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RESEARCH ARTICLE

Experiment and optimal design of a collection device for a residual plastic film baler

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Abstract It is imperative to carry out research on residual plastic film collection technology to solve the serious problem of farmland pollution. The residual plastic film baler was designed as a package for film strip collection, cleaning and baling. The collection device is a core component of the baler. Response surface analysis was used in this study to optimize the structure and working parameters for improving the collection efficiency of residual film and the impurity of film package. The results show that the factors affecting the collection rate of residual film and the impurity of the film package are the speed ratio (k) between the trash removal roller and eccentric collection mechanism, the number (z) and the mounting angle (θ) of spring teeth in the same revolution plane. For the collection rate, the importance of the three factors are in the order, $k > z > \theta$. Meanwhile, for the impurity, the importance of three factors are in the order, $z > k > \theta$. When the speed ratio, the mounting angle and the number of spring teeth was set at 1.6°, 45°, and 8°, respectively, the collection rate of residual film was 88.9% and the impurity of residual film package was 14.2% for the baler.

Keywords residual film, collection device, collection rate of residual film, impurity of film package, optimization, baler

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1 Introduction

Plastic film cultivation technology has been used around the world. It is widely recognized that plastic film cultivation technology can make a valuable contribution to the temperature increase of soil surface and moisture retention, weed control and alleviation of pests and diseases, thus prolonging the growth of crops and raising yield[1,2]. However, the application of plastic film mulch technology is evolving from “white revolution” to “white pollution” because the residual plastic film could damage the physical and chemical structure of soil. As a result, it affects the growth of crops and even causes farmland to become uncultivable[3]. This technology had been used in China since the late 1970s, and consequently the surface soil layer in China now contains the highest content of residual plastic film in the world[4,5], which is a big problem for agriculture in China. Therefore, the recycling and reuse of residual plastic film is being given much needed attention.

Several European countries have established a set of regulations for agricultural plastic film production and recycling. These stipulate that the thickness of plastic film should be not less than 0.02 mm, so the film can be collected by a rolling recycle machine and reused[6–8]. In contrast, the plastic film used in China is too thin to be completely collected by machine after being used to cover the whole production period of crops. Also, the mechanized collection rate of residual plastic film is quite low and there is a mass of soil and crop residues collected with the film, which prevents recycling of the film[9]. Recently, we designed a new type of residual plastic film baler. After machine raking of the residual film, the baler performs multiple tasks on the film, viz., collection, cleaning and baling the film as a package, in one operation. This paper describes the optimization of the design and experiments on the baler’s collection device conducted to increase the collection rate while concurrently decreasing the quantity of impurities in the residual film package produced.

2 Materials and methods

2.1 Working principle and main structural parameters of the collection device

2.1.1 Components and working principle of the collection device

As shown in Fig. 1, the collection device consists of a trash removal roller and an eccentric collection mechanism. When the trash removal roller rotates quickly, the teeth installed on the surface of the roller lift the residual plastic film from the soil and crop residuals, and then roll the film around the middle region by means of centrifugal force. The spring teeth of the rotary drum stretch out along the tangential direction of the drum by the eccentric mechanism to hook the cleaned film. When the drum rotates, the teeth retract into the rotary drum and release the film as it rotates up the film removal device.

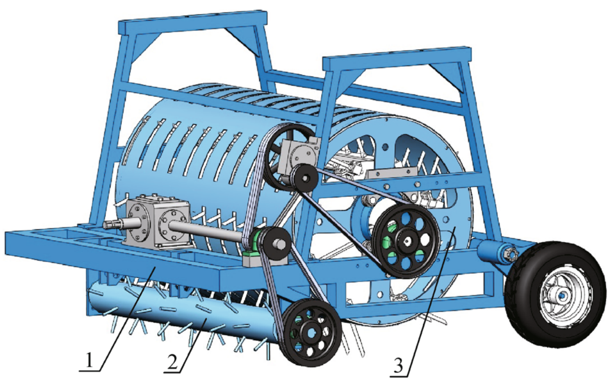

Fig. 1 Structural diagram of the collection device. 1, traction frame; 2, trash removal roller; 3, eccentric collection mechanism.

2.1.2 Teeth arrangement of trash removal roller

As shown in Fig. 2, the teeth are uniformly distributed on the surface of the trash removal roller in a symmetrical way. The angle between the adjacent teeth is 72°, and the axial pitch is 30 mm. Given that the working width is 1200 mm, there are 80 teeth[10].

2.1.3 Main parameters of eccentric collection mechanism

As shown in Fig. 3, the eccentric collection mechanism consists of five parts: a rotary drum, a double crank mechanism, a set of spring teeth, a centric spindle and a supporting frame for the teeth. The optimal design of the double crank mechanism, the length of the driving crank (AB), link (BC), driven crank (CD) and rack (AD) was determined as 280, 200, 340 and 75 mm, respectively. The spring teeth are arranged in a staggered mode at 100 mm between the adjacent teeth. In order to ensure higher collection efficiency, the maximum straight length of each spring tooth, was determined as 60 mm.

The force analysis of materials on the spring tooth is shown in Fig. 4. To ensure the residual plastic film follows the motion of spring teeth and reaches at the film removal device, the mechanical relationship should be:

$$f \geqslant F\sin(\theta - \alpha) \tag{1}$$

where f is the friction of residual plastic film, F is the film's centrifugal force, θ is the mounting angle between spring tooth and the supporting frame, α is the angle of the centrifugal force (F) with vertical direction. As can be seen from the Eq.1, the friction f will change as the mounting angle θ varies when the centrifugal force F is fixed. However, the working performance of spring teeth will be affected if the angle θ is too large, so the angle θ should be from 30° to 60°.

2.2 Experimental design performance of the collection device

The experiments were conducted in a soil bin laboratory, during August, 2015. To simulate the actual farming environment, a 0.008 mm thickness residual film collected from the cotton field by raking machine was arranged in the soil bin to form several 10 m ×1 m ×0.15 m residual film blocks. The film had been in the cotton field for more than 120 days. The speed of the residual plastic film baler powered by the soil bin tester was 1.8 km·h^{-1} and its working width was 1200 mm.

During the test three plots (1 m×1 m) where randomly selected, and the collection rate of residual film η was calculated as[11,12]:

$$\eta = \frac{\omega - \omega_0}{\omega} \times 100\% \tag{2}$$

where ω is the total weight of the film before test, and ω_0 is the weight after the test.

Three baled film packages where randomly selected, and the impurity of residual film package ε was calculated as:

$$\varepsilon = \frac{m - m_0}{m} \times 100\% \tag{3}$$

where m is the total weight of film package, m_0 is the weight of the film after removing the soil and crop residues

A three-factor response surface analysis was conducted based on the quadratic orthogonal rotation combination design principle[13–15], and the experimental factors and levels are given in Table 1. The optimal objects were set as: the collection rate of residual film (η), the impurity of residual film package (ε). The impact factors were set as:

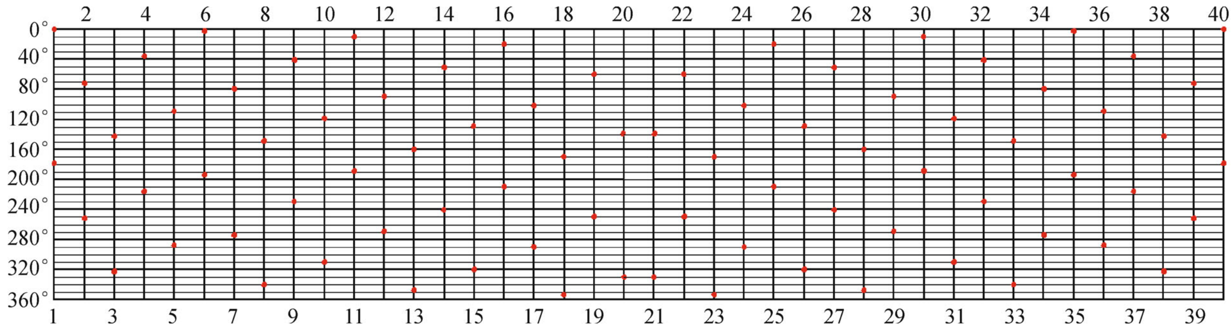

Fig. 2 Teeth arrangement on the trash removal roller

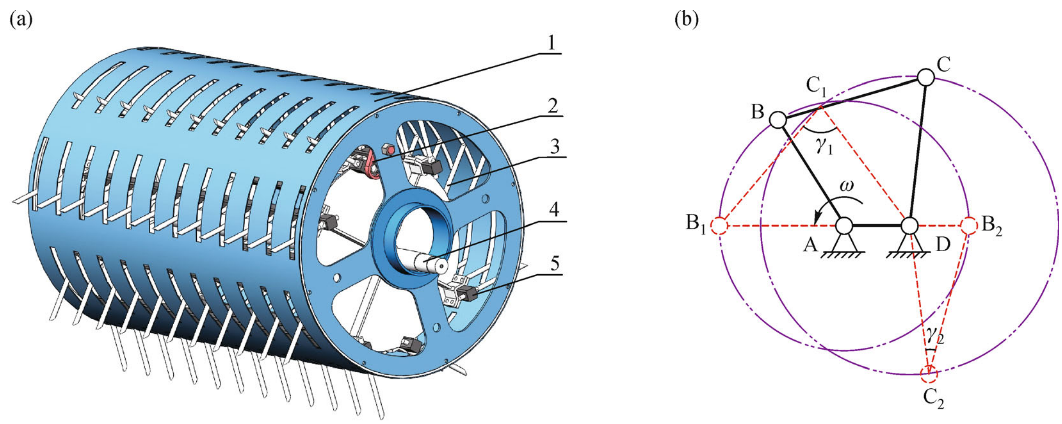

Fig. 3 (a) Structural diagram of eccentric collection mechanism. 1, rotary drum; 2, the double crank mechanism; 3, spring tooth; 4, the centric spindle; 5, the supporting frame for the teeth; (b) schematic diagram of the double crank mechanism. AB, the length of the driving crank; BC, the length of the link; CD, the length of the driven crank; AD, the length of the and rack; AB_1C_1D and AB_2C_2D, the two working positions when AB and AD are collinear; γ_1, γ_2, the transmission angle under the two position respectively; ω, the angular velocity of the driving crank.

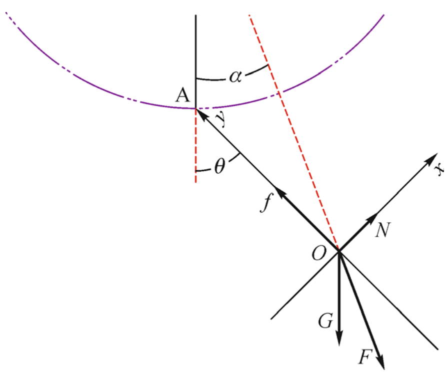

Fig. 4 Force analysis of the spring tooth on the eccentric collection mechanism. *N*, the supporting force of the film; *G*, the gravity of the film; *F*, the centrifugal force of the film; *f*, the friction force of the film; *θ*, the mounting angle; *α*, the angle between the centrifugal force and vertical direction.

the speed ratio (X_1) between trash removal roller and eccentric collection mechanism, the mounting angle (X_2) of spring teeth, the number (X_3) of spring teeth in the same rotary plane of rotary drum.

3 Results

The results of orthogonal rotation regression experiments with three factors and three levels are given in Table 2. The data in Table 2 were fitted by Design-Expert 8.05b, based on the multiple regression method. The coefficients and significance testing of regression equation are given in Table 3. The regression models were as follows:

$$\eta = 31.52 + 44.27X_1 + 0.62X_2 + 1.72X_3 + 0.13X_1X_2 + 1.20X_1X_3 + 0.01X_2X_3 - 18.44X_1^2 - 0.01X_2^2 - 0.24X_3^2 \quad (4)$$

$$\varepsilon = 37.15 - 13.42X_1 - 0.30X_2 - 1.31X_3 - 0.07X_1X_2 + 0.04X_1X_3 - 2.78 \times 10^{-3}X_2X_3 - 5.11X_1^2 + 4.68 \times 10^{-3}X_2^2 + 0.09X_3^2 \quad (5)$$

The variance analysis of the regression models is shown

Table 1 Coding of factors and levels

Coding	Factors		
	X_1	X_2	X_3
–1.682	1.20	30	4
–1	1.32	36	6
0	1.50	45	8
1	1.68	54	10
1.682	1.80	60	12

Table 2 Experimental plan and results of response surface analysis

Serial number	X_1	X_2	X_3	η	ε
1	1	1	1	89.32	14.61
2	1	1	–1	87.39	14.56
3	1	–1	1	88.69	15.07
4	1	–1	–1	87.12	14.86
5	–1	1	1	86.75	15.07
6	–1	1	–1	86.04	15.12
7	–1	–1	1	86.45	15.12
8	–1	–1	–1	87.11	14.93
9	1.682	0	0	89.63	14.23
10	–1.682	0	0	86.98	14.86
11	0	1.682	0	87.45	14.98
12	0	–1.682	0	87.89	15.32
13	0	0	1.682	88.64	14.86
14	0	0	–1.682	86.02	15.23
15	0	0	0	89.86	14.03
16	0	0	0	89.32	13.88
17	0	0	0	90.12	14.02
18	0	0	0	90.26	13.96
19	0	0	0	89.76	14.16
20	0	0	0	89.63	14.24

in Table 4. Both value F of the collection rate (1.45) and value F of the impurity (1.17) are less than $F_{0.95}$ (5, 5) = 5.05, indicating that the results of the regression equation are in good coincidence with the actual values and the quadratic regression equation.

4 Discussion

4.1 Effects on the collection rate of residual film

According to the regression equation for collection rate of residual film, the response surfaces and contour plots are shown in Fig. 5. The results showed that the three key factors in order of impact on the collection rate were the speed ratio, the number of spring teeth and the mounting angle of spring teeth. Also, there were some interactions among the three factors, and in particular the interaction between the speed ratio and the number of spring teeth had a significant impact on the collection rate of residual plastic film.

When there were eight spring teeth in the same revolution plane, the collection rate of residual film first increased to about 90% and then decreased to about 88%, with the speed ratio and the mounting angle of the spring teeth continuously increasing. As shown in Fig. 5a, the collection rate could maintain a higher level when the mounting angle ranged from 42° to 48°. With the speed ratio increased, the collection rate quickly increased for $k < 1.6$ and then slightly declined for $k > 1.6$. The decrease of the collection rate may be the reason that the collected film partly could not be lifted by the removal mechanism and fell out of the spring teeth, if rotation of the eccentric collection mechanism was too slow. When the mounting angle of spring teeth was 45°, the collection efficiency was significantly affected with less than 7 or more than 9 teeth. It can be figured from Fig. 5b that the collection rate showed a trend of first increasing and then decreasing with an additional number of spring teeth in the same revolution plane. When the speed ratio was 1.5, the curve of collection rate of residual film first went up then dropped quickly with the mounting angle as the number of spring teeth gradually increased (Fig. 5c). Importantly, the number of spring teeth had a greater impact on the collection rate.

4.2 Effects on the impurity of residual film package

Response surfaces and contour plots drawn by the regression equation of impurity of residual film are shown in Fig. 6. The factors affecting the impurity of the residual film package were in the order $z > k > \theta$. Also, there was significant interaction between the speed ratio and the mounting angle of spring teeth.

When there were eight spring teeth in the same revolution plane, the impurity of residual film package first decreased and then increased with the increase of the speed ratio and the mounting angle of spring teeth. The mounting angle, which was less than 42° or more than 48°, had an impact on the impurity of the residual film package. With the speed ratio and the number of spring teeth increased (θ = 45°), the impurity of residual film package decreased first and then increased. It could be seen from the Fig. 6b that the effect on the impurity was significantly influenced when k was below 1.5 and z was less than 7 or more than 9. This suggests that if the rotation of the eccentric collection mechanism is too fast, the soil and crop residues may not separate from the residual plastic film, and the excessive spring teeth will also increase the difficulty in removing the trash. As shown in Fig. 6c, if the

Table 3 Regression coefficient and significance test of response surface analysis

Measured value	Factor	Coefficient estimate	Standard error	F value	P value prob > F
Collection rate of residual film (η)	Intercept	89.83	0.150	30.40	< 0.0001**
	X_1	0.78	0.100	58.80	< 0.0001**
	X_2	– 0.05	0.100	0.19	0.6692
	X_3	0.58	0.100	32.96	0.0002**
	X_1X_2	0.21	0.130	2.48	0.1464
	X_1X_3	0.43	0.130	10.58	0.0087**
	X_2X_3	0.22	0.130	2.66	0.1339
	X_1^2	– 0.60	0.099	36.59	0.0001**
	X_2^2	– 0.82	0.099	69.25	< 0.0001**
	X_3^2	– 0.94	0.099	90.98	< 0.0001**
Impurity of residual film package (ε)	Intercept	14.05	0.056	24.55	< 0.0001**
	X_1	– 1.16	0.037	18.84	0.0015**
	X_2	– 0.09	0.037	5.53	0.0405*
	X_3	– 0.02	0.037	0.19	0.6703
	X_1X_2	– 0.11	0.048	5.38	0.0427*
	X_1X_3	0.02	0.048	0.10	0.7634
	X_2X_3	– 0.05	0.048	1.06	0.3267
	X_1^2	0.17	0.036	20.97	0.0010*
	X_2^2	0.38	0.036	110.25	< 0.0001**
	X_3^2	0.34	0.036	89.73	< 0.0001**

Note: **, $P < 0.01$ (very significant); *, $P < 0.05$ (significant).

Table 4 Variance analysis of quadratic regression model

Measured value	Source	Sum of squares	df	Mean square	F value	P value (prob > F)
Collecting rate of residual film (η)	Model	38.48	9	4.28	-	-
	Residual	1.41	10	0.14	-	-
	Pure error	0.57	5	0.11	-	-
	Lack of fit	0.83	5	0.17	1.45	0.3476
	Total	39.88	19	-	-	-
Impurity of residual film package (ε)	Model	4.16	9	0.46	-	-
	Residual	0.19	10	0.02	-	-
	Pure error	0.09	5	0.02	-	-
	Lack of fit	0.10	5	0.02	1.17	0.4321
	Total	4.34	19	-	-	-

speed ratio was 1.5, the impurity of the residual film package decreased generally with an increase of the mounting angle or the number of spring teeth, but obviously tended to increase as both factors increased.

4.3 Experimental verification

According to the analysis above, the speed ratio, the number and mounting angle of spring teeth in the same revolution plane were set at 1.6°, 8°, and 45°, respectively. The residual plastic film baler was then tested in the field. The collection rate of residual film was 88.9% and the impurity of the residual film package was 14.2% after three replications. Compared with the other film collection machines, the collection rate was higher and the impurity was lower. The working performance of this residual film baler is able to satisfy the requirements for recycling residual film.

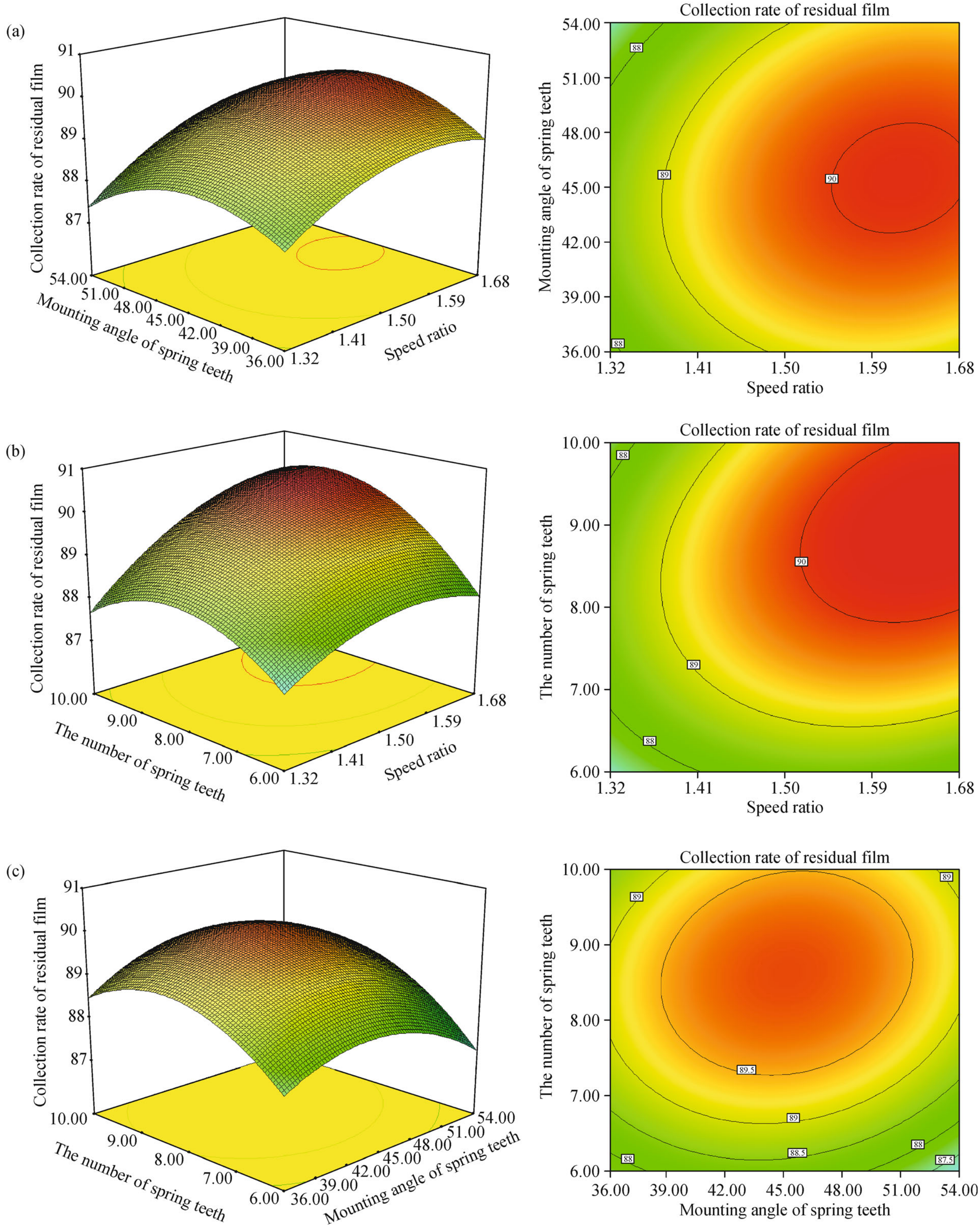

Fig. 5 Response surfaces and contour plots of effects of all factors on collection rate of residual film

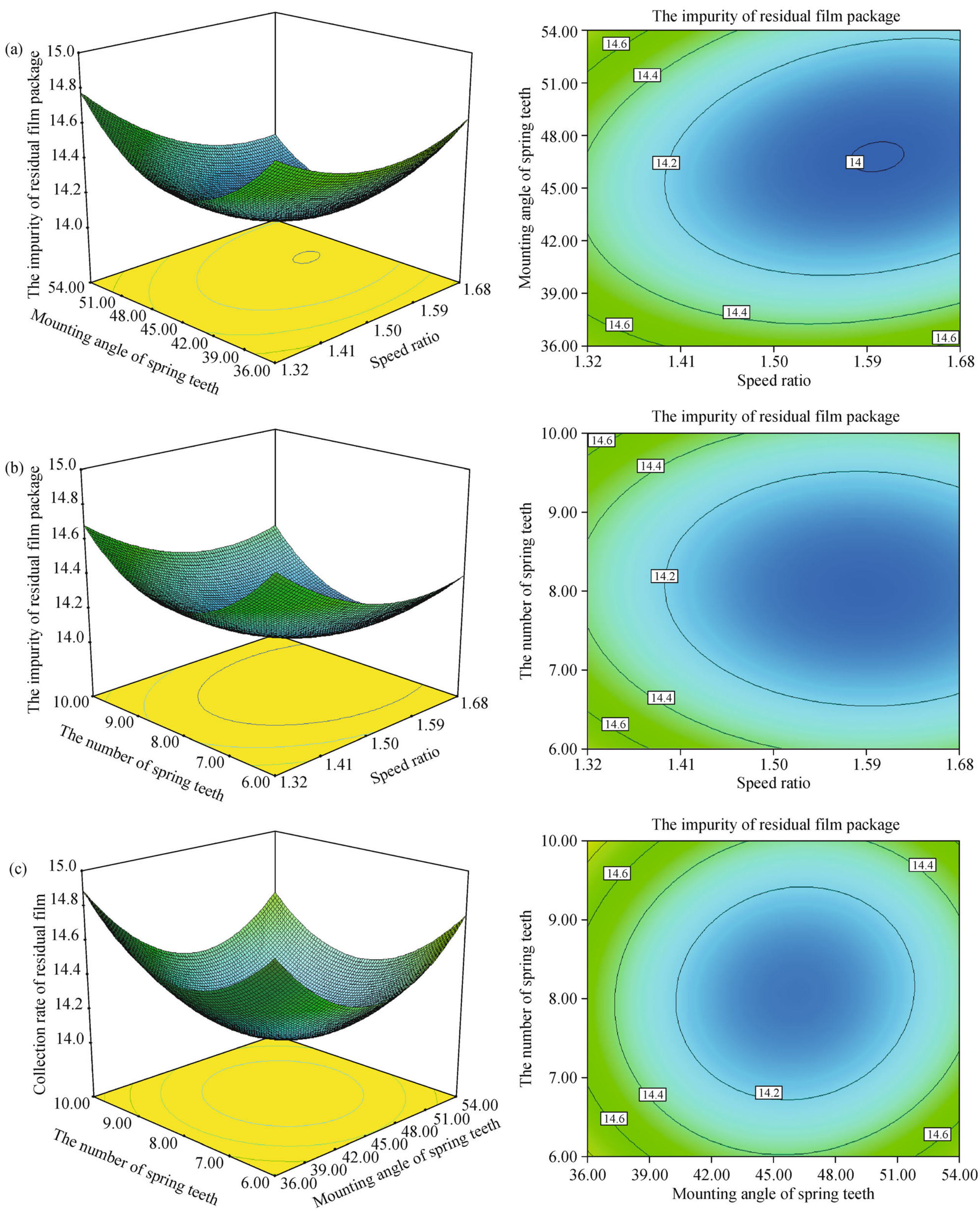

Fig. 6 Response surfaces and contour plots of the effects of all factors on the impurity of the residual film package

5 Conclusions

The factors affecting the collection rate were in order of importance: the speed ratio between trash removal roller and eccentric collection mechanism, the number of spring teeth in the same revolution plane, the mounting angle of spring teeth. Meanwhile, three factors affecting the impurity of film package were the number of teeth, the speed ratio, and the mounting angle.

When the speed ratio, the number and the mounting angle of spring teeth in the same revolution plane were set at 1.6°, 8°, and 45°, respectively, the field testing results of the baler showed that the collection rate of residual film was 88.9% and the impurity of residual film package was 14.2%.

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Compliance with ethics guidelines Qi Niu, Xuegeng Chen, Chao Ji, and Jie Wu declare that they have no conflict of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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