

Design and experiment of an upper-side-discharge straw-returning and bundle self-unloading integrated corn residual film recycling machine

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Abstract: Due to the arid climate, flat terrain, certain irrigation sources and high popularization of mechanical harvest in Hexi Irrigation Area of Gansu Province, the widely adopted half film-flat-mulching for corn cultivation faces serious adverse situations, such as high soil compactness, strong film-soil adhesion, significant straw stubble and thick covering accumulation on film. Therefore, a new kind of segmented combination upper-side-discharge straw-returning and bundle self-unloading integrated corn residual film recycling machine was proposed. The scheme was characterized by small volume, low resistance, low complexity and film-impurities twice separation. It is constructed based on the concept of module subsection combination. It was composed of film surface straw cleaning device and the followed residual film recycling machine, in terms of function, any usage requirements of separate and joint operations can be satisfied. The film surface straw cleaning device is responsible for the removal of vertical corn straw and ground covering beyond the film. Although its stubble cutter roller obtuse-angle L-shaped blades paired single-helix arrangement is simple, it runs smoothly and the straw crushing effect is good enough. The layout that upper-side-discharge straw-returning cross-range screw conveyor auger is back and beyond the stubble cutter roller, eliminates the common connecting transportation mechanism between crushing and straw-returning section, so that, the system structure can be optimized and the efficiency has been significantly improved. The integrated residual film recycling machine is composed of triangular pyramid arc two-stage wing (TPATSW) type film lifting shovel, rod-tooth-belt type film-impurities separation device and semi-enclosed shaftless bundle film collector. Among them, TPATSW type film lifting shovel has good corn root whisker cutting effect, low soil contact resistance and small soil congestion area, but its ability to lift film is strong, more importantly, the special segmented configuration of shovel handle and the body, shortens the overall machine length significantly. For semi-enclosed shaftless bundle film collector, however, a new scheme of eight sub-rolls rotate in the same direction, to roll the residual film into a bundle is innovatively adopted. Under its own parameters, the system has the lowest sub-roll rotation speed that can bundle the residual film without shaft inside the film collecting chamber, rather than on any sub-roll itself. The gap between the sub-rolls can separate impurities for the second time. After the film collection reaches the standard, the film collector can dump the residual film directly, which is simple and efficient. The field orthogonal test data of the prototype show that, the optimal parameter combination is: film lifting shovel earth angle is 30°, its operation depth is 50 mm and the machine forward speed is 5.0 km/h. The average residual film recycling rate and the crushed straw qualified rate under the optimal parameters are 84.9% and 90.3% respectively, which meet the requirements of the national and industrial standards. The research solved the passive situation that there was no matching equipment for the recycle of residual film in corn field in Hexi Irrigation Area effectively.

Keywords: corn, segmented combination, film surface straw cleaning, straw-returning, TPATSW type film lifting shovel, film-impurities twice separation, semi-enclosed shaftless bundle film collector, self-unloading

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1 Introduction

Hexi Irrigation Area in Gansu Province is located in the high altitude-cold-cool area, with flat land. In recent years, the way of half film-flat-mulching is mainly used to plant corn^[1-3]. However,

due to the lack of recycling technology, and the incomplete collection (or the usual server delay), a large number of residual films remain in field every year, resulting in increasingly serious white pollution^[4-7]. After the corn is mechanically harvested in this district, the field surface is always covered with a lot of corn straw

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and high stubble residue, which increases the difficulty of residual film recycling. What is more important, it is easy to make the impurity content of the recycled residual film high, which will greatly restrict the subsequent treatment. In addition, it is also necessary to declare that, inter-film irrigation and under-mulch drip irrigation often cause obvious soil hardening after autumn, on the one hand, which will lead to a sharp increase in the resistance of the film lifting mechanism. On the other hand, it is often very difficult to separate the hardened soil and the film because of the firm bond^[8]. The existing residual film recycling machines on the market are almost all customized for arid and semi-arid loose soil. Most of them have a single function and are only suitable for short and thin stubbles, so, it is difficult for them to shoulder the heavy responsibility of corn residual film recycling in Hexi Irrigation Area^[9,10]. Therefore, up to now, the residual film recycle in this area is still dominated by manual picking, with high labor intensity, low efficiency and high investment.

In fact, since the application of agricultural plastic film in the 1950s, the research on residual film pickup has been carried out subsequently^[11]. Internationally, not only the use area of plastic mulch very is limited, but also the high strength plastic film above 20 μm is dominant absolutely. The structure of their residual film recycling machinery is simple relatively. The key technology is limited to the speed matching between film lifting shovel and suspended sub-roll, and the goal is to recycle in rolls. Therefore, it has limited reference significance for China^[12,13]. Domestic research on residual film recycling technology has been more than 30 years. Due to regional differences, diversity of agronomic requirements and other reasons, many achievements have been born, but most of them are limited to the research and development of machines characterized by single function, simple structure and small portability. However, in recent years, a series of excellent achievements have emerged with the goal of film surface cleaning, film lifting soil breaking, film-impurities separation, efficient residual film collecting, energy saving & consumption reduction, and flexibility-composability. For example, in view of the severe situation that the average amount of residual film in cotton fields in Xinjiang is 259 kg/hm², even locally up to 381 kg/hm², many residual film recycling machines, such as Guided Chain Rake^[14], Follow-up^[15] and Roller^[16] types etc. were invented, they take the surface and shallow soil residual film as the object. While the Spring-Tooth^[17], Sawtooth Rolling^[18] and Telescopic Nail Tooth^[19] types etc., are good at picking up broken film from deep soil layers, and some of them are well popularized and applied. In view of the actual demand of the film covered potato mechanical harvesting, it is best to harvest both film and potato together at the same time. Advanced residual film recycling technologies such as Chain Guide Rail^[20] and Throwing Film Nail Tooth^[21] types have been put forward successively. The concept of two-stage potato-film collection and small taper coiling-unloading film roll is proposed by Sun et al.^[22], is even more a benchmark of innovation in this field. In general, the recycle of potato residual film has developed rapidly, and potato film mulching tends to thick black film, which is less difficult to be recycled. In contrast, the recycle of corn residual film needs to face more severe challenges. First of all, corn is the third largest staple food crop, with a broader area and a more urgent situation. Secondly, corn film is mostly transparent with a thickness of 10 μm or less, and the surface film is generally seriously damaged in autumn. Thirdly, the mechanical harvest of corn often leaves high stalk-stubble, and its root-stubble itself is huge, which multiplies the difficulty of film lifting. Nevertheless, the hob film

lifting device improved by Liu et al.^[23] on the basis of chain tooth residual film recycling machine, can not only pick up the surface film and deep film synchronously, but also realize the functions of root-stubble cutting, throwing, and soil preparation in one operation. The more concise schemes, such as rotary gear type^[24] have also been applied in a small range. Therefore, take a panoramic view of the situation, the recycle of corn residual film is still not optimistic, and there is a huge gap with the specific needs of Hexi Irrigation Area.

Driven by this demand, for Hexi Irrigation Area, a new scheme of segmented combination upper-side-discharge straw-returning and bundle self-unloading integrated corn residual film recycling machine, is put forward innovatively for this project. This machine, as a whole, is composed of two parts in series: film surface straw cleaning and residual film recycle devices. They can work together or separately to meet the needs of different working conditions. The film surface straw cleaning part needs to complete stalk-stubble removal and straw-returning. The core lies in the adoption and special arrangement of obtuse-angle L-shaped swing-blades, and its reasonable space combination with one-way upper-side-discharge cross-range screw conveyor auger, which makes the system compact and efficient. With the support of TPATSW type film lifting shovel, rod-tooth-belt type film-impurities separation device as well as semi-enclosed shaftless bundle film collector, the residual film recycling device works properly. This new scheme is expected to overcome the unfavorable situation of no machine or no good machine to be used for residual film pickup in corn field in this area effectively.

2 Structure and working principle of the machine

2.1 System requirement analysis

This study aims to develop a kind of targeted corn residue film recycling machine after autumn in Hexi Irrigation Area. Therefore, it should be steadily promoted according to the guiding ideology of flexibility and applicability, small volume, low power consumption, rich functions, high efficiency and reliability. The overall scheme can be shown in Figure 1. Based on specific dilemma, the new integrated residual film recycling machine can be composed of film surface straw cleaning and residual film recycling two parts. The first part is located in the front, which can work jointly or independently. It is used for residual stalk-stubble removal, and the straw-returning can be implemented with the cooperation of cross-range screw conveyor auger, so as to reduce the covering above the film surface as much as possible, which is conducive to the subsequent residual film recycling and the impurity reduction. The residual film recycling part needs novel film lifting shovel with low resistance and low congested soil volume, and then, driven by the film-impurities separation device, go a step further, enters the novel

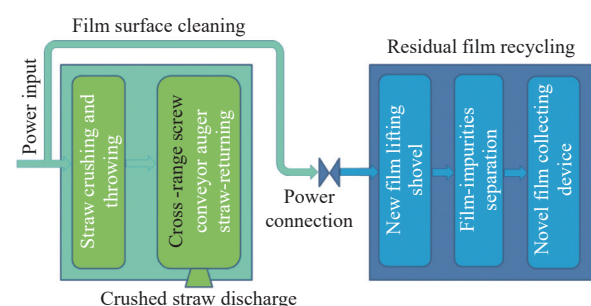
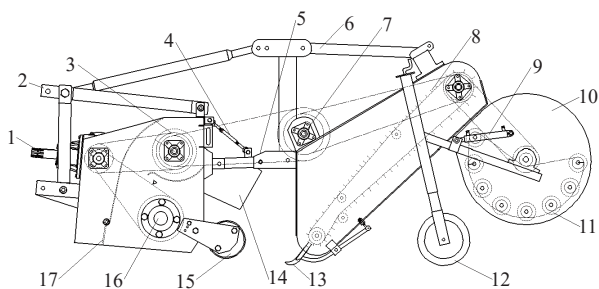


Figure 1 Functional block diagram of the new demanded residual film recycling machine

film collecting device. It should be emphasized that, necessarily, this film collector can not only unload the film easily, but also continue to separate impurities in the process of film collecting, so as to further reduce the impurity content of the collected residual film. Considering the wider universality, the whole machine should be based on the premise that, the total length is less than 3.3 m and the total power is not more than 75 kW, can complete film surface straw cleaning, film-impurities separation, residual film recycle and rapid film unloading at one time.

2.2 Structure of the new residual film recycling machine

According to the requirement analysis and the system composition logic shown in Figure 1, the new integrated residual film recycling machine is mainly composed of suspension frame, mechanical transmission system, film surface straw cleaning device, residual film pickup device and bundle film collecting device. Among them, the film surface straw cleaning device is composed of a horizontal stubble cleaner and a cross-range screw conveyor auger. The residual film pickup device is composed of a film lifting device, a rod-tooth-belt type film-impurities separation device, and a bundle film collecting device. The structure diagram of the combined residual film recycling machine can be shown in Figure 2.

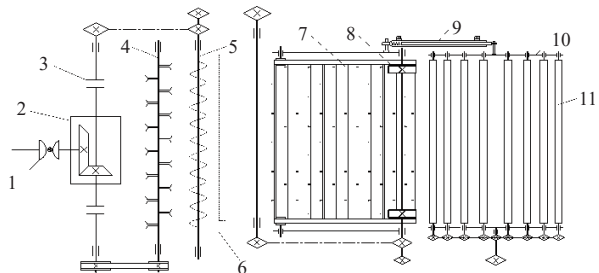


- 1. Power input shaft 2. Suspension frame 3. Straw cross-range screw conveyor auger 4. Film lifting shovel penetration depth adjusting rod 5. Connecting device 6. Rear adjusting yoke 7. Intermediate shaft 8. Rod-tooth-belt type film-impurities separation device 9. Film unloading hydraulic cylinder 10. Semi-enclosed shaftless bundle film collector 11. Sub-roll 12. Ground wheel 13. Film lifting shovel 14. Side-discharge chopped straw outlet 15. Stubble roller depth limiting wheel 16. Crushing device 17. Shelter curtain.

Figure 2 Structure diagram of the combined residual film recycling machine

2.3 Working principle of the machine

The transmission route of the combined residual film recycling machine shown in Figure 2 can be demonstrated in Figure 3. During field operation, the tractor rear output power shaft is connected through a cross universal joint to drive the straw crushing swing-



- 1. Power input shaft 2. Gearbox 3. Clutch 4. Straw crushing swing-blades shaft 5. Cross-range screw conveyor auger 6. Side-discharge chopped straw outlet 7. Rod-tooth-belt type film-impurities separation device 8. Drive wheel 9. Film unloading hydraulic cylinder 10. Side plate 11. Sub-roll.

Figure 3 Transmission route of the combined residual film recycling machine

blades shaft to rotate at high speed. After being crashed, the corn straw is thrown into the cross-range screw conveyor auger from its upper side, and then transported by the auger to one side of the machine for discharge, so as to complete the residual straw removal in the field. At the same time, the transmission system drives the rotation of the rod-tooth-belt type film-impurities separation device and the bundle film collecting device, so that to complete the residual film recycle.

During operation, under the power traction, the film lifting shovel teeth wedge under the film to separate the film from the soil. The excavated film rises to the conveying chain entrance of the residual film pickup device along the film lifting shovel teeth. Under the shaking of the conveying chain and the teeth on it, the first separation between the residual film and the soil adhered to the film is realized. With the forward movement of the machine, the film pick-up teeth on the rod-tooth-belt conveyor chain grab the film, and move to the top at the end of the conveyor chain along the rod upper surface. Then, the residual film falls into the bundle film collecting device to form a film bundle under the continuous drive of the sub-rolls. With the increase of the film recycled in the film collecting space, the diameter of the film bundle grows gradually. Before the diameter of the film bundle reaches to the inner cavity diameter of the film collecting chamber, it is necessary to turn on the control switch of the film unloading hydraulic cylinder to unload the film in time.

In addition, film surface cleaning and residual film recycling part can both work jointly or independently, fully demonstrating the flexibility of the system's operation method. The purpose of the joint work is to complete all the work of film surface straw cleaning and residual film recycle at one time. However, if work separately, the film surface straw cleaning or residual film recycle parts can be made to work independently according to needs to complete their respective missions.

2.4 Main technical indicators

Hexi Irrigation Area of Gansu Province is dry with less precipitation, but the terrain is flat and the soil is fertile. The conditions for planting corn are unique, especially the rapid development of seed corn in recent years. Therefore, the main cultivation mode of high yield and drought resistance for corn is half film-flat-mulching. This model is not only conducive to heat preservation and moisture conservation, but also conducive to a little snow water irrigation in summer plus the rainfall infiltration from the gap of corn roots and the edge of film mulching. Therefore, the film thickness used for mainstream film mulching planting is 12 μm, the film width is 1400 mm, and the soil covering belt is set in the middle of the row spacing as well as the film sides^[3,25], as shown in Figure 4. Referring to the existing achievements and considering the specific local production conditions, the main technical indexes of this integrated residual film recycling machine are listed in Table 1.

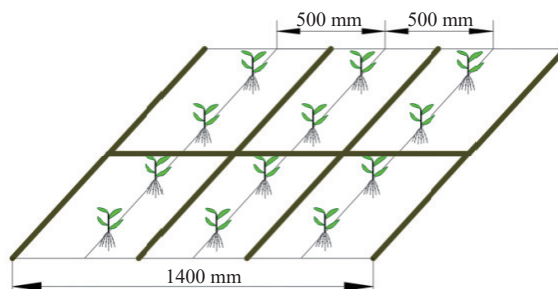


Figure 4 Corn cultivation mode in Hexi Irrigation Area

Table 1 Main technical parameters of the combined machine

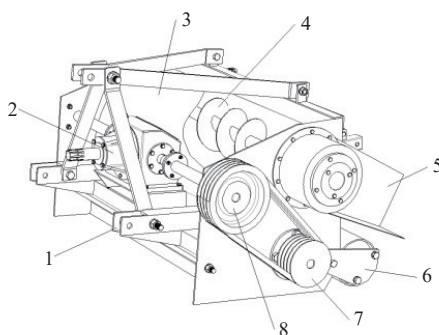
Parameter	Value
Implement size (Length×Width×Height)/m	3.15×1.78×1.30
Hitch type	Rear three-point suspension
Auxiliary power/kW	58.8-73.5
Working breadth/mm	1400
Tractor power shaft output speed/r·min ⁻¹	540
Film lifting shovel operation depth/mm	30-100
Productivity/hm ² ·h ⁻¹	0.5-0.8

3 Design and parameter determination of the key component

3.1 Film surface straw cleaning device

The premise of successful residual film recycle is that it should be exposed as much as possible, that is, there are as few other covers on the film surface as possible. This goal is achieved by using the film surface straw cleaning device. The device is mainly composed of a horizontal stubble cleaner equipped with a cross-range screw conveyor auger. During operation, the swing-blades hinged on the straw crushing swing-blades shaft of the crushing chamber rotate around its shaft and follows the machine advance. The rotating swing-blades first cut off the corn stalks from the roots and throw them forward. Under the repeated action of swing-blades, the crushed straw slides along the inner wall of the shell to the front of the crushing chamber, and is squeezed into the curved shell of the cross-range screw conveyor auger, which locates back and above of the stubble cutter roller, and then, the crushed straw can be discharged from the side-discharge chopped straw outlet by the auger.

In this scheme, the cross-range screw conveyor auger is arranged at the oblique-upper-rear of the stubble cutter roller group. Apart from the longitudinal length of the machine can be significantly reduced, the power consumption of the straw-returning section can be compressed also, because additional collection behavior is no longer necessary. Moreover, the whole machine can also be designed as three-point suspension, which will significantly increase the flexibility of its operation. The specific structural diagram for this section is shown in Figure 5.



1. Suspension frame 2. Gearbox 3. Curved shell 4. Cross-range screw conveyor auger 5. Side-discharge chopped straw outlet 6. Stubble roller depth limiting wheel 7. Straw crushing swing-blades shaft 8. Driving pulley.

Figure 5 Structural composition diagram of the film surface straw cleaning device

3.1.1 Rotary swing-blades arrangement and parameters selection

The commonly used swing-blades of straw stubble cleaner include hammer-claw, straight-blades, obtuse-angle-L and right-angle-L shapes. Because the obtuse-angle-L shape has good

working stability, so, it is selected in this study. According to the regulations of GB/T 699-2015, the swing-blades are made of 65Mn and heat treated to make its surface hardness meet the requirements of HRC48-56, the core hardness is HRC33-40.

In order to achieve the crushing, throwing effects and reduce energy consumption, according to the Agricultural Machinery Design Manual (Volume I)^[26], the arrangement density C of the blades should be 0.02-0.04 pieces/mm, and it is calculated as Equation (1).

$$C = \frac{N}{L} \quad (1)$$

where, N is the number of swing-blades, pieces; L is the working width of the machine, mm.

The arrangement of the swing-blades on the straw crushing swing-blades shaft, has an important impact on the crushing effect of corn straw. The common arrangement forms mainly include: symmetrical, single-helix, double-helix and staggered arrangements, etc.^[8,27]. In order to make the force on the cutter shaft uniform and the crushing-throwing effect of corn straw good enough, the single-helix arrangement mode is adopted, and the left, right obtuse-angle L-shaped blades are installed on the same hinge shaft in pairs. In this design, the chosen arrangement density C of the blades is 0.04 pieces/mm, and the working width L is 1400 mm. So, it can be calculated that the number of blades N is 56, and the radial included angle of two adjacent blades is 90°, as shown in Figure 6.

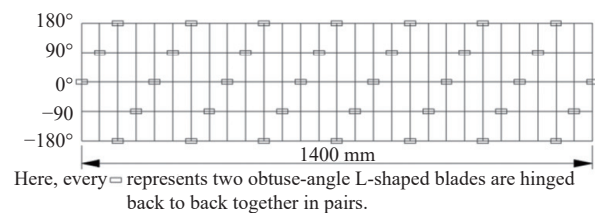


Figure 6 Array schematic diagram of rotary swing-blades

The key to the working effect of the film surface straw cleaning device is whether the unsupported cutting conditions can be met, which depends on the absolute linear velocity at the end of the swing-blades. When a swing-blade moves to the highest point, the traveling speed v_0 of the tractor is opposite to the horizontal component of the relative speed v at the end of the blade, which is helpful for the smashed corn straw being thrown into the auger. Therefore, the required straw crushing swing-blades shaft n (r/min) can be shown in Equation (2).

$$n = \frac{30(v + v_0)}{\pi R} \quad (2)$$

According to the basic requirements of local straw-returning, the rotating radius R of the obtuse-angle L-shaped blades in this scheme is 265 mm, and the traveling speed v_0 is 5-7 km/h. If the rotating speed n of the swing-blades shaft is 2000 r/min, the absolute linear velocity v at the end of the swing-blades will be obtained to be 48.47-50.47 m/s, which meets the basic requirements of the minimum speed 48 m/s for corn straw unsupported cutting^[26].

3.1.2 Cross-range screw conveyor auger parameters determination

Here, the function of the cross-range screw conveyor auger is to transport the crushed straw to the ground on one side of the straw stubble cleaner. The rationality of its working logic is that the pushing capacity per unit time is not less than the straw collection capacity.

The outer diameter D of cross-range screw conveyor auger designed in this project is 250 mm, its inner diameter d_1 is 60 mm,

the pitch P is 200 mm, and the filling factor can be taken as $\zeta=0.25$. Ignoring the spiral blade space, the volume of crushed straw that cross-range screw conveyor auger rotates one circle can be transported is:

$$V_1 = \frac{\pi P(D^2 - d_1^2)}{4} \zeta \quad (3)$$

So, $V_1=0.0023 \text{ m}^3/\text{r}$. According to the transmission ratio of the film surface straw cleaning device, the rotating speed of the cross-range screw conveyor auger can be calculated as 100 r/min, and the capacity of crushed straw that the conveyor auger can transport one minute can be expressed as

$$V_1 = V_1' n \quad (4)$$

Hence, it can be got $V_1'=0.55 \text{ m}^3/\text{min}$.

On the contrary, in 1-film-3-row planting mode, the plant spacing in row $L_1=220 \text{ mm}$, the average diameter of corn stalk-stubble $d_2=35 \text{ mm}$, and the tractor maximum speed is $v_0=7.0 \text{ km/h}$.

Therefore, within 1 min, the straw that can be collected by the film surface straw cleaning device is

$$V_2 = 3 \times \frac{7000}{60L_2} \cdot \frac{\pi d_2^2 h}{4} \quad (5)$$

So, $V_2=0.46 \text{ m}^3/\text{min}$.

Obviously, since $V_1 > V_2$, the cross-range screw conveyor auger can operate reasonably without blockage.

3.2 Residual film pickup system

3.2.1 TPATSW type film lifting shovel

In order to achieve the purpose of root cutting-soil crushing after autumn with as little power as possible, a kind of TPATSW type film lifting shovel scheme is proposed in residual film pickup section. The overall structure of the film lifting device based on the film lifting shovel unit is shown in Figure 7. Among them, the film lifting frame is used to fix and evenly arrange the film lifting shovel units, and the angle adjustment mechanism is used to adjust the earth angle of every unit.

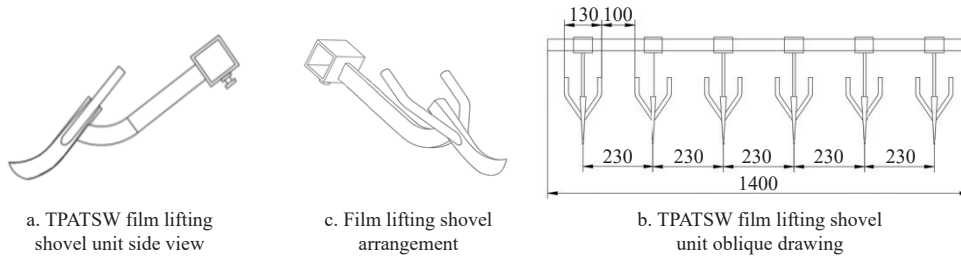


Figure 7 The film lifting device

The film lifting shovel unit is the core component of the residual film recycling machine. During operation, it is necessary to have strong earth ability and stable working depth. In addition, the unit shape selection and arrangement density are also very important to prevent over soil congestion and miss-picking. Therefore, the triangular-pyramid scheme is adopted for the front of the shovel unit. So, the shovel unit cutter head is arrow like and sharp, wide at the top and narrow at the bottom, and it is thin in generally, long and curved in an arc (as shown in Figures 7a and 7b), which significantly reduces the resistance of the soil contacting parts, is conducive to cutting off the surface corn root whisker, and also inhibits the upward movement of corn stubbles along with the film. The side wings, with round steel, are welded at the middle-rear of the shovel unit cutter head, so as to enhance the lifting capacity of the residual film under the condition of reducing the soil congestion. The tail of the shovel head is hinged with round steel by a long connecting rod, and an angle adjustment mechanism is installed on it to adjust its earth angle, so as its adaptability to different working conditions can be enhanced. According to the planting mode of one film-three rows of corn in Hexi Irrigation Area, the corresponding design number of film lifting shovels is 3 groups, which can ensure that there is one film lifting shovel on the left and right of each corn row, so as to prevent the corn stubble from tearing the film during the film lifting process (see Figure 7c).

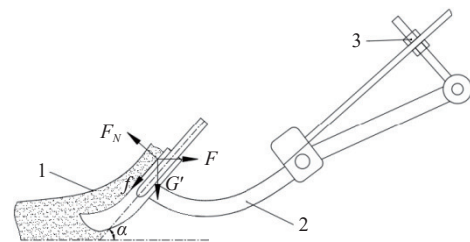
Figure 8 shows the film lifting shovel force analysis. Where, G' is the weight of the shoveled soil (N), F is the horizontal resistance of the soil (N), F_N is the forward traction of the film lifting shovel (N, from tractor), μ is the friction coefficient between the soil and the shovel surface, f is the soil friction resistance of the shovel surface, and α is the shovel earth angle. During stable operation, the force balance constraint relationship of the film lifting shovel is

$$\begin{cases} F \cos \alpha - f - G' \sin \alpha = 0 \\ F \sin \alpha + G' \cos \alpha - F_N = 0 \\ f = \mu F_N \end{cases} \quad (6)$$

Therefore,

$$\alpha = \arctan \frac{F - \mu G'}{\mu F + G'} \quad (7)$$

Consequently, the film lifting shovel earth angle is of great importance to its effect and quality. A really large earth angle is prone to easy the congestion of the excavated objects in front of the shovel and increase the power consumption. While a too small angle is difficult to lift the excavated objects to a certain height, which affects the operation effect. According to the existing literature^[14-16,22,28,29], the film lifting shovel earth angle α is generally taken $15^\circ-35^\circ$, in view of the machine parameters had been optimized several times, so, in this study, α can be $25^\circ-35^\circ$.



1. Plastic film 2. Film lifting shovel 3. Earth angle adjusting bolt.

Figure 8 Film lifting shovel force analysis

3.2.2 Rod-tooth-belt type film-impurities separation device

The rod-tooth-belt type film-impurities separation device is composed of rod-tooth-belt conveyor chain, soil shaking wheel, etc. Its main function is to accomplish the transportation of recycled

residual film and film-impurities separation. Its structure is shown in Figure 9.

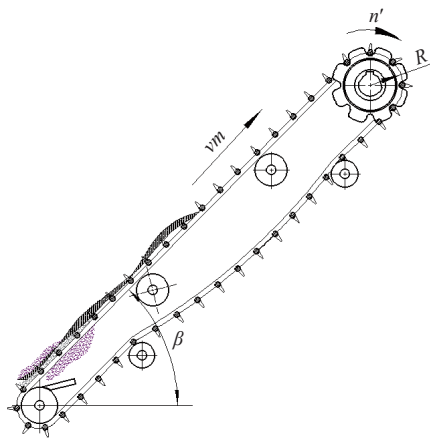


Figure 9 Rod-tooth-belt type film-impurities separation device

The main physical parameters relationship is expressed as Equation (8).

$$n' = \frac{30v_m}{\pi R} \tag{8}$$

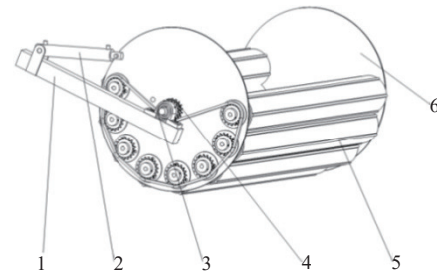
According to the transmission ratio, the rotation speed $n'=150$ r/min, and its radius is $R=100$ mm. Thereby, it can be calculated that the v_m is 1.57 m/s, which is located in the common parameter band of 1.30-1.80 m/s^[30]. The rod teeth on the rod-tooth-belt conveyor chain can increase the friction between the conveyor chain and the film, and can effectively grasp, transport the ribbon and strip residual film. Based on this function of rod-teeth, when designing the machine, the included angle β between the upper surface of the conveyor chain and the horizontal plane can be appropriately increased. When β is larger in a reasonable range, the film-impurities separation effect is better. According to the field test, if $\beta \geq 50^\circ$, although the effect of film-impurities separation is good, it is significantly that residual film could be grasped difficultly, and it often falls to the ground, especially when the film surface had been severely damaged. However, when $\beta \leq 40^\circ$, the effect of film-impurities separation is poor, and impurities such as corn straw and soil are generally more in the recovered residual film. In the end, $\beta=45^\circ$ is selected.

3.2.3 Bundle self-unloading residual film collecting device

For a long time, the difficulties in residual film collecting, film roller unloading and high impurity content have been the main constraints at the end of the residual film recycling process. Therefore, this research broke through the existing theoretical constraints, the traditional route of film winding around a roller must be abandoned, and several sub-rollers in the same rotating direction were used to generate continuous film winding power, so a new scheme to complete film collecting is proposed. Moreover, there is an obvious gap between adjacent sub-rollers, so that, further film-impurities separation can be carried out once more. When the system works, the collected residual film rotates in suspension in the semi-enclosed space surrounded by the sub-rollers. When the film roll reaches to a certain diameter, the film unloading hydraulic cylinder switch can be closed, the inclination of the semi-enclosed opening window formed by the sub-rollers can be large enough, and the collected residual film can fall naturally for the gravity, so as to complete the residual film self-unloading.

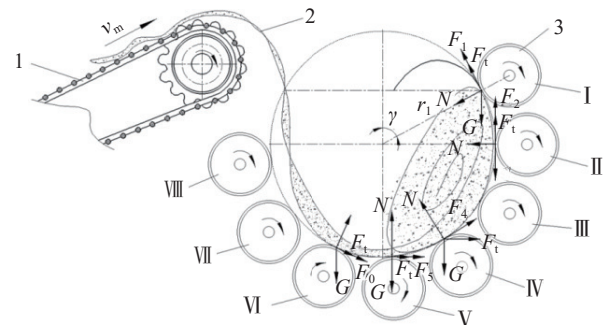
Based on the above ideas, the core of the bundle self-unloading film collecting device proposed in this study is the semi-enclosed shaftless bundle film collector, which is mainly composed of left

and right side plate and 8 sub-rolls. The bundle mechanism surrounded by the sub-rolls is a semi-cylindrical space, and its structure is shown in Figure 10. There are two key points for the success of this film collector: 1) the residual film cannot be wound on any sub-roll; 2) no residual film in the operation can be thrown out of the collecting space. To this end, it is necessary to pay attention to the motion state of the residual film before the continuous coiling state can be established successfully can be shown in Figure 11.



1. Frame 2. Film unloading hydraulic cylinder 3. Bearing 4. Drive idler 5. Sub-roll 6. Side plate.

Figure 10 Semi-enclosed shaftless bundle film collector



1. Rod-tooth-belt type film-impurities separation device 2. Residual film 3. Sub-roll.

Figure 11 Force analysis of residual film in semi-enclosed shaftless bundle film collector

According to Figure 11, the tractor power is transmitted to each sub-roll through chain drive. The residual film passes through three stages of falling, climbing and back throwing in the bundle film collecting device, and forms a film bundle under the continuous sub-rolls rotation. Relevant tests show that, the recycled film stagnates for a long time and accumulates in the rear half of the bundle film collecting device (No. II, III and IV sub-rolls), and the continuous roiling movement cannot be realized, which is the main reason for the blockage of the device and the sub-rolls film wrapping. For this reason, it is necessary to study the constraint conditions of the residual film movement and force condition in the above three stages in detail.

In the falling stage, the residual film dropped from the rod-tooth-belt type film-impurities separation device falls to the front of the film collecting chamber, contacts with sub-roll VIII, VII and VI first, and enters the next stage under the combined action of sub-rolls with uniform and constant speed. The force of the residual film falling on the VII and VIII sub-rolls is basically the same as that on the VI.

In the climbing section, the residual film starts to reach the IV sub-roll through VI and V. At this time, the residual film has begun to climb along the sub-roll surface, and the movement direction has changed from horizontal to right-oblique-upward. The force at

No. III sub-roll is similar to that at No. IV. In Figure 11, N is the support force of the sub-roll to the residual film, and the direction is perpendicular to the tangential direction of the sub-roll where the residual film is passing by; G is the self-gravity of the residual film (the corresponding self-mass is m), and the direction is vertical-downward; F_t is the thrust of the subsequent residual film, and the direction points to the inner side of the device along the tangential direction of a specific sub-roll; F_f is the friction force of a sub-roll, and the direction is along its tangential direction, $i=1, \dots, 8$. After the residual film reaches the No. III sub-roll, as long as it still has enough power to rush onto the subsequent arc surface surrounded by other sub-rolls, the film bundle can be completed smoothly, that is, the residual film roll can pass through No. II sub-roll. Referring to the force analysis of the residual film at the No. II sub-roll at this moment, the boundary condition for its continuous upward movement is

$$F_2 + F_t = G \quad (9)$$

$$\begin{cases} F_2 = \mu_1 N \\ N = m \frac{v_1^2}{r_1} \\ v_1 = v_2 = \frac{n_2 \pi r_2}{30} \end{cases} \quad (10)$$

where, μ_1 is the friction coefficient between the residual film and the sub-roll, taken as 0.4; v_1 and v_2 are the film collecting speed of the film collecting chamber and the linear speed of the sub-roll respectively; r_1 and r_2 are the equivalent radius of the film collecting chamber and the radius of the sub-roll individually; n_2 is the sub-roll rotation speed. According to the design requirements, the tangential force F_t generated by the rotation of the sub-roll (i.e., the friction pulling force from the sub-roll) is much greater than the thrust F_t , the subsequent residual film in the film collecting chamber. Therefore, F_t and the friction between the residual film and two side plates of the film collecting chamber can be ignored. In this investigation, r_2 is determined as 70 mm (the gap between adjacent sub-rolls is 18 mm), so the minimum allowed rotation speed $n_{2 \min}$ of the sub-roll free from wrapping is 169 r/min (the corresponding v_2 is 1.24 m/s). From the above conclusion, the relationship shown in Equation (11) should be met:

$$v_1 = v_m = 1.57 \text{ m/s} > 1.24 \text{ m/s} \quad (11)$$

In the back throwing process, when the residual film moves to the No. I sub-roll, the residual film begins to throw obliquely towards the inlet of the film collecting chamber. According to the static analysis, the resultant force of the residual film at the No. I sub-roll points to the film collecting chamber. In order to prevent the residual film from being thrown out of the film collecting chamber, or interfering with the falling residual film due to the excessive rotation speed, based on the analysis shown in Figure 11, the horizontal range S and height H of the oblique throwing movement of the residual film can be written as follows

$$\begin{cases} S = \frac{v_1^2 \sin 2\gamma}{g} \\ H = \frac{(v_1 \sin \gamma)^2}{2g} \end{cases} \quad (12)$$

In view of the included angle shown in Figure 11 $\gamma=45^\circ$, the horizontal range S and height H can be the biggest. While the project parameters $v_1=v_m=1.57$ m/s are brought into and calculated, $S=25.15$ cm and $H=6.29$ cm can be obtained. Considering the

geometric relationship, the motion interference between the thrown residual film from No. I sub-roll and the falling residual film from the rod-tooth-belt type film-impurities separation device has no possibility, and the residual film will not be thrown out of the film collecting chamber.

4 Field test

4.1 Test conditions

On October 26, 2021, test of the prototype based on the scheme described in this paper was carried out in Jinchang City, Gansu Province. The test field covers an area of 10 hm², the soil firmness is 2.68 MPa, and the soil surface moisture content is 13.33%. Corn planting mode: the row spacing is 500 mm, the plant spacing in row is 220 mm, film width is 1400 mm, the film thickness is 12 μm , and the film surface is partially covered with soil, the average straw laying thickness is 322 mm, the average straw moisture content is 21.2%, and the operating power is John Deere 1404 tractor (103 kW).

4.2 Test design

The prototype test of this study mainly focuses on two aspects: the first is the effect evaluation of TPATSW type film lifting shovel, and the second is the influence analysis of the main constraints on the operation effect of the whole machine. The performance of the film surface straw cleaning part is mainly evaluated by the comprehensive fuel consumption of the whole machine, which will be briefly discussed in the 'result verification'.

In addition to the force measuring device specially developed for this project, the effect evaluation of the TPATSW type film lifting shovel also needs the help of some intermediate results of the whole machine test. In order to prove the progressiveness of this new shovel, it is necessary to make a comparative analysis with the two representative film lifting shovel in the popular available market. The single shovel tillage resistance value F_z (N), root pulled up rate η_1 (Percentage of uprooted corn stubbles in all stubbles within the test range), impurity content of recycled residual film η_2 (The mass of all impurities in the film collecting chamber as a percentage of the total recycled material) and soil crushing effect will be used for comprehensive qualitative evaluation.

The impact on the whole machine operation effect mainly includes the film lifting shovel earth angle, the film lifting shovel operation depth and the machine operation speed. Residual film recycling rate η_3 (Percentage of the recycled pure residual film in the total mass of the film laid in a test section) and crushed straw qualified rate η_4 (Proportion of qualified straw in total crushed straw) can be used for comprehensive quantitative evaluation. The purpose of the test is to find the optimal parameters combination to guide the specific agricultural production. According to the design and relevant preliminary tests as well as analysis, the earth angle of the film lifting shovel is better in 25°-35°. Although the soil in Hexi Irrigation Area hardens and adheres to the residual film in autumn, the residual film is still mainly exposed or in the surface soil. Therefore, the film lifting shovel operation depth range can be 20-50 mm and the machine speed range can be 5.0-7.0 km/h. The value range of test factors is shown in Table 2.

Table 2 Test factors and levels

Levels	Factors			Error D
	Earth angle $A/(^\circ)$	Operation depth B/mm	Operation speed $C/\text{km}\cdot\text{h}^{-1}$	
1	25	20	5.0	1
2	30	35	6.0	2
3	35	50	7.0	3

4.3 Test results

4.3.1 Effect evaluation of TPATSW type film lifting shovel

About the effect evaluation of TPATSW type film lifting shovel, tractor horizontal traction F_z (N, F_N in Figure 8 is a part of it) is the first indicator to be concerned, which needs to be carried out on the force measuring device specially developed for this project (see Figure 12a). However, the effect inspection of root cutting-soil crushing requires the combined operation of the whole machine. In order to grasp the performance of the test object more intuitively, two representative film lifting shovels on the market were also included in the assessment, and were marked as test object 1 (long tooth film lifting blade, as shown in Figures 12b and 12c) and test object 2 (arc film lifting teeth, as shown in Figures 12d and 12e).

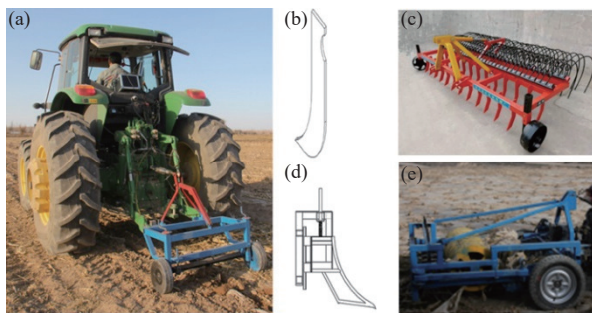


Figure 12 TPATSW type film lifting shovel operation effect evaluation test

The operation area with the length of 100 m (1400 mm wide) in each of the three sections is selected, with the operation speed of 5.0 km/h and the operation depth of 50 mm, which is used for the test data acquisition of F_z based on the force measuring device and the observation of root cutting effect. Before the test, it is necessary to use stubble cleaner to clean the film surface, so as to remove the excess straw and create the same conditions for the tests. The observation of soil crushing effect of the whole film lifting system will be carried out in the whole machine test. It should be stated that, the commercial residual film recycling machine using test object 1 and 2 is not suitable for the corn half film-flat-mulching cultivation in Hexi Irrigation Area. Therefore, for soil crushing effect, here, only the whole machine test results of this research is evaluated.

The variation curve of the required tractor horizontal traction F_z , when a single film lifting shovel to penetrate a typical corn stubble, can be shown in Figure 13a. In this figure, the data acquisition speed is 200 Hz, but the data required for the drawing are all available values after removing the unreliable sections. Curves I, II and III correspond to test objects 1, 2 and 3 (TPATSW type) respectively. Although the three curves in the figure fluctuate, it can still be clearly found that, the tillage resistance of the long tooth film lifting blade corresponding to test object 1 is the largest, followed by the arc film lifting teeth with test object 2, while the resistance of TPATSW type film lifting shovel of this project is the smallest. Specifically, during the root cutting process, the F_z required by test object 2 is about 90% of that of test object 1, and that of test object 3 is about 80%; while in non-stubble soil, the above indexes can be reduced to 85% and 70% respectively. Therefore, the TPATSW type film lifting shovel proposed in this study has obvious drag reduction effect.

Figures 13b and 13c show the root cutting-soil crushing effects of the TPATSW type film lifting shovel successively. Among them, Figure 13b is the result of the force measuring device shown in

Figure 12a, and Figure 13c is the result of the whole machine test. Figure 13b shows that, the TPATSW type film lifting shovel has a good effect on root cutting, the stubble cannot be easily pulled up as a whole. The average value of η_1 in the normal operation process is about 4%-6%, therefore, the stubble content in the subsequent recycled residual film will be significantly reduced. On this basis, Figure 13c shows the operation effect of the whole machine, which proves that the TPATSW type film lifting shovel group proposed in this study has a good overall soil crushing effect, almost no soil blocks larger than 5 cm were found, and the average η_2 usually does not exceed 16%. So the film-soil separation effect is good, which is of great significance for the operation object with solid film-soil adhesion under the film mulched irrigation mode.

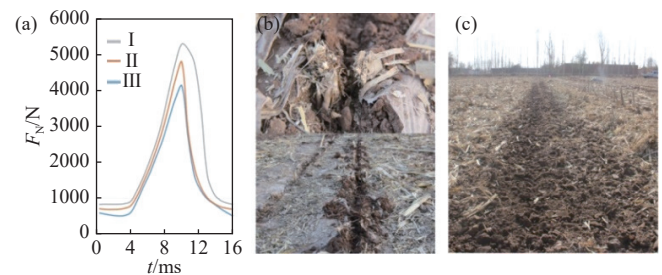


Figure 13 TPATSW type film lifting shovel root cutting-soil crushing effects evaluation test

4.3.2 Influence analysis of the main constraints on the operation effect of the whole machine

The influence of the main constraints on the operation effect of the whole machine was analyzed in the way of whole machine test, as shown in Figure 14. Figure 14a shows the real scene of the corn field surface in the Hexi Irrigation Area after autumn, which is characterized by thick aboveground mulch and more upright stalk-stubbles. Therefore, the recycle of residual film will be beset with difficulties. Moreover, Figure 14b mainly shows the working effect of the semi-enclosed shaftless bundle film collector. It can be seen that the residual film was winding itself. Even if the film surface was broken, it would not affect the subsequent film to continue to wind on the basis of the previous bundle further. In addition, impurities can further fall from the sub-rolls gap, which is the second film-impurities separation. Figures 14c and 14d continue to show the operation effect of the whole machine described in this study from different angles. It can be found that the residual film was picked up relatively clean, the film surface straw cleaning and root cutting-soil crushing capacity of the whole device is good, soil blocks were small and the residual film left in the field could seldom be found, which creates good conditions for subsequent farming.



Figure 14 Field test and effect display

In this section, the operation length of each sub-test is 100 m (the corresponding film width is 1400 mm), each group of tests is repeated three times, and the results obtained are the average of the three data. According to the setting of test factors and levels in Table 2, the orthogonal test scheme of 4 factors and 3 levels was adopted to determine η_3 and η_4 , the comprehensive scoring method is used to determine the arrangement order of factors and the combination of better operation parameters. Therefore, in the calculation of comprehensive score Q , the weight of η_3 is 0.9. In addition, since the main function of the machine as a whole is to recycle the residual film, the weight of η_4 (measurement index of film surface straw cleaning device) is only 0.1. The test results are listed in Table 3. For the specific definition of the above indicators, please refer to the relevant parts of literatures [31,32].

Table 3 Test scheme and results

Test No.	Levels of factors				Main indicators		Comprehensive score Q
	A	B	C	D	$\eta_3/\%$	$\eta_4/\%$	
1	1	1	1	1	76.4	89.6	77.72
2	1	2	2	2	82.5	81.1	82.36
3	1	3	3	3	80.1	91.2	80.21
4	2	1	2	3	80.2	89.9	81.17
5	2	2	3	1	84.3	95.2	85.39
6	2	3	1	2	89.6	95.3	90.17
7	3	1	3	2	78.0	91.5	79.35
8	3	2	1	3	87.2	91.7	87.65
9	3	3	2	1	86.3	92.0	86.87
K_1	80.43	79.413	85.18	83.327			
K_2	85.58	85.133	83.467	83.96			
K_3	84.62	86.083	81.983	83.343			
Range	5.15	6.67	3.197	0.633			
Optimal choice	A_2	B_3	C_1				
Importance order	B	A	C				

The comprehensive score and range analysis of the test data in Table 3 show that, from strong to weak, the order of influence on the operation performance of the residual film recycling machine is as follows: operation depth (B), penetrating angle (A) and operation speed (C). It should be noted that, the range of error term D is far lower than that of other factors, indicating that this factor has no significant impact on the test index and cannot be considered. Consequently, the recommended scheme is $B_3A_2C_1$, that is, the operation depth of the film shovel is 50 mm, the earth angle of the film shovel is 30°, and the operation speed of the whole machine is 5.0 km/h.

4.4 Results verification

The prototype was tested in the field under the recommended parameters. A wider range and deeper degree of η_3 and η_4 were tested, also, the reliability of film surface straw cleaning device, film lifting device, rod-tooth-belt type film-impurities separation device and bundle self-unloading film collecting device during the machine operation are also tested. After the machine operate stably, five test areas with a working length of 100 m are randomly selected for the test, the received data are shown in Table 4, the field test and effect comparison can also be found in Figure 14.

The statistical results in Table 4 show that, the average η_3 is 84.9%, and the average η_4 is 90.3%. The test indicators meet the requirements of national and industrial standards.

Therefore, the comprehensive evaluation believes that, in the same effect under the current conditions, this machine is one of the joint operation equipment with the simplest structure and the most

efficient use. Its total length is 3.15 m. Even if John Deere1404 tractor was used in the test, its average diesel consumption was only 45.30 L/hm², which is about equivalent to other single-function residual film recycling machines with the same working efficiency. Therefore, the achievements of this project are green and energy-saving, with potential market promotion and application value.

Table 4 Results of field tests

Number of test area	$\eta_3/\%$	$\eta_4/\%$
1	82.5	91.8
2	87.6	87.6
3	84.2	91.3
4	86.6	92.4
5	83.5	88.4
Average value	84.9	90.3

5 Conclusions

(1) In view of the prominent problems faced by the residual film recycle in corn field after autumn in Hexi Irrigation Area, a new scheme of segmented combination upper-side-discharge straw-returning and bundle self-unloading residual film recycling machine is proposed. The system focuses on the joint operation under the concept of compact space, low power consumption, flexible combination as well as efficient film collection, and all the parameters meet the agronomic requirements.

(2) For film surface straw cleaning device, 56 obtuse-angle L-shaped blades paired single-helix layout, on the premise of reducing the installation complexity of crushing rotating parts, the total length of blade unsupported cutting is increased, and the crushing effect is ensured. In addition, the arrangement of placing the cross-range screw conveyor auger behind and above the stubble cleaner roller, makes the longitudinal length of the film surface straw cleaning device greatly reduced.

(3) In the residual film recycling part, the TPATSW type film lifting shovel not only greatly reduces the tillage resistance on the surface of the soil contacting parts, but also effectively reduces the length proportion of the film lifting shovel in the residual film pickup system, and also avoids soil blocking. Semi-enclosed shaftless bundle film collector takes 8 film reeling sub-rolls as the carrier, aims at sub-roll free from wrapping, thrown film inside boundary, the minimum speed of the sub-roll is determined to be 1.24 m/s, the horizontal range of throwing the film at the maximum running speed is 25.15 cm and the vertical range is 6.29 cm, and the shaftless film collection can be completed under the collective action of all the sub-rollers in the same direction at the same speed. The film unloading can be accomplished by turning the semi-enclosed shaftless bundle film collector by the hydraulic mechanism to dump, which is simple to be operated.

(4) The included angle between the upper surface of the conveyor chain and the horizontal plane of the rod-tooth-belt type film-impurities separation device is determined $\beta=45^\circ$; the diameter of the sub-roll is 140 mm, the gap between adjacent sub-rolls is 18 mm, and the diameter of the film collecting chamber is 500 mm. According to the orthogonal test, the optimal parameter combination can be: earth angle of the film lifting shovel is 30°, its operation depth is 50 mm and the machine walking speed is 5.0 km/h. The field test results under the optimal parameters showed that, on average, the residual film recycling rate is 84.9% and the crushed straw qualified rate is 90.3%. The test indexes met the requirements of national and industrial standards.

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