (0.05%+1 digit)), tape measure (range 50 m, accuracy 0.002 m), etc.

Figure 13 Field test of plastic film picking up device and its constituted recycle machine

The actual operation requirements of the picking up device of the strip-type residual film recycling and baling machine were comprehensively weighed[22], and the forward speed of the machine v_m (1.38-1.94 m/s), the pickup speed ratio λ (1.0-1.2), and the number of auxiliary film removing mechanisms N_0 (4-8) were selected respectively as the test factors. The residual film picking rate, the cotton stalk content in recycled residual film and the residual film winding rate were taken as the operational performance indicators. The power of the film pickup mechanism is provided by the traveling wheel through the 3-stage chain drive and the 1-stage gear box drive, and the different pickup speed ratios can be obtained by changing the number of teeth of the transmission sprocket. The length of the experiment area was 100 m and the width was 2.05 m. After the test, the mulching film on the surface layer that had not been picked up was collected, weighed and recorded as m_1. The residual film and cotton stalk mass in the packaging device were measured and recorded as m_2 and m_3. At the same time, the mass of the residual film wound on the film picking up device was measured as m_4. According to Equations (38)-(40), the test indicators were calculated.

$$Y_1 = \frac{m_2 + m_4}{m_1 + m_2 + m_4} \times 100\% \tag{39}$$

$$Y_2 = \frac{m_3}{m_2 + m_3} \times 100\% \tag{40}$$

$$Y_3 = \frac{m_4}{m_2 + m_4} \times 100\% \tag{41}$$

where, Y_1 is the residual film picking rate, %; Y_2 is the cotton stalk content in recycled residual film, %; Y_3 is the residual film winding rate, %; m_1 is the mass of mulching film on the surface layer that had not been picked up, g; m_2 and m_3 are the mass of residual film and cotton stalk in the packaging device, g; m_4 is the mass of the residual film wound on the film picking up device, g.

Using the Box-Benhnken experimental design principle[23], the experimental factors and their value ranges are listed in Table 2. A total of 17 groups of response surface analysis experiments were implemented. Each group of tests was repeated three times, and the average of the three results was taken as the test results, as listed in Table 3.

Table 2 Test factors and levels

Coding table	Factors		
	Forward speed of the machine/m·s^{-1}	Pickup speed ratio	Number of auxiliary film removing mechanisms
–1	1.38	120	4
0	1.66	138	6
1	1.94	156	8

Table 3 Experiment design and results

Test No.	Forward speed of the machine X_1/m·s^{-1}	Pickup speed ratio X_2	Number of auxiliary film removing mechanisms X_3	Residual film pickup rate Y_1/%	Cotton stalk content of recycled residual film Y_2/%	Residual film winding rate Y_3/%
1	1	1	0	82.2	4.3	1.4
2	1	–1	0	84.1	6.4	1.4
3	1	0	1	86.3	5.5	1.4
4	1	0	–1	85.9	4.5	2.2
5	–1	1	0	79.1	6.1	1.6
6	–1	–1	0	81.2	7.1	1.5
7	–1	0	–1	81.8	5.9	2.1
8	–1	0	1	80.9	7.5	1.5
9	0	1	–1	86.1	2.4	1.9
10	0	1	1	86.4	2.7	1.6
11	0	–1	–1	88.4	5.5	1.8
12	0	–1	1	87.7	6.2	1.7
13	0	0	0	89.3	4.1	1.2
14	0	0	0	90.1	4.3	1.3
15	0	0	0	89.5	3.6	1.2
16	0	0	0	90.1	3.4	1.1
17	0	0	0	89.7	3.2	1.0

4.2 Experiment results and analysis

4.2.1 Regression model establishment and significance test

Data processing analysis was performed by Design-Expert 8.06 software. Multivariate regression fitting analysis was performed on the test results in Table 3. The regression equations about the residual film pickup rate, the cotton stalk content and the residual film winding rate were established, i.e.,

$$Y_1 = 89.74 + 1.94X_1 - 0.95X_2 - 0.11X_3 + 0.05X_1X_2 + 0.32X_1X_3 + 0.25X_2X_3 - 5.76X_1^2 - 2.33X_2^2 - 0.26X_3^2 \quad (42)$$

$$Y_2 = 3.72 - 0.74X_1 - 1.21X_2 + 0.45X_3 - 0.27X_1X_2 - 0.15X_1X_3 - 0.10X_2X_3 + 1.95X_1^2 + 0.30X_2^2 + 0.18X_3^2 \quad (43)$$

$$Y_3 = 1.16 - 0.038X_1 + 0.013X_2 - 0.23X_3 - 0.025X_1X_2 - 0.05X_1X_3 - 0.05X_2X_3 + 0.18X_1^2 + 0.13X_2^2 + 0.46X_3^2 \quad (44)$$

The variance analysis and the significance test of regression coefficients were carried out for the above quadratic regression model. The results are listed in Table 4.

According to the analysis in Table 4, the regression model P values of the test indicators were all less than 0.01, indicating extremely significant. The F value of 4.04, 3.00, and 3.53 respectively implied that the lack of fit was not significant relative to the pure error. For the three models there were respectively 10.53%, 15.82%, and 12.75% chances that "Lack of Fit F value" those large could occur due to noise. Non-significant lack of fit was good[24]. The R^2 values of the three models of residual film pickup rate, cotton stalk content and residual film winding rate were 0.9902, 0.9260, and 0.8953, respectively, and the coefficients of variation ($C.V$) were 0.63%, 13.05%, and 10.80%, respectively. The results showed that the three models respectively can explain more than 99%, 92%, and 89% of the changes of response values. There was a high correlation between the predicted values and the actual values, and the experimental errors were small, which indicated that the regression models had a good fit with the actual situation.

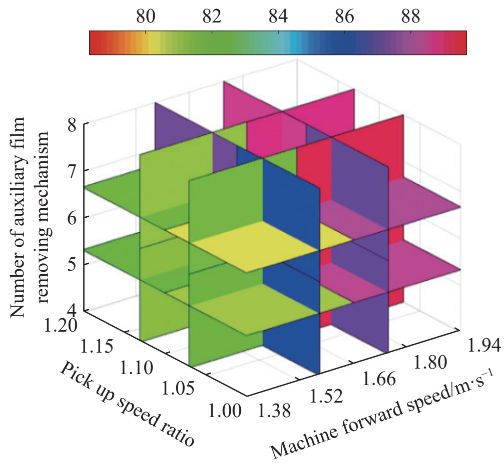
Table 4 Variance analysis results of response surface model

Source	Y_1			Y_2			Y_3		
	Sum of squares	F-value	p-value	Sum of squares	F-value	p-value	Sum of squares	F-value	p-value
Model	209.05	78.76	<0.0001**	35.30	9.73	0.0033**	1.62	6.65	0.0103*
X_1	30.03	101.83	<0.0001**	4.35	10.08	0.0134*	0.011	0.42	0.5397
X_2	7.22	24.48	0.0017**	11.76	29.19	0.001**	1.25×10^{-3}	0.046	0.8360
X_3	0.10	0.34	0.5763	1.62	4.02	0.0850	0.40	14.96	0.0061**
X_1X_2	0.01	0.034	0.8591	0.30	0.75	0.4149	2.5×10^{-3}	0.092	0.7700
X_1X_3	0.42	1.43	0.2703	0.09	0.22	0.6509	0.01	0.37	0.5625
X_2X_3	0.25	0.85	0.3878	0.04	0.099	0.7619	0.01	0.37	0.5625
X_1^2	139.57	473.25	<0.0001**	16.05	39.84	0.0004**	0.14	5.18	0.0570*
X_2^2	22.91	77.67	<0.0001**	0.39	0.96	0.3607	0.074	2.73	0.1424
X_3^2	0.28	0.95	0.3630	0.13	0.33	0.5841	0.88	32.55	0.0007**
Residual	2.06			2.82			0.19		
Lack of fit	1.55	4.04	0.1053	1.95	3.00	0.1582	0.14	3.53	0.1275
Pure error	0.51			0.87			0.052		
Cor Total	211.12			38.12			1.81		
R^2		0.9902			0.9260			0.8953	
C.V.		0.63%			13.05%			10.80%	

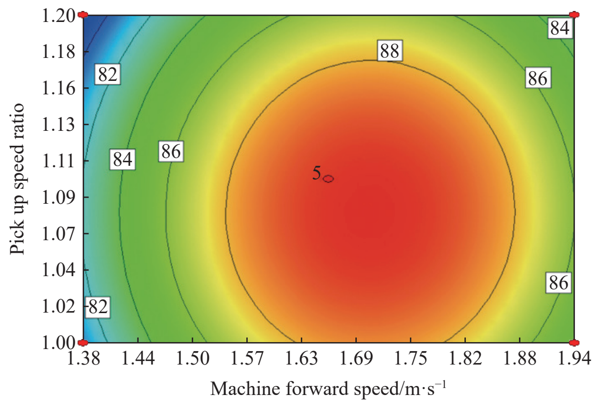
Note: 0.01<p<0.05, * significant; p<0.01, ** extremely significant.

4.2.2 Analysis of the effect of factors

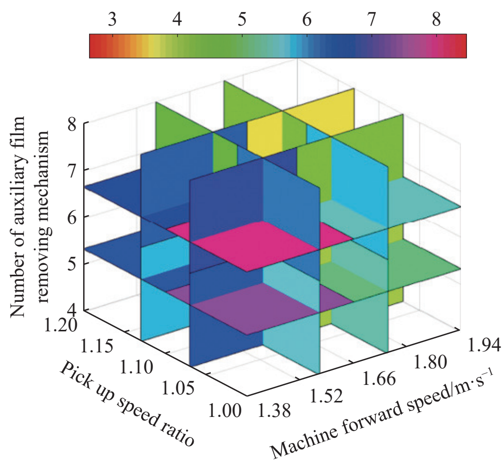
By analyzing the F value of each test factor in Table 4, it can be seen that the influence of the three test factors of machine forward speed X_1, pickup speed ratio X_2 and the number of auxiliary film removal mechanisms X_3 on the residual film pickup rate Y_1 is in the order of importance: X_1, X_2, and X_3. The order of importance of the influence on the cotton stalk content in the recycled residual film Y_2 is X_2, X_1, and X_3. The order on the residual film winding rate Y_3 is X_3, X_1, and X_2. The analysis shows that there is interaction between various factors, but it is not significant. In order to more intuitively analyze the effect of the test factors on the operation performance of the picking up device, the four-dimensional slice diagram was drawn using MATLAB software[25]. Established the slice diagram corresponding to six coordinate points with the forward speed of machine of 1.57 and 1.75 m/s, the pickup speed ratio of 1.07 and 1.13, and the number of auxiliary film removal mechanisms of 5.33 and 6.67. The color of the cut surface was used to describe the test evaluation index. At the same time, draw the contour map of factors that had a great influence on the test indicators, as shown in Figure 14.



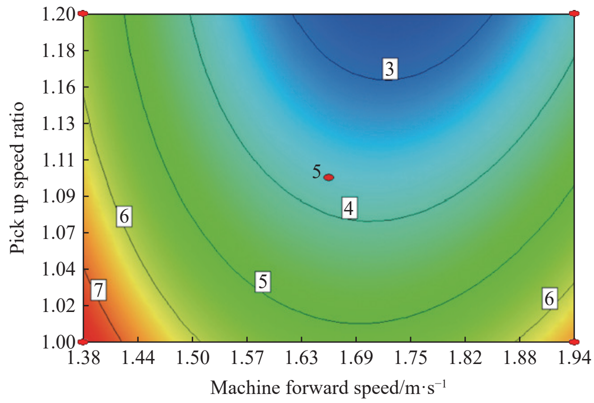
a. 4D slice diagram of residual film pickup rate



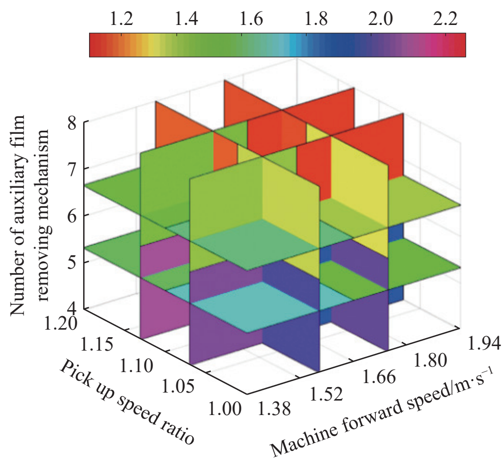
b. Contour map of residual film pickup rate



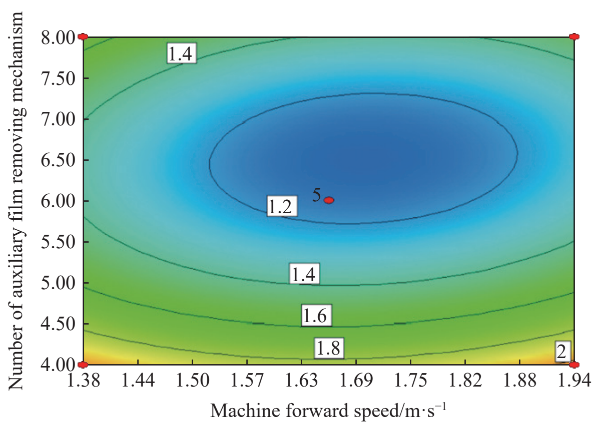
c. 4D slice diagram of cotton stalk content



d. Contour map of cotton stalk content



e. 4D slice diagram of residual film winding rate



f. Contour map of residual film winding rate

Figure 14 4D slice diagram and contour map of test indexes and test factors

Effect analysis of residual film pickup rate and test factors: From the analysis of Figures 14a and 14b, within the parameters of the test factors, the greater the forward speed of the machine and the pickup speed ratio were, the higher the residual film pickup rate was. But the number of auxiliary film removing mechanisms had no significant effect on the residual film pickup rate. From Figure 14b, when the forward speed of the machine was between 1.57-1.88 m/s, and the pickup speed ratio was between 1.00-1.18, the residual film pickup rate was higher.

Effect analysis of cotton stalk content and test factors: As shown in Figures 14c and 14d, the greater the pickup speed ratio was, the lower the cotton stalk content in the recycled residual film was. The more the number of auxiliary film removal mechanisms was, the higher the cotton stalk content was. When the forward speed of the machine was between 1.63-1.82 m/s, and the pickup speed ratio was between 1.11-1.20, the cotton stalk content was lower (Figure 14d). The larger the pickup speed ratio was, that was, the speed of the pickup nail teeth was higher than the forward speed of the machine, and the residual film was stretched during the picking up and conveying operation. Under the action of the vibration mechanism, the cotton stalk and soil were separated more effectively, reducing the impurities content in the recycled residual film.

Effect analysis of residual film winding rate and test factors: From the Figures 14e and 14f, the more the number of auxiliary film removal mechanisms, the higher the forward speed of machine, and the smaller the pickup speed ratio, then the lower the film winding rate. When the pickup speed ratio was larger, the picking up and conveying speed of the residual film was higher, and the interaction time between the auxiliary film removal mechanisms and the mulch film was shorter, which reduced the film removal rate. When the number of auxiliary film removal mechanisms was 5-7 and the forward speed of machine was 1.55-1.88 m/s, the residual film winding rate was lower (Figure 14f).

4.3 Optimization of operating parameters and experimental verification

Based on the above analysis, in order to achieve the best operation quality of the picking up device, it was necessary to maximize the pickup rate of the residual film, and at the same time, the cotton stalk content and residual film winding rate were low. Therefore, the mathematical model of multi-objective functions of residual film pickup rate Y_1, the cotton stalk content in recycled residual film Y_2 and the residual film winding rate Y_3 was established, and the regression model was optimized[26]. The optimization constraints were as follows:

$$\begin{cases} \mathrm{Max} Y_1 \\ \mathrm{Min}(Y_2, Y_3) \\ -1 \leq X_1, X_2, X_3 \leq 1 \\ Y_1 \leq 100 \\ Y_2, Y_3 > 0 \end{cases} \tag{45}$$

where, X_1, X_2, and X_3 are factor coding values.

The parameters of the regression equation were optimized by Design-Expert software, and the optimal combination of operating parameters of the picking up device was obtained: the forward speed of the machine of 1.71 m/s, the pickup speed ratio of 1.13, and the number of auxiliary film removal mechanisms of 6 after rounding. The theoretical values of the optimized performance indices of the picking up device were: the residual film picking rate of 89.49%, the cotton stalk content in the recycled residual film of 3.4%, and the residual film winding rate of 1.2%.

In order to verify the reliability of the optimization results, and the operation performance of the picking up device of the strip-type residual film recycling and baling machine to pick up the residual film, separate the impurities and remove the film, the optimal combination was used for field experiments. Considering the actual operation requirements, the forward speed of the machine was selected as 1.67 m/s (6 km/h), the pickup speed ratio of 1.13 (the speed of the film pickup mechanism of 99 r/min), and the number of auxiliary film removing mechanisms of 6. The distance of each experiment was 150 m, which was repeated three times. The average value of the three repeated tests was taken as the test result. The field experiment situation was shown in Figure 15. The experimental results showed that the residual film pickup rate was 88.9%, the cotton stalk content was 3.9%, and the film winding rate was 1.5%. The absolute errors with the theoretical values were 0.59%, 0.5% and 0.3% respectively. The results show that the picking up device can meet the operation requirements of residual film recycle, separation of residual film and impurities and film removal.

a. Effect of picking up residual film and impurities separation   b. Surface effect after picking up residual film   c. Recycling film roll effect

Figure 15 Application effect of the picking up device

The deficiency of this spring experiment was that the integrity and mechanical properties of the mulching film had decreased compared with the autumn experiment due to the long laying time. During the recycling process, part of the mulching film was pulled and shredded to produce small pieces of film, which could not be recycled by the picking up device (as shown in Figure 15b), reducing the pickup rate of residual film. There was a big gap between the working conditions in spring and autumn. There was some lodging cotton stalks on the film surface, which could not be shredded during the straw shredding operation and were picked up together with the mulching film. During the separation operation, part of the cotton stalks could not be effectively separated, which increased the stalk content of the recycled residual film.

5 Conclusions

1) The mulching film picking up device of strip type residual film recycling and baling machine is designed and analyzed. Through the kinematic analysis of the pick-up nail tooth, the motion

equation and trajectory of the pick-up nail tooth are determined. The condition to complete the mulching film picking is also determined. That is, the ratio of the pick-up nail tooth speed to the forward speed of the machine $\lambda \geq 1$. The key parameters of the mulching film picking up device are determined by analyzing the conditions of no missing picking up and the stress of the residual film.

2) Combined with the Box-Benhnken experimental design principle, the forward speed of the machine, the pickup speed ratio, and the number of auxiliary film removing mechanisms are used as the test factors, and the residual film pickup rate, the cotton stalk content and the film winding rate are used as operational performance indicators. The performance test of the mulching film picking up device is carried out using the 3 factors and 3 levels response surface analysis method. The factors affecting the operation performance index of picking up device and their relationship are analyzed. The order of importance of the influence on the residual film pickup rate Y_1 is a descending order: forward speed of the machine, pickup speed ratio, number of auxiliary film removing mechanisms, on the stalk content of the recycled residual film Y_2 is a descending order of pickup speed ratio, forward speed of the machine, number of auxiliary film removing mechanisms, on the wrapping rate Y_3 is a descending order of number of auxiliary film removing mechanisms, forward speed of the machine, pickup speed ratio.

3) The quadratic polynomial regression models between test factors and indexes is established. The optimal combination of operation parameters of the picking up device is obtained as follows: the forward speed of machine is 1.67 m/s, the pickup speed ratio is 1.13, and the number of auxiliary film removal mechanisms is 6. Field experiment verification shows that under the optimal parameters the pickup rate of residual film is 88.9%, the cotton stalk content is 3.9%, and the film winding rate is 1.5%. The research shows that the mulching film picking up device has stable operation performance and good residual film recycling effect, which meets the actual operation requirements.

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