DESIGN AND EXPERIMENTAL OPTIMIZATION OF VEGETABLE SURFACE RESIDUAL FILM RECYCLING MACHINE

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蔬菜地表层残膜回收机的设计与试验研究

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ABSTRACT

To solve the problems such as low film recovery rate and high soil content of the recovered film of the surface residual film recycling machine, the parameters of the vegetable surface residue recycling machine were optimized. After modelling and theoretical analysis of the loosening shovel and film sweeping device, the key structural parameters of the machine were determined. The Box-Behnken Design analysis test results in Design-Expert were used to establish the comprehensive effects of speed, rotational speed, and angle of membrane picking device on the recovery and soil content. Then MATLAB was adopted to analyse the law of the comprehensive influence of three factors on two responses. The most significant factor affecting pickup net rate J was rotational speed Y_2, and the most significant factor affecting soil percentage was the angle Y_3 of the film picking device. By optimizing the experimental results by Design-Expert, the optimum operating parameters of the machine were obtained as follows: the forward speed of the machine was 3.2 km/h, the revolution speed was 10.5 r/s, the angle of the film picking device was 65.4°, the scavenging rate J and soil rate H of the residual film recycling machine were 87.084% and 10.382%, respectively.

摘要

为解决残膜回收机起膜率低、回收的残膜含土率高等问题，对蔬菜地表层残膜回收机进行参数优化。对起膜铲和扫膜装置建模和理论分析，确定该机具关键结构参数。利用 Design-Expert 中的 Box-Behnken Design 分析试验结果，建立速度、转速和挑膜装置角度对回收率和含土率的综合影响效应。运用 MATLAB 对三因素对两响应的综合影响规律进行分析得出结论：对拾净率 J 影响最显著的因素为转速 Y_2，对含土率影响最显著的因素是挑膜装置角度 Y_3。通过 Design-Expert 对实验结果进行优化，得到机具的最佳作业参数：机具前进速度为 3.2km/h，转速为 10.5 r/s，挑膜装置的角度为 65.4°，残膜回收机的拾净率 J 和含土率 H 分别为 87.084%、10.382%。

INTRODUCTION

Since the 1970s, plastic film mulching technology has been introduced from abroad to China and applied to agricultural production, providing China's solutions and strength for solving world food security problems *(Zhao et al., 2017; Li &Ma, 2014)*. The application of plastic film mulching technology has the function of heat preservation and moisture preservation, which is conducive to the propagation of microorganisms in the soil, speeding up the conversion of organic matters into inorganic matters, preventing waterlogging, and inhibiting the growth of weeds in plum rain season, so as to improve the crop yield *(Zhou, Tang & Xie, 2019; Zhang et al., 2013)*. So far, plastic film covering technology has been popularized and used in China for 40 years, and the usage and coverage area of plastic film rank first in the world *(Li, 2017)*. However, residual film pollution causes serious damage to the ecosystem. When seen from a microscopic perspective, the plastic film forms microplastics after weathering and decomposition, and then it is absorbed into the crops through the root system of plants, and some of the microplastics remain in the body after being eaten by humans, which harms human health *(An, 1996)*. When seen from a macroscopic perspective, the residual film winds the machine in the seeding process, which reduces the working efficiency.

At the same time, due to the inability to recover the residual film exposed on the soil surface, the problems such as choking caused by accidental ingestion of livestock often occur, bringing serious economic losses to farmers.

In the current Chinese market, there are many different types of residual film recycling machines, which can be divided into residual film recycling machines before seeding, residual film recycling machines during the seedling stage as well as residual film recycling machines after autumn according to different film lifting operation time *(Tian et al., 2018)*. The residual film recycling machine before seeding has been widely used, but because the residual film is seriously damaged in this stage, the residual film picking up rate is relative and the recovered residual film contains a large number of straws *(Chen et al., 2020)*. In China, residual film recycling mainly adopts two methods, including manual picking up and mechanized recycling. Manual picking up is characterized by high labour intensity and low efficiency, while mechanized recycling is characterized by high soil content and low scavenging rate. To solve the above problems, a film-soil separation residual film recycling machine was proposed, which can effectively reduce the soil content of the residual film and improve the cleaning rate of the machine.

MATERIALS AND METHODS

Overall structure

According to the characteristics of the vegetable land surface residual film *(Zhang et al., 2019)*, a surface residual film recycling machine was designed and manufactured. The structure of the whole machine was shown in Fig. 1. The residual film recycling machine mainly includes the reducer, loosening shovel, film sweeping device, traction device, film-soil separation device, film picking device, machine frame, machine box, film collection box, as well as depth-controlled device.

The tractor was connected with the power source tractor Dongfanghong-404 by using the mode of traction. The rear output shaft of the tractor was connected with the reducer of the residual film recycling machine to provide power, and the whole machine was powered by a chain drive and belt drive. When the machine was working, the loosening shovel scooped up the mixture of film and soil on the surface and swept the mixture to the film-soil separation device through the film sweeping device. Then the soil adhered to the film was shaken off by using the inertia of the device produced by the shaking. The film-soil separation machine moved upward and threw the residual film to the film picking device and caught the residual film through the film picking teeth on the device, and then the residual film was transported to the film collecting box as the film picking device moves upward. Since the film-soil separation device threw the residual film to the film picking device, the problem of difficult removal of the residual film due to the elastic tooth piercing was solved. When the film picking device transported the residual film to the upper end of the film collecting box, it fell off and into the film collecting box, thus improving the problem that the residual film winds the machine.

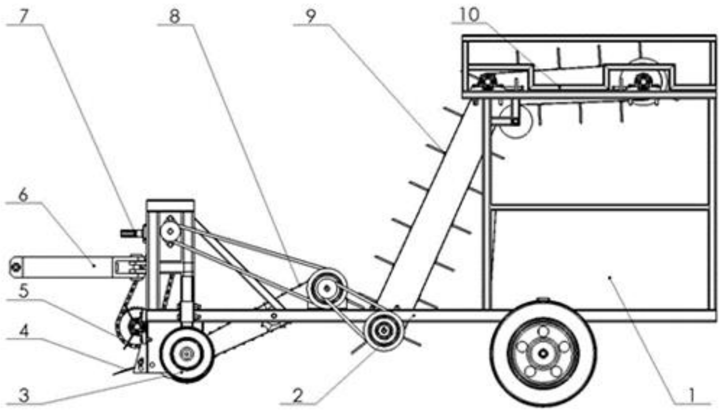

Fig. 1 - Schematic diagram of the physical design of vegetable surface residual film recycling machine

1. Film collecting box; 2. The frame of the machine; 3. Depth limiting device; 4. Loosening shovel; 5. Film sweeping device; 6. Traction device; 7. Reducer; 8. Film soil separation device; 9. Film picking device; 10. Machine box

Analysis of the angle of the loosening shovel

The stress diagram of the loosening shovel during the operation was shown in Fig. 2. The stress model of the loosening shovel unit was established by analysing the force of the loosening shovel unit. Taking the forward direction of the machine as the X-axis and the vertical direction as the Y-axis, the coordinate system was established, as shown in Figure 2, and then the stress analysis was conducted to the loosening shovel.

According to the analysis in Fig. 2, the gravity imposed on the film-soil mixture was G; the frictional force between the upper surface of the loosening shovel and the film-soil mixture was f. The normal load generated by the membrane soil mixture on the upper surface of the loosening shovel was Fn. The force needed to dig up the film-soil mixture along the loosening shovel was Ft. By analysing the stress condition during the operation of the loosening shovel, the stress balance equation of the loosening shovel was obtained as follows:

$$\begin{cases} f\sin\alpha - Fn\cos\alpha - G = 0 \\ Ft - Fn\sin\alpha - f\cos\alpha = 0 \\ f - \mu Fn = 0 \end{cases} \tag{1}$$

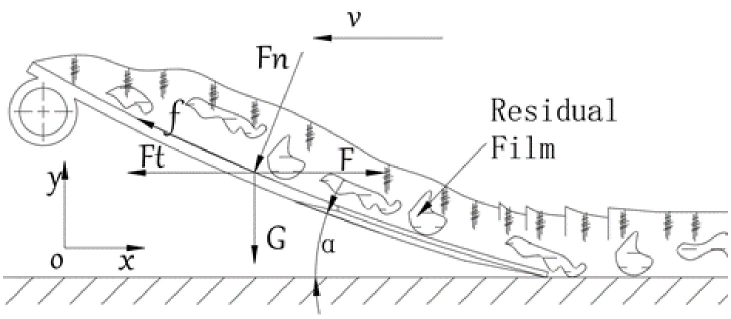

Fig. 2 - Schematic diagram of the entry angle of the loosening shovel

f - frictional force between the film-soil mixture and the upper surface of the loosening shovel, N;

F_n - normal load generated by the film-soil mixture on the upper surface of the loosening shovel, N;

G-gravity of the film-soil mixture itself, N; Ft - The force required to move along the loosening shovel to scoop up the film-soil mixture, N;

After analysing the resistance imposed on the loosening shovel, the soil resistivity was K, and the harder the soil texture was, the larger the coefficient would be. The soil area cut by the loosening shovel was S; the friction coefficient of the film-soil mixture on the loosening shovel $\mu=\tan\varphi$; the frictional angle of the film-soil mixture to the loosening shovel was φ, which was usually 30 ° ~ 36 °; the force required by the film-soil mixture to slip through the loosening shovel surface was P; the length of the loosening shovel was L; the soil density was ρ; by ignoring the impact of the moving speed of the machine on the resistance of the loosening shovel, resistance Ft could be expressed as *(Zhai et al., 2018)*:

$$Ft = P + Ps = SL\rho\tan(\alpha+\varphi) + Ks \tag{2}$$

By combining Formula (1) with Formula (2), the following formula could be obtained:

$$\alpha = \cot^{-1}\frac{\mu\ \left(SL\rho\tan(\alpha+\varphi) + Ks\right)\ - G}{SL\rho\tan(\alpha+\varphi) + Ks - \mu G} \tag{3}$$

As shown in Formula (3), when the machines conduct residual film recycling, the larger the entry angle α was, the more the film-soil mixture scooped up by the loosening shovel would be, the greater the resistance generated would be, and the greater the force Ft required by the machine to dig up the film-soil mixture would be. When the buried angle was less than 25°, and at this time the resistance was relatively small *(Wang, 2010; Xue et al., 1987; Liu et al. 2018)*.

If the angle was too small, the soil breaking ability of the loosening shovel would be relatively poor *(Li, 2017)*. To adapt to different regions, soil texture, and soil moisture, the loosening shovel was designed into a fine-tuning structure, with an angle adjustment range of 23°~26°.

Analysis of the motion process of the film sweeping device

The heap soil condition is a common problem existing in the residual film recycling machine. To solve this problem, a film sweeping device was designed, as shown in Fig. 3.

By analysing the motion process of the film sweeping device, the influence laws of the film sweeping blades on the film-soil mixture were determined.

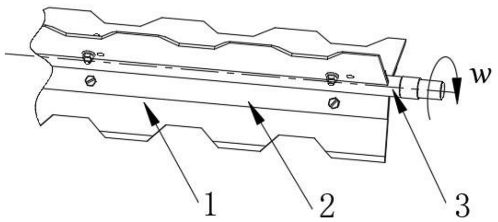

Fig. 3 - Partial diagram of the film sweeping device
1. Film sweeping blade; 2. Blade base; 3. Film sweeping spindle

Taking the axis of the film sweeping spindle as the origin, the operation direction of the machine as X-axis, and the direction perpendicular to the ground as Y-axis, the xoy rectangular coordinate system was established to analyse its motion process. In the process of residual film recycling operation, the machine moved along a straight line, and the film sweeping device carried out the film sweeping operation by rotating motion. The absolute motion of the film sweeping blade was synthesized by the above two motions.

By analysing Fig. 4, the absolute velocity of the film sweeping blades was obtained as follows:

$$v_1 + v_2 = v_0 \tag{4}$$

According to the basic principle of kinematics, the trajectory of point B of the film sweeping blade at any time could be obtained. Based on the analysis, the motion trajectory equation of the film sweeping blade at point B with time T could be obtained as follows:

$$\begin{cases} x = v_1 t + l\,sin(\omega t) \\ y = -l\,cos(\omega t) \end{cases} \tag{5}$$

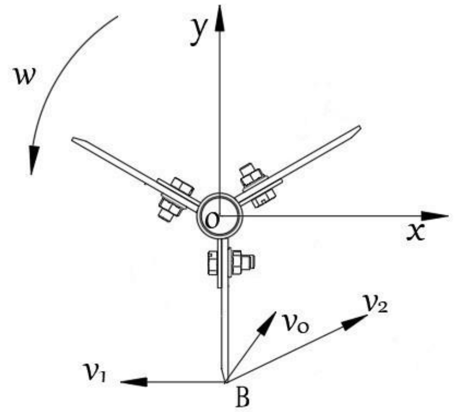

Fig. 4 - Motion trajectory analysis diagram of the film sweeping device
ω - angular velocity of the structure moving; v_1 - the forward speed of the implement;
v_2- the rotating speed of film sweeping blades moving.

To obtain the motion velocity of point B of the film sweeping blade at time T, the derivative of t in formula (5) was obtained, and the motion velocity equation of point B of the film sweeping blade at any time was obtained as follows:

$$\begin{cases} v_x = v_1 + l\,sin(\omega t) \\ v_y = \omega l\,sin(\omega t) \end{cases} \tag{6}$$

By combining the above equations, the relationship among velocity v_x of point B at any time and the horizontal motion velocity v_1, angular velocity ω, and the distance l between point B of the film sweeping blade and the axis were as follows:

$$v_x = v_1 + \omega l\,cos\,cos^{-1}\frac{v_y}{\omega l} \tag{7}$$

According to Equation (7), the velocity v_x of point B at any time was mainly related to the machine's horizontal movement velocity v_1 and angular velocity ω. To further analyse the motion trajectory of point B of the film sweeping device, the film sweeping velocity ratio λ was introduced *(Deng et al., 2016; Zhao, & Wu, 2019)*.

$$\lambda = \frac{v_2}{v_1} = \frac{\omega l}{v_1} \tag{8}$$

Substituting Formula (8) into Formula (5), then the following formula could be obtained:

$$x = \sqrt{l^2 - y^2} + \frac{l}{\lambda} cos^{-1} \left(-\frac{y}{l}\right) \tag{9}$$

According to Formula (9), point B of the film sweeping blade of the film sweeping device moved in a way of cycloid, and the sweeping velocity ratio λ was the determinant factor of the cycloid trajectory. Different velocity ratios would form different cycloid diagrams, thus affecting the film sweeping effect. Next, the cycloid diagrams under the situation for λ >1, B =1, and B <1 would be analysed. When v_2 was greater than v_1, namely, B >1, the trajectory was a trochoid. At this time, the film-soil mixture was thrown above the rear of the film sweeping device, which swept the film and alleviated the heap soil phenomenon, but the large amount of dust pollution generated by the throwing of a large amount of soil damaged the environment. When v_2 was smaller than v_1, the track was a short cycloid, namely, B <1, and at this time, the film sweeping effect could not be achieved as the angle and distance of the throwing of the film-soil mixture. When v_2 was equal to v_1, namely, B =1, the film sweeping blade could drop the film-soil mixture onto the separation device at a height of 45° to achieve the film sweeping effect.

Experimental materials

This prototype test was conducted in Gu'an County, Langfang City, Hebei Province. The harvested vegetable fields were selected as the test pilots, and the plastic film remaining on the surface of the field was mainly recovered. Fig. 5 shows the field experiment scene. The plastic film laid in the test field is a black plastic film with a thickness of 0.008 mm. The surface of the land contained a small number of weeds and vegetable leaves. The average moisture content of the soil was about 10.1%, and the test field was cohesive soil. After field investigation, the residual film was mainly buried in the surface soil or exposed on the surface, so in the test process, the machine mainly carried out the recycling test on the residual film on the surface.

Fig. 5 - Field test diagram

The main testing equipment includes a tractor Dongfanghong-404, vegetable surface film recycling machine, shovel, rotational speed meter, tape measure, electronic balance as well as an adjustable wrench.

Test indexes

To analyse the operation effect of the machine and test the stability and reliability of the operation, the picking up rate of the machine and the soil content of the residual film were taken as the test indexes *(Li, 2017)*, denoted as J and H, respectively. Next, these two indexes will be introduced, respectively.

Picking up rate: The ratio of the total film mass recovered by the machine and the total film mass in the soil before recycling is called picking up rate, which can be expressed in Formula (10):

$$J = (1 - D_1/D_2) \times 100\% \tag{10}$$

where:

J is the residual film pickup rate, %, D_1 is the total surface residual film mass after the residual film recycling operation, g, D_2 is the total surface residual film mass before the residual film recycling operation, g.

Soil content: The mass ratio of the total mass of the soil in the film collecting box to the residual film and soil is called soil content, which can be expressed by Formula (11):

$$H = (D_4 - D_3)/D_4 \times 100\% \tag{11}$$

where: H is soil content, %, D_4 is the total mass of soil and residual film in the film collecting box in a test field, g. D_3 is the total mass of residual film in the film collecting box in a test field, g.

Test parameters and methods

Table 1

Test factors and test levels

Level	Factor		
	Machine forward velocity (km/h)	rotational speed ($r \cdot s^{-1}$)	The angle of PVC conveyer belt (°)
1	5	12	66
0	4	10.5	64.5
-1	3	9	63

According to the content described above, we took pickup rate J (%) and soil content rate H (%) as the two response values of the test. The forward speed of the machine (km/h), the rotational speed of the tractor (r/s), and the angle of the film picking device (°) were selected as the factors for the prototype test, which were denoted as Y_1, Y_2, and Y_3, respectively.

The speed of the output shaft of the Dongfanghong tractor was 9~12 r/s. The designed operating speed of the machine was 3 ~ 5 km/h, and the angle of the film picking device was 63°~66°. The test factors and horizontal coding table were determined based on the above data, as shown in Table 1. By combining different test factors, 17 groups of experiments were designed.

RESULTS

Experimental results

According to the three factors and two responses designed before, the test model of the three factors to the two responses was set up. Through analysing the influence laws of the three factors on the machine's performance, the main factors affecting the machine's pickup rate and soil content were obtained. Then the experimental results were optimized through the function Optimization in Design-Expert to optimize the experimental results, thus improving the operation effect of the residual film recycling machine.

Table 2

Field test results

Test number	Y_1 ($km \cdot h^{-1}$)	Y_2 ($r \cdot s^{-1}$)	Y_3 (°)	J (%)	H (%)
1	4	10.5	64.5	84.7	12.5
2	5	10.5	66	81.3	10.8
3	5	9	64.5	79.7	14.1
4	4	10.5	64.5	85.1	12.8
5	5	12	64.5	81.6	12.7
6	4	10.5	64.5	85.3	12.5
7	4	10.5	64.5	85.5	12.3
8	3	10.5	66	86.8	9.4
9	3	10.5	63	83.8	14.5
10	3	9	64.5	82.5	13.2
11	4	12	66	86.7	8.5
12	4	9	66	83.1	10.1
13	4	12	63	86.2	14.6
14	4	9	63	80.5	15.8
15	5	10.5	63	81.4	16.1
16	3	12	64.5	88.6	11.9
17	4	10.5	64.5	85.7	12.7

Y_1 - the machine's forward speed; Y_2 - revolving speed; Y_3 - Angle of the film picking device; J - pickup rate; H - soil content

By analysing the experimental design and results in Table 2, it could be found that by adjusting the level of the three experimental factors, the pickup rate of the machine fluctuated between 79.7% and 88.6%, and the soil content rate between 9.4%~16.1%, so it could be seen from the test data that the prototype basically met the design requirements. To further analyse the comprehensive influential effect of the three factors on the machine's operation performance, Plackett-Burman designs (PB) in Design-Expert were adopted to build the regression model and regression equation of the three factors to the two responses *(Geng, 2019; Zhao & Wu, 2019)*, and then the factors which decided the test results were selected from the experimental factors to further adjust the machine's parameters to achieve the best-operating conditions.

Regression analysis of test results

Through Design-Expert fitting, the regression equation of the three factors to the pickup rate J and the regression equation of the three factors to soil content H were obtained, as shown in Formulas (12) and (13).

$$J = -828.1375 + 48.8625A + 23.95833B + 20.78333C - 0.7AB - 0.51667AC \\ - 0.23333BC - 1.3A^2 - 0.22222B^2 - 0.12222C^2 \quad (12)$$

$$H = -382.4625 - 0.7875A + 2.38533B + 13.8C - 0.01667AB - 0.033333AC \\ - 0.044444BC + 0.4625A^2 + 0.00555556B^2 - 0.11667C^2 \quad (13)$$

Table 3

Significance test on the regression analysis model of the recovery rate of film residues and potato damage rate

Sources	Degree of freedom	Residual film recovery rate			soil content rate		
		Sum of square	Values of F	Values of P	Sum of square	Values of F	Values of P
Model	9	98.06	51.97	< 0.0001	69.34	117.89	< 0.0001
Y_1	1	39.16	186.80	< 0.0001	2.76	42.5	0.0003
Y_2	1	37.41	178.45	< 0.0001	3.78	57.86	0.0001
Y_3	1	4.50	21.47	0.0024	61.61	942.59	< 0.0001
$Y_1 Y_2$	1	4.41	21.04	0.0025	2.5×10^{-3}	0.038	0.8505
$Y_1 Y_3$	1	2.40	11.46	0.0117	0.010	0.15	0.7073
$Y_2 Y_3$	1	1.10	5.26	0.0555	0.040	0.61	0.4597
Y_{12}	1	7.12	33.49	0.0006	0.9	13.78	0.0075
Y_{22}	1	1.05	5.02	0.06	6.6×10^{-4}	0.01	0.9229
Y_{32}	1	0.32	1.52	0.2576	0.29	4.44	0.0731
Residual	7	1.47			0.46		
Pure Error	4	0.80			0		
Cor Total	16	99.53			69.80		

p <0.01, Extremely significant; 0.01 <p <0.05, Significant; p >0.05, Not significant

Table 3 shows the variance analysis of the prototype's pickup rate regression model. The fitting degree of the regression model was judged by analysing P value, F value, P value of the misfit term, determination coefficient R^2 value as well as P value of the test factors *(Zhang et al, 2019; Deng et al, 2016).* The significance test of the pickup rate model was F = 51.97 and P < 0.0001, indicating that the pickup rate regression equation had a high significance. The significance test of the soil content model was F =117.89 and P < 0.0001, indicating the regression equation had a higher significance.

A four-dimensional slice figure was drawn with MATLAB to depict the comprehensive influential effects of the three factors on the pickup rate. By analysing the comprehensive influential effects of the three factors in Fig. 6 on the pickup rate, it could be seen that the pickup rate basically did not change with the change of the angle of the film picking device Y_3, but increased with the increase of revolving speed Y_2 and the decrease of the machine's forward speed Y_1, among which the change of revolving speed was more significant to the pickup rate.

Based on the analysis of the comprehensive influential effects of the three factors in Fig. 7 on the soil content, it could be seen that the soil content gradually decreased rapidly with the increase of the angle of the film picking device Y_3, while the soil content basically remained unchanged with the changes of the operating speed of the machine Y_1 and Y_2. Based on analysing the comprehensive influential effects of the three factors on the pickup rate and soil content, it could be seen that the significance of the three factors to the pickup rate is the rotational speed Y_2 > speed Y_1 > the angle of the film pickup device Y_3. Among the three factors, the most significant one on the pickup rate is the angle of the film pickup device.

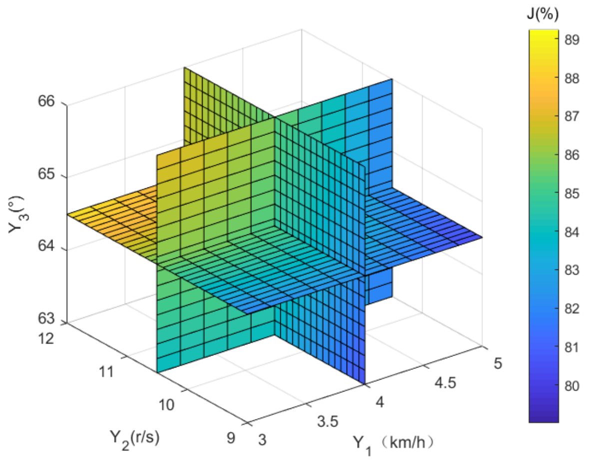

Fig. 6 - Comprehensive influential effects of three factors on pickup net rate

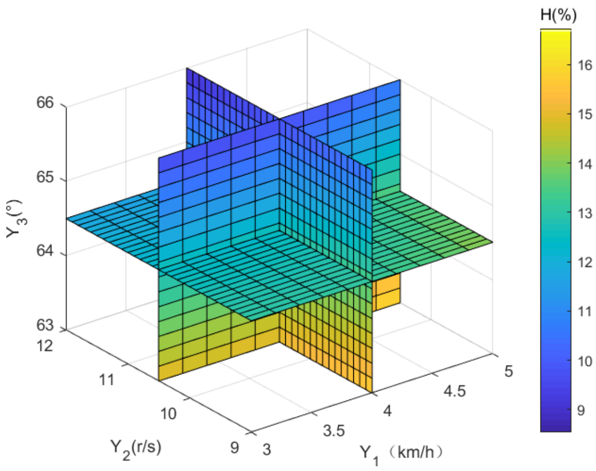

Fig. 7 - Comprehensive influential effects of three factors on soil content

Parameter optimization

To improve the operating performance of the residual film recycling machine *(Sun et al., 2018; Wu, J. 2018)*, the function Optimization in Design-Expert was used to optimize the test results, and the constraint conditions were selected according to the operational requirements, working conditions and relevant theoretical analysis of the high pickup rate and low soil content, and then the objective function (14) was established:

$$\begin{cases} max\,J\ (Y_1,\ Y_2,\ Y_3) \\ minH\ (Y_1,\ Y_2,\ Y_3) \end{cases} \tag{14}$$

and

$$\begin{cases} 3\ \text{km/h} \le Y_1 \le 5\ \text{km/h} \\ 9\ \text{r/s} \le Y_2 \le 12\ \text{r/s} \\ 63° \le Y_3 \le 66° \end{cases}$$

The optimization range of objective function J was 80~100%, the optimization range of objective function R was a range of 0~2%, and the optimization of objective function H was 0~20%. Then the experimental results were optimized and solved, and the optimal parameters of the machine were obtained as follows: the machine's forward speed was 3.2 km/h; the revolving speed was 10.5 r/s, the angle of the film pickup device was 65.4 °, the film pickup rate J of the residual film recycling machine under these parameters was 87.084 %, and the soil content H was 10.382 %.

Experimental verification

To verify the performance of the machine under the optimized parameters, the experiment was carried out again in the harvested vegetable fields in Hebei Province. The test was conducted according to the standard of Residual Plastic Film Recycling Machine. The soil firmness of the test field was 3.82 MPa and the average moisture content of the soil was 12.3%.

Table 4

Results of the field test

Test number	Y_1 (km/h)	Y_2 (r/s)	Y_3 (°)	J (%)	H (%)
1	3.2	10.5	65.4	87.3	11.5
2	3.2	10.5	65.4	86.6	10.8
3	3.2	10.5	65.4	86.2	11.1
4	3.2	10.5	65.4	86.9	11.3
5	3.2	10.5	65.4	86.7	10.6
6	3.2	10.5	65.4	87.1	11.4

The operating effectiveness of the machine was obtained by averaging the results of the six tests. Test results are shown in Table 4. The average pickup rate J was 86.6%, and the average soil rate H was 11.12%, which was close to the optimization solution results. In the experiment, the pickup rate was slightly lower than the optimization solution, and the soil content was slightly higher than the optimization solution. This was because there were weeds, sand, and residual vegetables in the vegetable field recycling process, leading to a slight difference between the experimental value and the theoretical value, so it indicated that the model was reliable to a certain extent.

CONCLUSIONS

In this paper, the processing and production process of the machine was briefly introduced, and then the field experiment was carried out on the prototype. The comprehensive influential effects of the three factors on the two responses were established by using Design-Expert on the experimental data, and the following conclusions were drawn:

(1) The comprehensive influential laws of the three factors on the two responses were reflected by drawing the contour line and response surface of the two responses and the four-dimensional slice figure of the three factors on the two responses. The factor with the most significant influence on the pickup rate J was revolving speed Y_2, and the factor with the most significant influence on the soil content rate was the angle of the film picking device Y_2.

(2) The optimum operating parameters of the machine were obtained by using Design-Expert to optimize the experimental results: the machine's forward speed was 3.2 km/h, the revolving speed was 10.5 r/s, the angle of the film picking device was 65.4°, the pickup rate of the residual film recycling machine J was 86.6%, and the soil rate H was 11.12%.

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