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Design, Simulation and Experimentation of a Polythene Film Debris Recovery Machine in Soil

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Abstract: With the rapid development of planting techniques using plastic film mulching, the content of residual plastic film in soil increases year by year, which pollutes the soil and water, endangers the growth of crops and reduces the quality and yield of agricultural products. Therefore, in order to solve the problem that plastic film with a thickness of 0.008 mm, commonly used in China, is difficult to recycle, this study designed the residue film recycling machine based on the existing research results. After harvesting cotton in Xinjiang, the working performance of the residue film recovery machine of plough layer was measured. Through theoretical optimization and field experiments, the effects of conveyor speed, distance between elastic teeth and type of elastic teeth on residual film recovery were studied. The relationship between the parameters of the residual film recovery machine and the recovery effect of the residual film was analyzed. When the rotational speed and inclination angle of the conveying and separating device were 74 rpm, 35° and 120 rpm, 45°, respectively, under the condition that the distance between C-shaped elastic teeth was 59 mm, the recovery and separation rate of residual plastic film were 88.12% and 83.27%, respectively. Based on the study results, it is recommended to accelerate the development of naturally degradable agricultural plastic film or to popularize and apply thickened film. Relevant local standards and policies have been formulated to address the problem of residual film pollution, and a governance system has been established for the benefit of the government, scientific research institutions, enterprises and farmers. This study provides a reference for mechanized recovery of residual plastic film in soil and treatment of soil pollution.

Keywords: agricultural field; residue film recycling machine; conveying device; separating device; elastic teeth structures; recovery and separation rate

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1. Introduction

In the middle of the 20th century, with the development of the plastic industry, and especially the emergence of agricultural polythene film (PF), some industrially developed countries used agricultural PF to cover the ground. As a result, the production of vegetables and other crops achieved good results [1,2]. Agricultural PF mulching technology changes the growing environment of vegetables and other crops, improves the yield and quality of crops and has achieved remarkable production and economic benefits in agricultural production [3–5]. However, agricultural PF mulching technology has some adverse effects, for example, mulching for many years will cause the removal of agricultural PF with difficulty. In addition, agricultural PF is not clean, resulting in farmland environmental pollution, soil fertility decline, seed emergence rate decreases and other problems which have attracted the attention of some researchers [6–8]. At present, the agricultural PF mulching area in China exceeds 20 million hm^2, and the annual use of agricultural PF exceeds 1.5 million tons, accounting for about 90% of the total annual use of agricultural PF in the world. Xinjiang is China's main agricultural PF covering area, mainly growing cotton, corn, pepper and other crops [9]. According to statistics, in 2018, the total sown area of crops in Xinjiang was 6.126 million hm^2, and the total area of agricultural PF mulching was about 3.478 million hm^2, including 2.491 million hm^2 of cotton. In Xinjiang, agricultural PF, seeds, chemical fertilizers, pesticides and so on have become indispensable means of production in agricultural production [10,11]. The researchers call the residue of PF debris the plough layer, which have not been reverted to a clean state for many years and has remained in the soil for a long time. The problem of soil contaminated by residual PF is becoming more and more serious, and people are paying more and more attention [12–14]. It is a great challenge and urgent problem to recover and reuse the residual PF debris of the plough layer [15,16].

Although a lot of research has been performed on degradable PF at home and abroad, it is still in the stage of research, development and experimentation, and has not been popularized on a large scale [17]. Currently, the most widely used agricultural PF is a PE material that naturally degrades over hundreds of years, whereas biodegradable film is costly and less effective [18]. The harmful substances decomposed by agricultural PF directly enter the soil and enter the crop body with water and nutrients, which again affect the growth of crops and the quality of agricultural products. Residual PF debris hinders the infiltration of water in soil, reduces soil moisture content, weakens the drought resistance of cultivated land, leads to a decrease in soil porosity and permeability and destroys soil gas phase exchange. Residual PF not only has adverse effect on soil properties but also endangers crop growth, such as reducing seed emergence rate and affecting seedling survival [19].

The thickness of 0.008 mm PF is commonly used in agricultural production in China, so it is difficult to recycle mechanically. Most farmers give up on the recovery of PF, instead directly discarding it in the soil. The hazards of agricultural PF, especially those of residual PF debris in the soil, have attracted increasing interest in China [20,21]. The promulgation of the Action Plan for Soil Pollution Control in China has defined the goal of recovery and reuse of agricultural PF. The area covered by agricultural PF throughout China has basically achieved zero growth, and the regions with serious PF pollution are the first to realize negative growth. Relevant local standards and policies have been formulated to address the problem of residual PF pollution, and a governance system has been established for the benefit of the government, scientific research institutions, enterprises and farmers [22].

Although biodegradable film has been developed, the technology is still immature. Innovation in the technology of the biodegradable film is urgent to overcome the technical difficulties. The inclusion of some natural fertilizers in the film for the agricultural land that are specific to each crop may be an effective way to make new materials to replace agricultural PF. We should innovate the industrial chain circulation mode of agricultural PF, overcome technical difficulties and break through the technical bottleneck of recycling residual PF. Recycling or harmless treatment of agricultural PF has become a research focus, but there is no effective method to deal with agricultural PF [22]. In the future, we can use the recycling and utilization methods of plastic products for reference to explore new ways of recycling and harmless treatment of residual PF.

Due to the high price of the biodegradable film, the thickened PF is being promoted and applied in China. This is because the thickened PF has better mechanical properties which are conducive to mechanized recovery. At present, many types of residual film recovery machines have been developed, but there are few that can be popularized and applied [23,24]. It is still necessary to constantly improve and optimize the structure and working parameters of the residual film recovery machine. Mechanical recovery of residual PF is the main method at this stage, so we should increase our support for research and development of new machines [25,26].

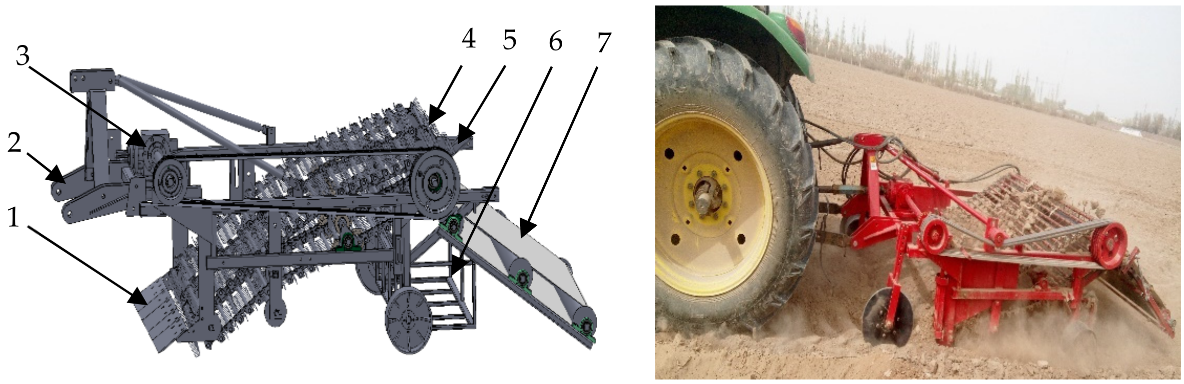
In order to solve the problem of the difficult recovery of PF debris and pollution of the soil environment, this paper designs a PF debris collector of the plough layer and carries out the field experiment. Specifically, a soil shovel, power transmission system, conveying device for chains and elastic teeth, PF recycling box and a device for separating residual PF from soil and impurities were designed, and the response of the rotation speed of the transportation chain, the variety and the distance between the elastic teeth to the recovery rate and separation from impurities rate of residual film were analyzed. The working parameters of the PF debris collector were optimized by field experiment. The research results can provide a new scheme for the mechanized recovery of residual PF technology and the treatment of agricultural environmental pollution.

2. Materials and Methods

2.1. Materials

The experiment was conducted during the cotton sowing season in Xinjiang (April–May 2020). The test site was Aksu City of Precision Agricultural Machinery Manufacturing Company in Xinjiang Uygur Autonomous Region, China (41° N, 80° E, elevation = 1105 m). The light intensity in Xinjiang is sufficient and suitable for growing cotton. In 2020, the planting area of cotton covered with PF in Xinjiang was 2.502 million hm^2, accounting for more than 80% of the cotton planting area in China [23]. The experiment was carried out in a cotton field after ploughing, at which time the cotton straw was crushed and buried in the soil as an organic fertilizer. PF was more difficult to recycle and contained a lot of soil and other impurities, because it was broken into smaller pieces in the soil.

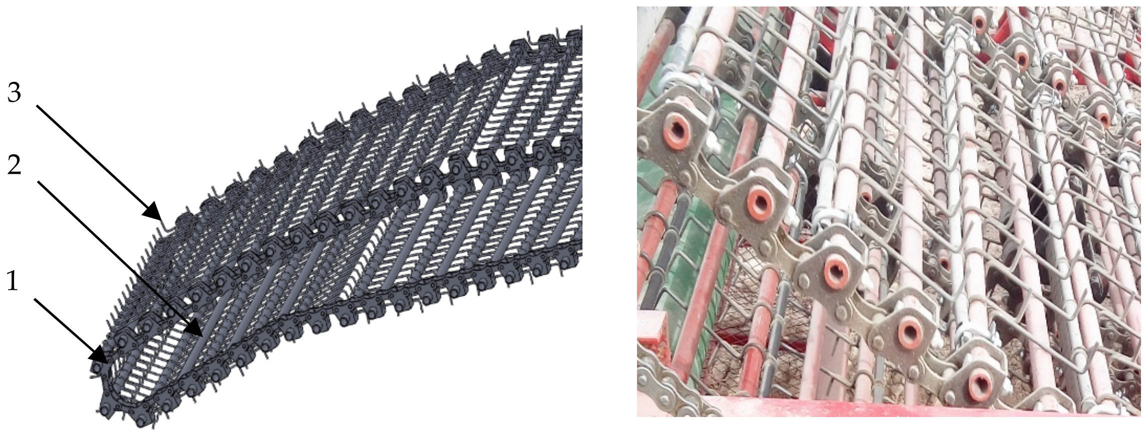
The soil moisture content and broken rate were 9.67% and 70.56%, respectively, and the thickness of residual PF was 0.008 mm. The length of cotton stalks in the plough layer were about 10 mm to 50 mm, and the moisture content was about 14.75% [26]. In the above-mentioned experimental environment, the PF debris collector of the plough layer was tested and evaluated. The PF debris collector used in the current work had dimensions of 3500 mm, 1500 mm and 1200 mm for its length, height and width, respectively, as shown in Figure 1.



(a) (b)

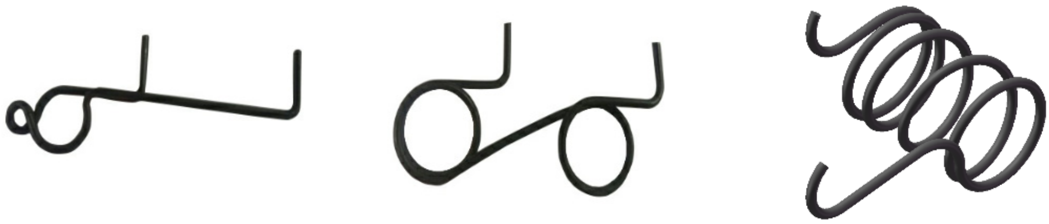
Figure 1. Designed model (**a**) and prototype (**b**) of the PF debris collector, consisting of the following functional parts: soil shovel (1), suspension frame (2), power transmission system (3), conveying device of chains and elastic teeth (4), frame of the PF collector (5), PF recycling box (6) and device for separating residual PF from soil and impurities (7).

The conveying device of chains and elastic teeth consisted of elastic teeth, chains and steel bars that were fixedly connected with chains. Elastic teeth were installed on the steel bars at a certain distance, but the elastic teeth could not move in the axial direction and the circumferential direction could rotate (Figure 2). Three types of elastic teeth made of steel with a diameter of 5 mm were designed in this paper, as shown in Figure 3a–c. Residual PF, soil and impurities were shoveled into the conveying device of chains and elastic teeth. Residual PF and larger soil particles were transported back to the separator by the elastic teeth, but small soil particles and impurities could fall to the surface of the cotton field through the gap between the elastic teeth.



(**a**) (**b**)

Figure 2. Designed model (**a**) and prototype (**b**) of the conveying device, showing the chains (1), steel bars (2) and elastic teeth (3).



(**a**) (**b**) (**c**)

Figure 3. Designs of three types of elastic teeth, A, B and C, as shown in Figure (**a**–**c**).

The mechanism for separating residual PF from soil and impurities was composed of a conveyer belt, supporting roller and roller chain system, and the rotating direction of the conveyer belt was counterclockwise. The separation of residual PF from soil and impurities was realized by the difference in the falling velocity of residual PF and soil particles and impurities on the belt.

The PF recycling box, installed at the rear and lower position of the conveyor chain, was a rectangular screen box with dimensions of 500 mm × 1500 mm. After the separation of PF debris entering into the rectangular screen box, the smaller size of impure particles fell to the surface through the screen holes.

The mainframe was constructed from 60-mm square steel pipes to carry the power transmission system, soil shovel, conveying device of chains and elastic teeth and mechanism for separating residual PF from soil and impurities. The power was transmitted from the tractor (55 kW) through the reducer and a V-belt to the conveying device of chains and elastic teeth, which was transmitted through the roller chain system to the separating unit.

The conveying device's rotational speed was determined by a digital tachometer with an accuracy of $\pm$0.05% + 1, ranging from 1 to 19,999 rpm. The distance between the elastic teeth was determined by electronic digital caliper with an accuracy of 0.01 mm, ranging from 1 to 1500 mm. The method of replacement sprockets was used to control the transmission ratio, which led to controlling the conveying device's rotational speed. Electronic precision balance that was capable of measuring the quality of the residual PF and soil particles and impurities with a current accuracy of 0.001 g was used to measure the recovery rate and separation from impurities rate of residual film, in order to determine the performance for the working process.

2.2. Methods

2.2.1. Experiments Design

When the soil shovel depth was adjusted to 117 mm, the forward speed of the machine was 1 m/s, the reciprocating motion frequency of the separating device was 255 rpm and the motion amplitude of the separating device was 80 mm; the machine was tested at four conveying device rotational speeds (30, 50, 70 and 90 rpm) and at four distances between the elastic teeth (35, 45, 55 and 65 mm), respectively. All treatments were replicated three times and the PF and impurities were collected in the recycling box. In the meantime, the quality of the PF and soil particles and impurities was measured and recorded for each experimental test.

2.2.2. Throwing Velocity of PF and Impurities

The rotating speed of the conveying device determines the throwing velocity of PF and impurities, which provides a theoretical reference for the design of the mechanism for separating PF from soil and impurities. The throwing velocity of PF and impurities can be calculated as a function of the rotating angular velocity and radius of the conveying device with the following equation [24]:

$$v = \omega r, \tag{1}$$

where v is the throwing velocity of PF and impurities (m/s), ω is the rotating angular velocity of the conveying device (rad/s) and r represents the radius of the conveying device (mm).

Usually, ω depends upon the rotational speeds of the conveying device, and it can be predicted from the following equation:

$$\omega = 2\pi n, \tag{2}$$

where π represents the circular constant (i.e., the ratio of circumference to diameter of a circle), the approximate value of π is 3.14 and n is the rotational speeds of the conveying device (rpm).

2.2.3. Throwing Distance of PF and Impurities

The residual PF and impurities thrown out by the conveying device can be simplified as falling body motion with a certain initial velocity and subjected to air resistance and gravity. Mixtures fall into the separating device with the interaction of gravity and air resistance. Due to the different resistances of the mixtures, such as residual PF, soil and straw, in the process of movement, the movement characteristics of the materials are quite different. The throwing horizontal distance of residual PF and impurities can be calculated with the following equation:

$$l = (v \cos \alpha - at \cos \alpha)t, \tag{3}$$

where l is the throwing horizontal distance of residual PF and impurities (mm), α is the angle between the conveying device and the horizontal plane (°) and a represents the drag acceleration of the mixtures (m/s^2). The movement time of the mixtures is given as:

$$t = \frac{v \sin \alpha}{g + a \sin \alpha}, \tag{4}$$

The drag acceleration a of the mixtures is calculated as:

$$a = \frac{k_1 \rho_1 v^2 s}{2m_0}, \tag{5}$$

where k_1 is the coefficient of air resistance, ρ_1 is the air density (g/m^3), s is the windward area of mixtures (m^2) and m_0 is the quality of mixtures' particles (g).

2.2.4. Recovery and Separation Rate of Residual PF

In the above conditions and environment, five test areas were selected randomly and the residual PF recovery test was carried out. Under the same test conditions, the residue film mixture was collected and emptied in the residue PF recycling box, and the test was repeated five times. The recovery and separation rate of residual PF were calculated by the weighing and ratio method. The methods are given in NYT1227-2006 and GB/T 25412-2010. The recovery and separation rate of residual PF under different conditions were calculated by the Equations (6) and (7), and the test results were taken as the average of the five test results to ensure accuracy [26]:

$$\eta = \frac{m_1}{m_2} \times 100\%, \tag{6}$$

where η is the recovery rate of residual PF (%), m_1 is the quality of residue PF in the recycling box in test area (g) and m_2 is the quality of residual film in the test area before the experiment (g).

$$\gamma = \frac{m_1}{m_1 + m_3} \times 100\%, \tag{7}$$

where γ is the separation rate of residual PF (%) and m_3 is the quality of soil particles and impurities in the recycling box in the test area (g).

2.2.5. Treatment Process for Measuring Quality of Residual PF

As shown in Figure 4, when calculating the recovery and separation rate of the residual PF, the experimental data were obtained by sampling, cleaning, drying and measuring the quality. The data were substituted into Equations (6) and (7) to calculate the test results. When the parameter m_2 was calculated, an area of 1m^2 was randomly selected in the test site as the test sampling area. The area of the rectangular frame shown in Figure 4a was 1 m^2. The experimental data were obtained by collecting the residual PF in the soil within 150 mm depth. When calculating the parameters m_1 and m_3, samples should be taken in the recycling box of residue PF. The quality of impurities could be measured directly without the cleaning and drying process, but the quality of residual PF needed to be measured after treatment.

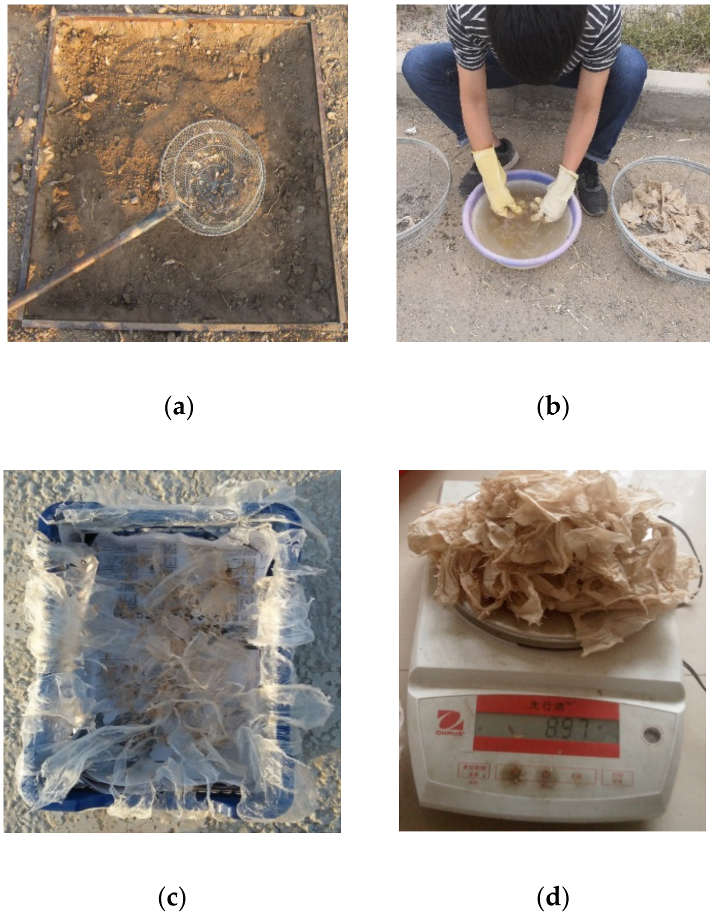


Figure 4. Shows the treatment process for measuring quality of residual PF: (**a**) selecting an area of 1 m^2 in the test site and collecting the residual PF in the soil within 150 mm depth, (**b**) cleaning the residual PF, (**c**) drying the residual PF after cleaning, (**d**) measuring the quality of the residual PF and obtaining experimental data.

3. Results

3.1. Effect of the Different Elastic Teeth Structures on the Recovery Rate of PF

The experimental results obtained from the present study were represented by curved surfaces. The response of the interaction between the rotating speed of the conveying device and the distance between the elastic teeth to the recovery rate of the residual PF was analyzed under the condition that the elastic teeth were A-shaped, B-shaped and C-shaped structures, respectively. As could be seen in Figure 5, under the same conditions, the structure type of the elastic teeth directly affected the experimental results of the recovery rate of the residual PF. As is shown in Figure 5c, when the rotating speed of the conveying device and the distance between the elastic teeth are 74.08 rpm and 59.61 mm, respectively, the maximum recovery rate of PF is 88.62%. The rotating speed of the conveying device, the distance between the elastic teeth and the type of elastic teeth had a significant influence on the recovery rate of residual PF in the soil. With the increase in the conveying device's rotational speed and the distance between elastic teeth, the recovery rate of the residual PF reached the maximum value and then decreased. Compared with the test results of Figure 5a–c, it could be concluded that the recovery rate of residual PF of C-shaped elastic teeth was the highest, and the recovery effect of residual PF was the best.

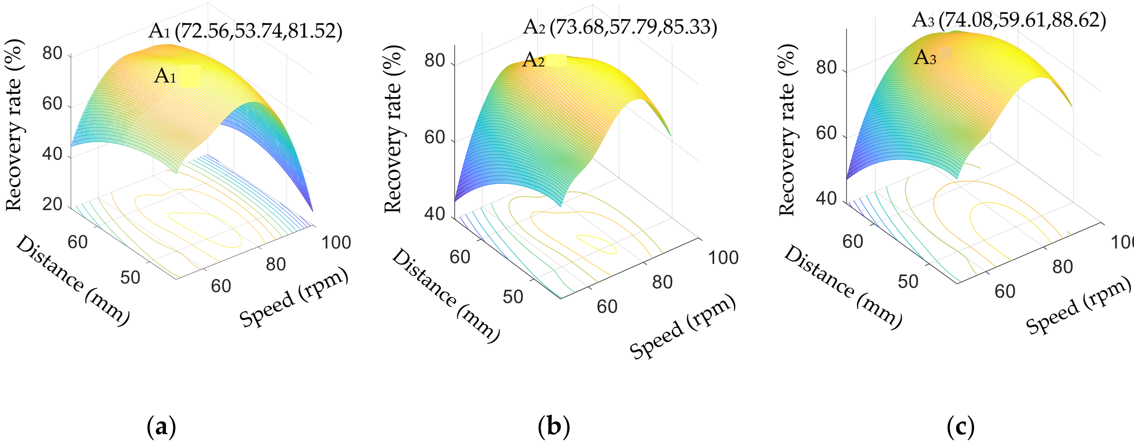


Figure 5. Effect of the conveying device's rotational speed (rpm) and the distance between elastic teeth (mm) on the recovery rate of PF (%) at three types of elastic teeth, (**a**) A, (**b**) B and (**c**) C.

Under the condition of different elastic teeth types, the response regularity of the interaction between the rotating speed of the conveying device and the distance between the elastic teeth to the recovery rate of the residual PF could be clearly observed by using the three-dimensional surface diagram.

3.2. Effect of the Rotational Speed on the Throwing Horizontal Distance of PF at Different Inclination Angles

Figure 6 explains that the throwing horizontal distance of PF is directly affected by the rotational speed and inclination angle of the conveying device. Under the condition of constant inclination angle between the conveying device and the horizontal plane, the horizontal distance of the residual PF thrown by the conveying device also increased with the increase in the rotational speed of the conveying device.

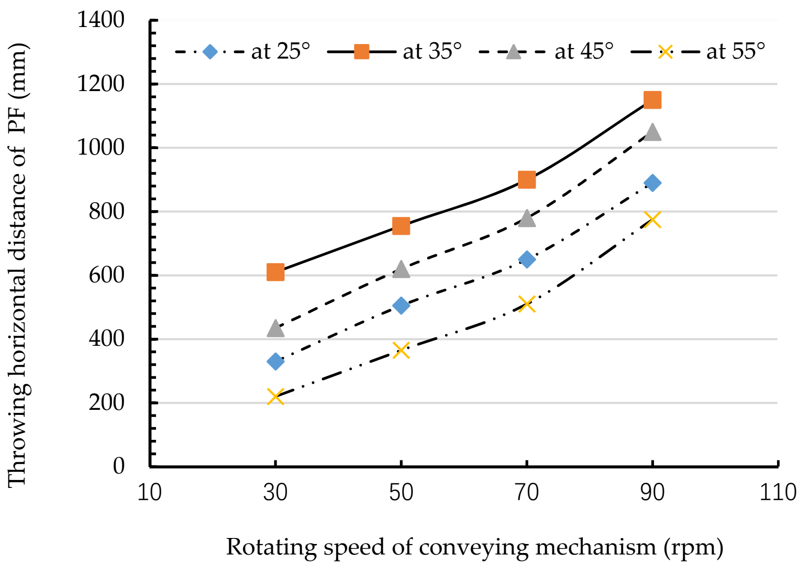


Figure 6. Effect of the conveying device's rotational speed (rpm) on the throwing horizontal distance of PF (mm) at different inclination angles between conveying device and the horizontal plane (°).

As is represented in Figure 6, the horizontal distance to which PF was thrown also increased with the increase in the inclination angles of the conveying device from 25° to 35°, but it began to decrease as the inclination angle increased from 35° to 55°. The horizontal distance to which PF was thrown increased from 331 mm to 893 mm, 610 mm to 1156 mm, 433 mm to1056 mm and 224 mm to 776 mm when the conveying device's rotational speed increased to 30 rpm, 50 rpm, 70 rpm and 90 rpm at inclination angles of 25°, 35°, 45° and 55°, respectively, which was consistent with the results of previous field experiments. The bigger the horizontal distance of the residual PF thrown by the conveying device, the better the separation effect of the residual PF and impurities. Compared with the test results of Figure 6, it could be concluded that when the inclination angle between the conveying device and the horizontal plane was 35°, the horizontal distance of residual PF was the largest, but there were few research data on the distances to which residual PF and impurities were thrown [27].

3.3. Effect of the Rotational Speed on the Separation Rate of Residual PF at Different Inclination Angles

When the rotating speed of the conveying device and the distance between elastic teeth are 74 rpm and 60 mm, respectively, the experiment is carried out [27]. As is represented in Figure 7, with the increase in the inclination angle and rotating speed of the separating device, the separation rate of the residual PF also changes. The separation rate of residual PF also increased with the increase in the separating device's rotational speed from 80 rpm to 120 rpm, but it began to decrease when the rotational speed increased from 120 rpm to 160 rpm. The separation rate of residual PF increased from 61.45% to 67.47%, 73.87% to 82.69%, 70.50% to 77.94% and 65.23% to 73.54% when the separating device's rotational speed increased to 80 rpm, 100 rpm and 120 rpm at inclination angles between the separating device and the horizontal plane of 35°, 45°, 55° and 65°, respectively. However, the separation rate of residual PF decreased from 67.47% to 60.28%, 82.69% to 75.64%, 77.94% to 68.69% and 73.54% to 65.07% when the separating device's rotational speed increased to 120 rpm, 140 rpm and 160 rpm at inclination angles between the separating device and the horizontal plane of 35°, 45°, 55° and 65°, respectively, which were obtained in field experiments. Compared with the experimental results in Figure 7, it could be concluded that when the rotational speed and inclination angle of the separation device were 120 rpm and 45°, respectively, the highest separation rate of the residual PF was 82.69%, and the recovered residual PF contained fewer impurities. The separation rate of residual PF was directly affected by the rotational speed and inclination angle of the separation device.

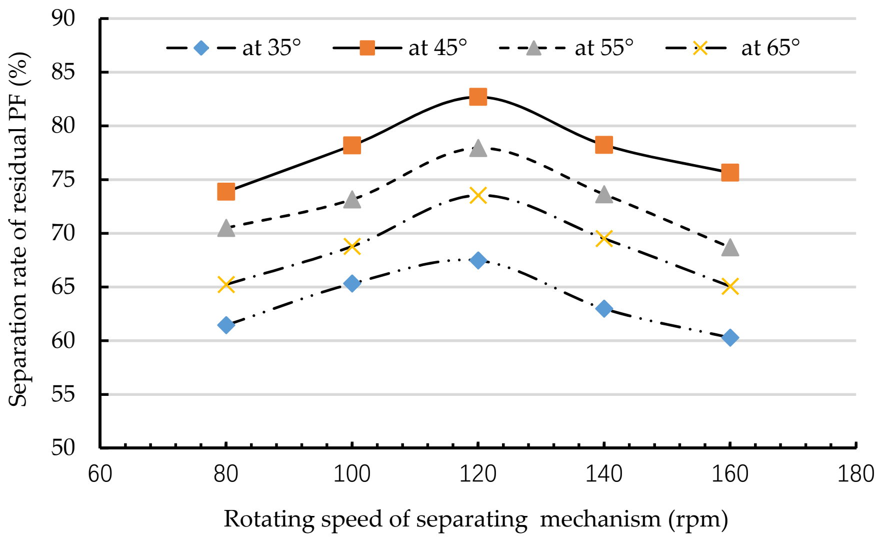


Figure 7. Effect of the separating device's rotational speed (rpm) on the separation rate of residual PF (%) at different inclination angles between the separating device and the horizontal plane (°).

3.4. Effect of the Different Distances between Elastic Teeth on the Recovery and Separation Rate of PF

When the rotational speed and inclination angle of the conveying device and the separating device were 74 rpm, 35° and 120 rpm, 45°, respectively, the experiments of recovering and separating the residual PF were carried out under the condition that the distance between the elastic teeth was 35 mm, 45 mm, 55 mm and 65 mm, respectively. The quality of residual PF and impurities collected during each test was measured and the test data were recorded. The experimental results obtained from the present study are presented by column charts and line charts [28–30].

As can be seen from Figure 8, the column chart shows the experimental results of the separation rate of the residual PF, and the line chart shows the experimental results of the recovery rate of the residual PF. The separation rate of residual PF was increased from 69.35% to 82.84% when the distance between elastic teeth was increased to 35 mm and 65 mm, respectively, under the condition of C-shaped elastic teeth. The recovery of residual PF increased from 60.24% to 85.57% when the distance between elastic teeth increased to 35 mm and 65 mm, respectively, under the condition of C-shaped elastic teeth, but when the distance between elastic teeth increased to 55 mm and 65 mm, the recovery of residual PF increased slightly. The line chart was at the top of the column chart, which showed that the experimental results of the recovery rate of the residual PF were greater than the separation rate of the residual PF under the same experimental conditions. In order to obtain better test results, it is necessary to fit the experimental data and obtain the optimal test parameters.

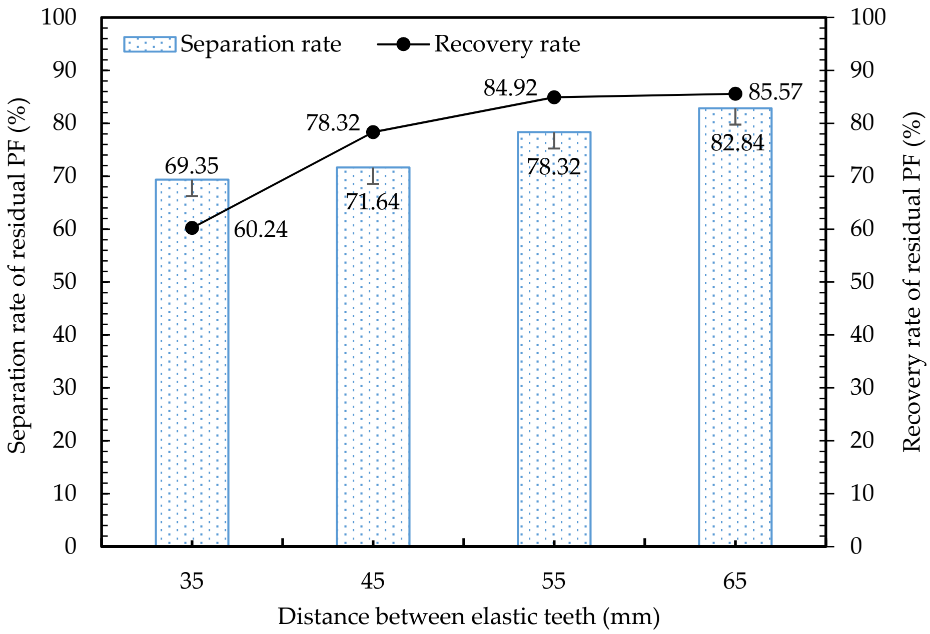


Figure 8. Effect of the distance between elastic teeth (mm) on the recovery and separation rate of residual PF (%) when the rotational speed and inclination angle of the conveying and separating device were 74 rpm, 35° and 120 rpm, 45°, respectively.

3.5. Mathematical Modeling for Recovery and Separation Rate

The most important evaluation parameter for a residual film recovery machine is the recovery and separation rate of PF. In this study, the monadic linear regression model and the principle of least square method were used to find the relationship between the recovery and separation rate of residual film and the distance between the elastic teeth when the rotational speed and inclination angle of the conveying and separating device were 74 rpm, 35° and 120 rpm, 45°, to predict the recovery and separation effect of residual film [27]. This would help to reduce the number of field tests necessary to assess the recovery and separation rates of the residual PF. According to the experimental results in Figure 8, the relationship between the recovery and separation rate of residual film and the distance between the elastic teeth was fitted. The following mathematical equations are used to calculate the recovery rate, the separation rate and the optimized test parameters by the Equations (8) and (9).

$$y_1 = -0.0461{x_1}^2 + 5.4244x_1 - 71.9, \quad (8)$$

$$y_2 = 0.4487x_2 + 54.712, \quad (9)$$

Figure 9 presents the relation between the observed and predicted recovery rate, with a correlation coefficient R^2 of 0.9585. In the fitting curve, when the distance between elastic teeth was 58.83 mm, the maximum recovery rate of residual film was 87.67%.

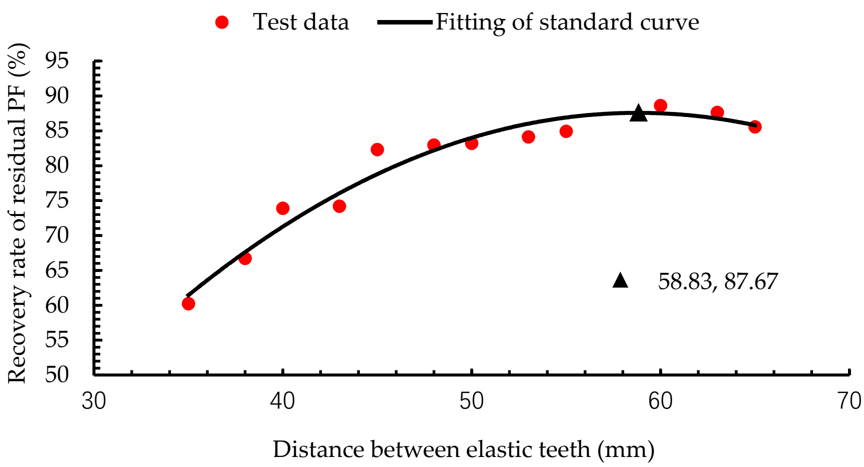


Figure 9. The relation between the observed and predicted recovery rate of residual PF (%).

Figure 10 presents the relation between the observed and predicted separation rate, with a correlation coefficient R^2 of 0.9643 [27].

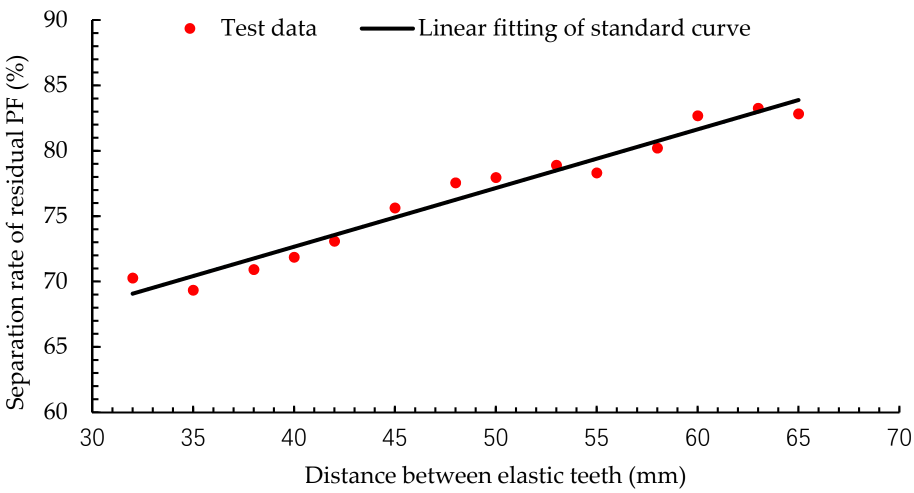


Figure 10. The relation between the observed and predicted separation rate of residual PF (%).

3.6. Parameter Optimization and Experimental Verification

In order to accomplish the best performance of the residual film recovery machine, it is necessary to optimize the experimental parameters to achieve the highest recovery and separation rate of residual PF. Through the design and test of the key parts of the recovery machine, the response relationship of each factor level to the test index is analyzed, and the optimized parameter combination is finally obtained. Therefore, in order to verify the accuracy of the theoretical prediction, the optimized parameters were tested in the field. However, considering the actual working situation, the optimized parameter needs to take its integer [26]. When the rotational speed and inclination angle of the conveying and separating device were 74 rpm, 35° and 120 rpm, 45°, respectively, under the condition that the distance between C-shaped elastic teeth was 59 mm, validation tests were carried out and test results were recorded, as shown in Table 1.

Table 1. Compare the theoretical optimization results of recovery and separation rate with the field test results.

Parameter	Theoretical Optimization Value	Field Test Value
Rotational speed of conveying device (rpm)	74.08	74
Inclination angle of conveying device (°)	35	35
Rotational speed of separating device (rpm)	120	120
Inclination angle of separating device (°)	45	45
Distance between elastic teeth (mm)	58.83	59
Type of elastic teeth	C	C
Recovery rate of residual PF (%)	87.67	88.12
Separation rate of residual PF (%)	81.19	83.27

As is represented in Table 1, it can be seen that the results of the field test are close to the results of the theoretical optimization, and the relative errors between the experimental values and the theoretical optimization values are less than 5%. Therefore, the theoretical analysis and parameter optimization results of recovery and separation rate of residual PF are accurate. Through theoretical analysis and experimental verification, the optimum parameter combination was obtained. When the rotational speed and inclination angle of the conveying and separating device were 74 rpm, 35° and 120 rpm, 45°, respectively, under the condition that the distance between C-shaped elastic teeth was 59 mm, the recovery and separation rates of residual PF were 88.12% and 83.27%, respectively.

4. Discussion

(1) According to the test results of the different elastic teeth structures on the recovery rate of PF, the rotating speed of the conveying device, the distance between the elastic teeth and the type of elastic teeth had a significant influence on the recovery rate of residual PF in the soil. This is because the above test factors determine the number of soil particles in the conveying device, so that some residual PF debris contains soil particles which cause the residual PF to fall into the soil from the distance between the elastic teeth, thus reducing the recovery rate of residual PF. It is necessary to create an experimental stand to test the recovery rate of obtained residual film. Using this experimental stand, we can optimize the test parameters in the future [31].

(2) According to the test results of the rotational speed on the separation rate of residual PF at different inclination angles, the inclination angle and rotating speed of the separation device determine the impurities content of the residual PF. Since there are more soil particles in the mixture and the parameters of the separation device are not set properly, the separation of the recovered PF from impurities is not complete. It is necessary to install sensors in the recovery and separation device so that the operating parameters are detected and adjusted in time. Of course, it is urgent to innovate the industrial chain circulation mode of agricultural PF, overcome technical difficulties and break through the technical bottleneck of recycling residual PF at present [32].

5. Conclusions

(1) When the rotational speed and inclination angle of the conveying device and the separating device were 74 rpm, 35° and 120 rpm, 45°, respectively, the experiments of recovering and separating the residual PF were carried out under the condition that the distance between the elastic teeth was 35 mm, 45 mm, 55 mm and 65 mm, respectively.

The separation rate of residual PF was increased from 69.35% to 82.84% when the distance between elastic teeth was increased to 35 mm and 65 mm, respectively, under the condition of C-shaped elastic teeth. The recovery of residual PF increased from 60.24% to 85.57% when the distance between elastic teeth increased to 35 mm and 65 mm, respectively, under the condition of C-shaped elastic teeth.

(2) Through theoretical analysis and experimental verification, the optimum parameter combination was obtained. When the rotational speed and inclination angle of the conveying and separating device were 74 rpm, 35° and 120 rpm, 45°, respectively, under the condition that the distance between C-shaped elastic teeth was 59 mm, the recovery and separation rates of residual PF were 88.12% and 83.27%, respectively.

(3) The monadic linear regression model and the principle of least square method were used to find the relationship between the recovery and separation rate of residual film and the distance between the elastic teeth when the rotational speed and inclination angle of the conveying and separating device were 74 rpm, 35° and 120 rpm, 45°, respectively, to predict the recovery and separation effect of residual film. This paper provides a reference for mechanized recovery of residual film in soil and treatment of soil pollution.

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