Simulation and test on the operation process of an intermittent film-picking component on full-film mulched double ditches

Fei Dai[1], Feng Wang[1], Wenjuan Guo[1,2], Ruijie Shi[1], Shanglong Xin[1], Xiaolong Liu[1], Wuyun Zhao[1*]

(1. *College of Mechanical and Electrical Engineering, Gansu Agricultural University, Lanzhou 730070, China*;
2. *School of Cyber Security, Gansu University of Political Science and Law, Lanzhou 730070, China*)

Abstract: In view of the problems in operation process of fixed rake-type residual recycling component, such as poor individual profiling effect in film picking, easy clogging of the compound of films, soil and maize stubbles, high power consumption in film picking, and strong disturbance to seedbed soil, in this study, an operation model of intermittent film-picking on full-film mulched double ditches was proposed and an intermittent film picking component was designed. The DEM-MBD coupled algorithm was adopted for numerical simulation on the operation process of the intermittent film-picking component on full-film mulched double ditches, and a comparative analysis was carried out on the seedbed disturbance effect and resistance variation characteristics in film-picking by fixed and intermittent film-picking components. By taking the forward speed in film-picking, cam arrangement angle of the film-picking component and rotating speed of the cam shaft as independent variables, film-picking rate as the response value, a mathematical model between test factors and the film-picking rate was established, to explore the influence order of the factors on film-picking rate, and the optimal working parameters of the intermittent film-picking component were obtained as follows: the forward speed in film-picking was 2 km/h, cam arrangement angle was 180°, rotating speed of the cam shaft was 120 r/min. Under the optimal parameter combination, the average film-picking rate of the simulation test was 96.1%. Field test showed that, the average film-picking rate of the intermittent film-picking component was 95.6%, and 0.5% higher than that of the simulation test. The working condition of the sample machine was basically consistent with the simulation process, and can accurately represent the operation mechanism of intermittent film-picking on full-film mulched double ditches, showing that the established discrete element simulation model and its parameters were accurate and reasonable.

Keywords: full-film mulched double ditches, residual film recovery, intermittent film-picking component, DEM-MBD, parameter optimization

DOI: 10.25165/j.ijabe.20241701.8348

Citation: Dai F, Wang F, Guo W J, Shi R J, Xin S L, Liu X L, et al. Simulation and test on the operation process of an intermittent film-picking component on full-film mulched double ditches. Int J Agric & Biol Eng, 2024; 17(1): 99–108.

1 Introduction

Furrow sowing technology on full-film mulched double ridges is a breakthrough and innovative technology for dry land farming in Northwest China. The technology integrates the functions of steam suppression, rain collection on film surface, and ridge and furrow planting[1,2]. For many years, the large-scale promotion and application of this agronomic technology has improved the efficient water use mechanism in the rain-fed agricultural areas of the loess plateau. As a result, water productivity in the field has been greatly enhanced, and the comprehensive agricultural production capacity in northwest arid area has been significantly strengthened, which is of key importance to ensure state food security and production and income increase for farmers[3]. However, with the constant increase of mulching film application volume and areas, a great deal of residual films are retained in the field, causing serious soil pollution and environmental pollution, also restricting maize stalk stubble returning to the field and soil preparation. Therefore, the autumn film-mulching on seedbed and slush covering in the next year is seriously affected. Therefore, the effective and mechanized recycling of residual films on the full-film mulched double ditches has become an inevitable trend[4,5].

In recent years, the researchers in China have developed various types of equipment for field residual recycling for crops of maize, potato and cotton, and have achieved very significant results[6-9]. Restricted by the special agronomic technology requirement for full-film mulched double ditches, the rake-type residual film recycling has become the main operation mode, however, currently developed sample machine cannot implement residual film recycling very well, and the fixed rake-type residual recycling component has some problems in operations, such as poor individual profiling effect in film picking, easy clogging of the compound of film, soil and stubbles, high power consumption in film picking, and strong disturbance to seedbed soil[10,11]. To address the problems, the research group of this study developed a full-film double-ditch residual plastic film collector with an intermittent film-picking component in preliminary study, which could alleviate the problems of poor local profiling of the film-picking mechanism, soil clogging and rake interference to some extent, and is suitable for the residual film recycling operation on full-film mulched double

Received date: 2023-05-19 **Accepted date:** 2024-01-07

Biographies: Fei Dai, PhD, Professor, research interest: design of agricultural mechanization equipment, Email: daifei@gsau.edu.cn; **Feng Wang**, PhD candidate, research interest: agricultural mechanization engineering, Email: 452950191@qq.com; **Wenjuan Guo**, PhD candidate, research interest: computer simulation, Email: 565105996@qq.com; **Ruijie Shi**, Lecturer, research interest: agricultural mechanization engineering, Email: 1139230110@qq.com; **Shanglong Xin**, Lecturer, research interest: agricultural mechanization engineering, Email: 528980725@qq.com; **Xiaolong Liu**, Senior Experimentalist, research interest: agricultural mechanization engineering, Email: 1102368434@qq.com.

***Corresponding author: Wuyun Zhao**, PhD, Professor, research interest: farm machine and mechanical reliability. College of Mechanical and Electrical Engineering, Gansu Agricultural University, Lanzhou 730070, China. Tel: +86-451-7632472, Email: zhaowy@gsau.edu.cn.

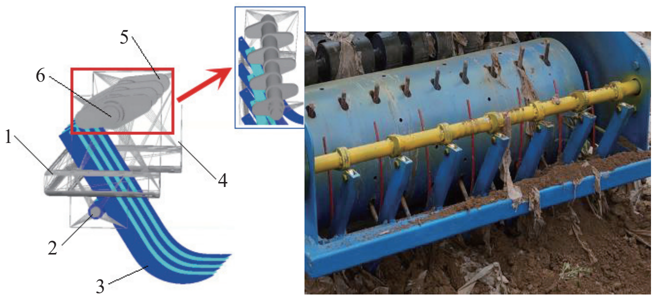
ditches[12], and the average film-picking rate was 90.26%.

In order to further reveal the operation mechanism of the intermittent film-picking component, in this study, based on the developed full-film double-ditch residual plastic film collector[12], through numerical simulation and tests, the film-picking performance of the intermittent film-picking component was further improved. By taking the related working parameters in film picking as independent variables, through simulation test, the film-picking rate under the combination of different factors and levels was measured, and the influence of the factors and their interaction effect on film-picking rate was determined through response surface analysis, finally the optimal control variable combination of the working parameters of the intermittent film-picking component was obtained, to achieve the low power consumption and efficient residual film recycling on full-film mulched double ditches.

2 Overall structure and working principles

2.1 Overall structure

The intermittent film-picking component on the full-film mulched double ditches is mainly composed of the body frame, film-picking teeth, cam shafts, cams, fixed shafts, and side plate, as shown in Figure 1[12]. Among them, all the 7 groups of profiling film-picking teeth in horizontal arrangement are made up of single-joint film-picking teeth and a cam shaft, and each single-joint film-picking teeth could do individual profiling under the action of the cam shaft, on which two neighboring cams (with radius of base circle of 25 mm) could be fixed at different angles, and under the forced rotation of the cam shaft, two neighboring film-picking teeth could be in staggered arrangement to move intermittently. The structure was designed to solve the problems of poor local profiling capacity, clogging of the compounds of films, soil and stubbles and rake interference.



a. Structural diagram b. Structure of the component

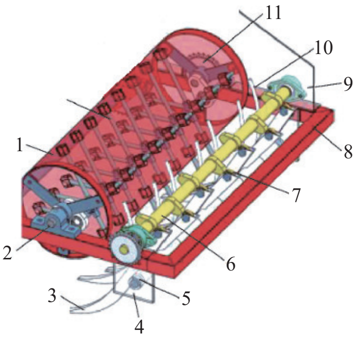
1. Body frame 2. Fixed shaft 3. Film-picking teeth 4. Side plate 5. Cam 6. Cam shaft

Figure 1 Structure of the intermittent film-picking component on full-film mulched double ditches

2.2 Working principle

As shown in Figure 2, the intermittent film-picking component on full-film mulched double ditches requires the coordination of eccentric teeth shifting cylinder to finish residual film collecting.

When the tractor drives the device to work, the cam shaft rotates immediately, and the neighboring film-picking teeth on the film-picking component pick up the films intermittently, so that the device can avoid the obstacles, such as maize stubbles and big film-soil compounds. The films are lifted up by the teeth and delivered along the arc teeth, and finally delivered to the upper side of the cylinder by the telescopic teeth in the eccentric teeth shifting cylinder. After the telescopic teeth totally enter into the cylinder, stirred by the reverse film scraper, the collected residual films enter between the delivery rollers. With the continuous rotation, the residual films are uniformly delivered into the film curling device, to finish the film recycling operation.



1. Eccentric teeth shifting cylinder 2. Axle shaft 3. Film-picking teeth 4. Fixed axle bed 5. Fixed shaft 6. Cam shaft 7. Bearing 8. Body frame 9. Side plate 10. Arc guide bar 11. Chain wheel 12. Telescopic teeth

Figure 2 Setup diagram of the intermittent film-picking component on full-film mulched double ditches and eccentric teeth shifting cylinder

2.3 Analysis of key working parameters

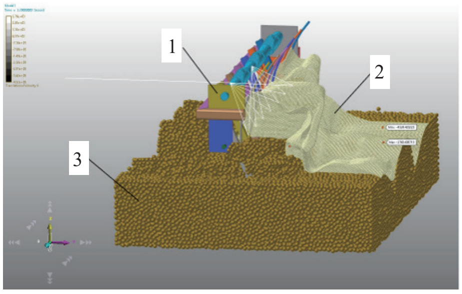
As shown in Figure 1a and according to the conclusions of the preliminary research of the research group, the working parameters that affect working performance of the intermittent film-picking component and their value range are: forward speed (2-4 km/h), cam arrangement angle (90°-180°), rotating speed of the cam shaft (120-140 r/min).

3 Simulation test on the operation process of the intermittent film-picking component on full-film mulched double ditches

3.1 Numerical simulation of the intermittent film-picking process

In order to explore the influence of working parameters on film-picking effect during the working process, considering that the intermittent film-picking component conforms to the characteristics of field movement, DEM-MBD coupling algorithm was used for numerical simulation[13]. The interaction model between the intermittent film-picking component and the double-ridge seedbed is realized by the EDEM-RecurDyn coupling, which mainly includes establishment of the seedbed model and the DEM-MBD coupling model[14].

As shown in Figure 3, the seedbed with full-film mulched double ditches is mainly composed of films and the soil below. Mesh generation was performed by ANSYS Workbench, and the meshes underwent udf file compiling in fluent, after obtaining the coordinate information, read the revised Block_Factory_Data.txt file in EDEM, and the model of the seedbed with full-film mulched double ditches was established rapidly. In order to facilitate modeling and computer simulation speed, at the same time to ensure that the seed bed film thickness and soil particle size equal proportion setting, the particle radius of the selected PE mulching film model was 2.5 mm, radius of soil particles was 8 mm, and the size of the established seedbed model was 1000 mm×1340 mm×310 mm. The small ridge height was 160 mm, the big ridge height was 120 mm, the PE film model was covered over the small ridge, double ditches and the big ridges along the centerline of the small ridge, with a full width of 1200 mm and depth of 5 mm (one layer of particles). Among them, Hertz-Mindlin with Bonding was adopted for soil-soil particle, soil-film particle contact model, and the Hertz-Mindlin (no-slip) was adopted for the mulched seedbed-film-picking component contact model, and the parameter setting of the simulation test is listed in Table 1[14-19].



1. Intermittent film-picking component 2. Residual films 3. Double-ditch seedbed

Figure 3 Interaction model between the intermittent film-picking component and the seedbed with full-film mulched double ditches based on EDEM-RecurDyn coupling

Table 1 Parameters of the simulation test

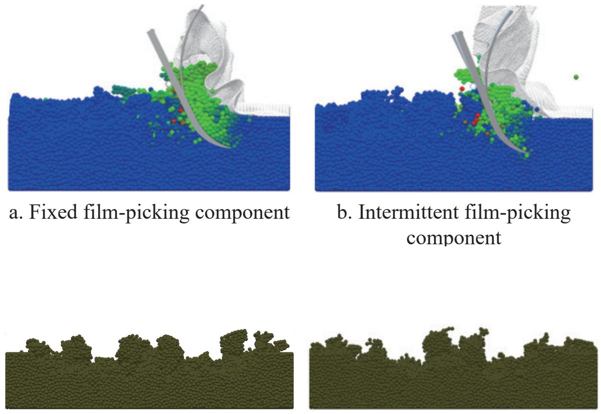
Items	Parameters	Values
Soil particles	Poisson's ratio	0.3
	Shear modulus/Pa	5.00×10^{7}
	Density/kg·m^{-3}	2600
Film particles	Poisson's ratio	0.41
	Shear modulus/MPa	6.50×10^{8}
	Density/kg·m^{-3}	930-950
Film-picking component	Poisson's ratio	0.28
	Shear modulus/Pa	3.50×10^{10}
	Density/(kg·m^{-3})	7850
Particle-particle	Recovery coefficient	0.21
	Static friction coefficient	0.68
	Dynamic friction coefficient	0.27
Particle-film	Recovery coefficient	0.20
	Static friction coefficient	0.40
	Dynamic friction coefficient	0.05
Film and film-picking component	Recovery coefficient	0.50
	Static friction coefficient	0.50
	Dynamic friction coefficient	0.05
Particle and film-picking component	Recovery coefficient	0.54
	Static friction coefficient	0.31
	Dynamic friction coefficient	0.13

In Solidworks, the 3D model of the intermittent film-picking component was established in a scale of 1:1, and the interaction between the intermittent film-picking component and the seedbed was simulated by using EDEM RecurDyn. Then save the simplified 3D model of the intermittent film-picking component in the format of step, and import it into RecurDyn, set the material as steel, and the film-picking depth as 50 mm. According to the motion characteristics of residual film recycling in the field, the motion properties and contact properties of the intermittent film-picking component were added. After exporting the wall file of the model, load it in EDEM, and then add the contact parameters and intrinsic parameters (Table 1). Taking the forward speed of the device at 3 km/h as an example, set the time step to 1×10^{-5} s, the Rayleigh time step to 12.1545%, and the total time to 1.6 s. Start the joint simulation channel, set the motion time in RecurDyn to 1.6 s, and the step size is 360 time intervals. After setting, solve the problem in RecurDyn[14].

3.2 Comparison of the working performance of two types of film-picking components

The fixed rake-type residual film collecting is the chief working mode for residual film recycling on full-film mulched double ditches at present, however, the fixed rake-type residual film collecting has the disadvantages of poor individual profiling effect in film picking, easy clogging of the compound of films, soil and stubbles, high power consumption in film picking, and strong disturbance to seedbed soil[20]. To solve this problem, the research group proposed the intermittent film-picking mode on full-film mulched double ditches, and designed an intermittent film-picking component. To further verify the working performance of the intermittent film-picking component in residual film recycling on full-film mulched double ditches, and compared the working performance of the two types of film-picking components.

In the simulation test, the fixed rake-type film-picking component and intermittent rake-type film-picking component were selected (Figures 4a and 4b). The forward speed of the two types of film-picking components was 3 km/h; the cam arrangement angle of the intermittent film-picking component was 90°, the rotating speed of its cam shaft was 130 r/min. The working process of the two types of film-picking components and their disturbance effect to the double-ridge seedbed are shown in Figure 4.



a. Fixed film-picking component b. Intermittent film-picking component

c. Disturbance effect of fixed film-picking on seedbed d. Disturbance effect of intermittent film-picking on seedbed

Figure 4 Comparison of the working effect of the two types of film-picking components

Figures 4c and 4d show the disturbance effect of the two types of film-picking methods on double-ridge seedbed. Since the small ridge in the center of the full-film mulched double ditches is high (150-200 mm in height), the disturbance to the small ridge by the two types of film-picking components had no significant difference. It can be obtained from the comparison of disturbance effect on seedbed by the two types of film-picking components that, the fixed film-picking component had relatively stronger disturbance to the big ridges on both sides, causing higher dispersion of the big ridges, which were almost at the same level of the ditches. The intermittent film-picking component can basically maintain the symmetrical arrangement of big ridges and the small ridge, and the transfer volume of soil particles on ridges was relatively small. Therefore, fixed film-picking had stronger disturbance to the double-ridge seedbed compared with intermittent film-picking.

It can be known from the resistance variation curve of the two types of film-picking components in Figure 5 that, the resistance to the fixed film-picking component had a relatively concentrated distribution (among –400 to –1300 N), with insensitive fluctuation, showing the sustained raking effect of the fixed film-picking component on the film-mulched seedbed. At the same time, the distribution range of resistance to the intermittent film-picking component was relatively large (among 0 to –1400 N), except for some resistance values at impulse peak, other resistance values were all lower than the resistance to the fixed film-picking component, demonstrating the intermittent interaction rule between the film-picking component and the film-mulched seedbed. Therefore, based on the disturbance effect comparison and analysis on resistance variation characteristics of the two types of film-picking components, the intermittent film-picking component was more suitable to the efficient mechanized residual recycling operation on full-film mulched double ditches. Thus, it is necessary to optimize the working parameters of it through tests.

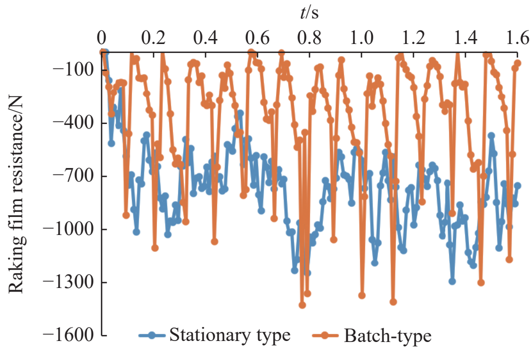
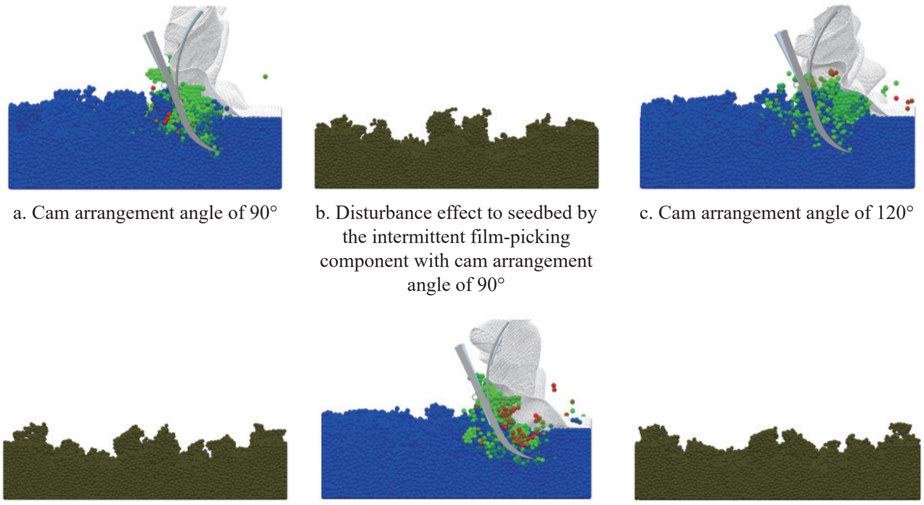


Figure 5 Resistance variation curve in film-picking of the two types of film-picking components

3.3 Influence of cam arrangement angel on film-picking effect

In order to further explore the influence of the cam arrangement angle on the working performance of the film-picking components and their disturbance to seedbed, the cam arrangement angle was set to 90° (Figure 6a), 120° (Figure 6c), and 180° (Figure 6e) for three types of intermittent film-picking components. Set the forward speed to 3 km/h, rotating speed of the cam shaft to 130 r/min to carry out the simulation test on film-picking effect. It can be known from the simulation test process that, due to the intermittent vibration of three types of film-picking components, the soil and films were separated relatively completely, so that the cleanliness of recycled films was higher. Especially for the film-picking component with cam arrangement angle of 180°, its movement in collecting residual films was stretched flat, which is conducive to the collecting movement of the front-mounted eccentric teeth shifting cylinder. However, the intermittent vibration of the three types of film-picking components made disturbance to the whole seedbed, especially stronger disturbance to the big ridges on both sides.

Figure 7 shows the resistance variation curves of the three types of intermittent film-picking components, and their variation law of resistance in film-picking were basically in agreement, similar to the feature of the film lifting component, it presents intermittent changes. Meanwhile, affected by different cam arrangement angles, the film-picking component with cam arrangement angle of 180° had relatively gentle fluctuation of resistance, other than some "pulse" peak values, the film-picking resistance kept among 0 to –600 N. More over, the film resistance fluctuation of the film-picking component with cam arrangement angle of 90° is the most drastic, which is appearing more frequently between –600 to –900 N.



a. Cam arrangement angle of 90° b. Disturbance effect to seedbed by the intermittent film-picking component with cam arrangement angle of 90° c. Cam arrangement angle of 120° d. Disturbance effect to seedbed by the intermittent film-picking component with cam arrangement angle of 120° e. Cam arrangement angle of 180° f. Disturbance effect to seedbed by the intermittent film-picking component with cam arrangement angle of 180°

Figure 6 Comparison of the working effect of the three types of intermittent film-picking components

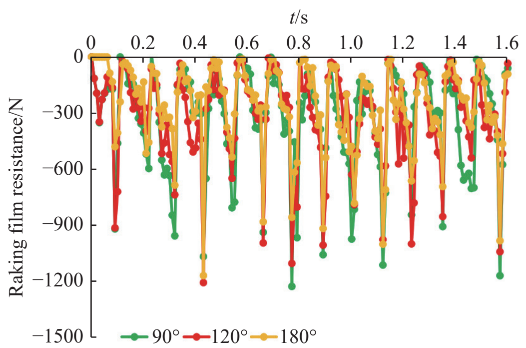


Figure 7 Resistance variation curve in film-picking of the three types of intermittent film-picking components

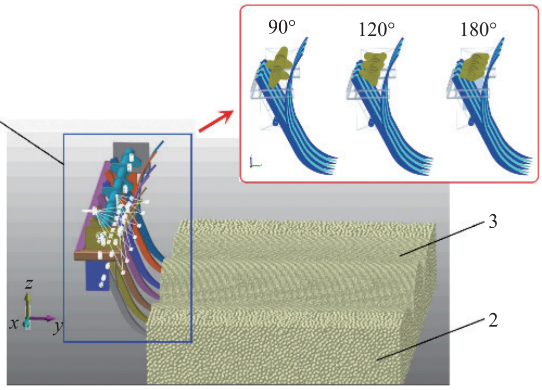
4 Optimization of the working performance of the intermittent film-picking component

4.1 Test design and method

The simulation test on the working performance of the intermittent film-picking component on full-film mulched double ditches was carried out according to GB/T 25412-2021 Farm waste film-pick up machines. Taking film-picking rate as the evaluation index, the simulation test on optimization of working parameters was performed. Based on the simulation model established in Figure 8, after each time of simulation test, sections were obtained at different positions of the seedbed to measure the film-picking rate[20]. The equation for the film-picking rate is

$$Y = \frac{N_1}{N} \times 100\% \quad (1)$$

where, Y is the film-picking rate, %; N_1 is the qualified film-picking points on the seedbed; N is the total tested points.



1. Intermittent film-picking component 2. Double-ditch seedbed 3. Residual films

Figure 8 Simulation model of the intermittent film-picking component

According to the analysis results of the key working parameters of the intermittent film-picking component, the simulation test was performed by taking forward speed of 2 km/h, 3 km/h, and 4 km/h, cam arrangement angle of 90°, 120°, and 180°, rotating speed of cams of 120 r/min, 130 r/min, and 140 r/min were taken as test factors, and film-picking rate Y as evaluation index. The three-factor and three-level response surface analysis method was adopted in the test. The codes of factors and levels of the test are listed in Table 2. A total of 17 groups of response surface analysis tests (Table 3) were carried out, and each group of tests was repeated three times. The average of the results was taken as the test results, and the data was processed and analyzed by applying Design Expert 13[21,22].

Table 2 Test factors and levels

Level codes	Factors		
	Forward speed x_1/km·s^{-1}	Cam arrangement angle x_2/(°)	Rotating speed of the cam shaft x_3/r·min^{-1}
–1	2	90	120
0	3	120	130
1	4	180	140

Table 3 Results of response surface analysis

Test No.	X_1	X_2	X_3	Y/%
1	–1	1	0	94.6
2	1	–1	0	90.3
3	0	0	0	92.2
4	–1	0	1	90.5
5	–1	0	–1	93.9
6	1	0	–1	89.5
7	0	0	0	91.2
8	1	0	1	88.8
9	0	–1	–1	91.1
10	0	1	–1	93.8
11	0	–1	1	90.5
12	–1	–1	0	91.2
13	1	1	0	91.3
14	0	0	0	92.2
15	0	0	0	92.5
16	0	0	0	92.6
17	0	1	1	90.2

4.2 Establishment of the regression model and verification

The simulation test results show that, the film-picking rate of the intermittent film-picking component could achieve 88.8%-94.6%, but its performance stability in film picking, film-picking quality and resistance in operation had relatively great fluctuations.

The software Design-Expert 13 was applied to analyze the test results, and the quadratic regression model of the film-picking rate Y represented by coded values is

$$Y = 92.14 - 1.29X_1 + 0.85X_2 - 1.04X_3 - 0.5075X_1^2 + 0.2175X_2^2 - 0.9575X_3^2 - 0.6X_1X_2 + 0.675X_1X_3 - 0.75X_2X_3 \quad (2)$$

where, Y is the film-picking rate, %; X_1 is the coded value of the forward speed during film picking; X_2 is the coded value of cam arrangement angle; X_3 is the coded value of rotating speed of the cam shaft.

A variance analysis and regression coefficient significance test were made on the quadratic regression model above, and the results are listed in Table 4.

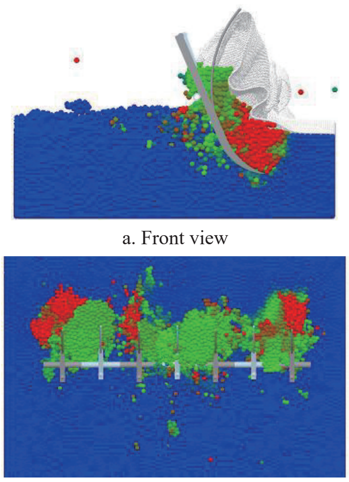
Table 4 Variance analysis of the regression equation

Source of variation	Sum of squares	Degree of freedom	Mean square	F	P
Regression	38.42	9	4.27	13.68	0.0012**
X_1	13.26	1	13.26	42.49	0.0003**
X_2	5.78	1	5.78	18.52	0.0036**
X_3	8. 61	1	8. 61	27.59	0.0012**
X_1X_2	1.44	1	1.44	4.61	0.0688
X_1X_3	1.82	1	1.82	5.84	0.0463*
X_2X_3	2.25	1	2.25	7.21	0.0313*
X_1^2	1.08	1	1.08	3.47	0.1046
X_2^2	0.1992	1	0.1992	0.6383	0.4506
X_3^2	3.86	1	3.86	12.37	0.0098**
Residual error	2.18	7	0.3121		
Lack of fit	0.9525	3	0.3175	1.03	0.4685
Error	1.23	4	0.3080		
Sum	40.60	16			

Note: * means significant (p<0.05); ** means very significant (p<0.01).

Table 4 lists that, the p value of the established quadratic regression model (0.0012)<0.01, which shows that the regression model was extremely significant; the p value of Lack-of-fit (0.4685)>0.05, which shows that Lack-of-fit was not significant and the fitted quadratic regression equation was in accordance with actual situation, and could correctly reflect the relationship between film-picking rate Y and X_1, X_2 and X_3, and the regression model could better predict the results of the optimization test. The monomial coefficient of the model X_1 (forward speed), X_2 (cam arrangement angle), X_3 (rotating speed of the cam shaft) and quadratic term X_3^2 (rotating speed of the cam shaft) had extremely significant effect on the film-picking rate; the interaction item X_1X_3 (the interaction between cam arrangement angle and the rotating speed of the cam shaft) had relatively significant influence, while the other terms had no significant effect. Based on the values of the regression coefficients of the factors, it can be concluded that the order of the influence of various factors on the qualified rate of seed bed tillage is X_1, X_3, X_2, that is, the advance speed of film lifting, the speed of camshaft and the angle of cam arrangement.

Figure 9 shows the 8th group of simulation tests on the working performance of the full-film double-ditch intermittent film-picking component, that is, the film-picking process of the intermittent film-picking component on double ridges from different views, when the forward speed was 4 km/h, the cam arrangement angle was 120° and the rotating speed of the cam shaft was 140 r/min. It can be obtained from the speed of seedbed soil particles, under such parameter combination, the interaction force between the intermittent film-picking component and the mulched seedbed was too large, and film-picking rate on the double-ridge seedbed was relatively low (88.8%).

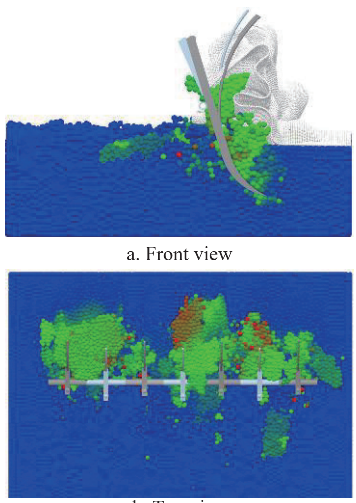


a. Front view

b. Top view

Figure 9 The 8th group of tests for response surface simulation analysis

Figure 10 shows the 1st group of simulation tests on the working performance of the full-film double-ditch intermittent film-picking component, that is, the film-picking process of the intermittent film-picking component on double ridges from different views, when the forward speed was 2 km/h, the cam arrangement angle was 180° and the rotating speed of the cam shaft was 130 r/min. Under such parameter combination, relatively speaking, the interaction force between the intermittent film-picking component and the mulched seedbed was proper, and film-picking rate on the double-ridge seedbed was relatively high (94.6%).



a. Front view

b. Top view

Figure 10 The 1st group of tests for response surface simulation analysis

It can be obtained from the simulation tests that, under different combination of test factors, the film-picking effect of the intermittent film-picking component was different. Through comparing the 1st and the 8th simulation tests for response surface simulation analysis (Figure 9 and Figure 10) and the variation curves of film-picking resistance of them (Figure 11), after 0.5 s, with smaller film-picking resistance (the resistance is less than 1250 N) on the intermittent film-picking component, the film-picking effect was more significant. After 1.4 s, the working resistance of the 1th group was significantly less than that of the 8th group.

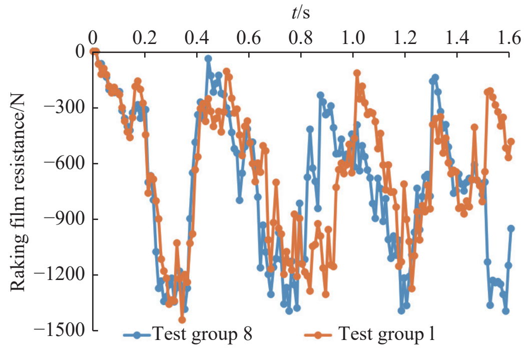


Figure 11 Resistance variation curves in film-picking of the film-picking component in the 1st and the 8th groups of tests

4.3 Analysis on the interaction item of the model

According to quadratic regression model (2), the response surface diagram on the relationship of the factors can be drawn, as shown in Figures 12-14. It can be known from the results of Table 4, among the three test factors, the interaction effect between forward speed and the rotating speed of the cam shaft, and between cam arrangement angle and the rotating speed of the cam shaft had very significant effect on film picking rate, while other interaction factors had no significant effect.

It can be obtained from the interaction response surface of the two factors and the contour plot that, when forward speed was 4 km/h, cam arrangement angle was 90°, the film-picking rate was relatively low (between 89%-91%), under the interaction of the two factors, the maximum film-picking rate is between 94%-95%. The density of the contour plot shows that, the influence of the interaction effect between the forward speed and the cam arrangement angle had insignificant affect on the film-picking rate, which was consistent with the results of variance analysis and the simulation process.

Figure 13 shows that, when rotating speed of the cam shaft kept at a certain level, the forward speed reduced from 4 to 2 km/h, the film-picking rate presented an increasing trend (from 90% to 95%), when forward speed was 2 km/h, rotating speed of the cam shaft was 120 r/min, the film-picking rate was the maximum value. The reason is that, in the process of film-picking operation, when the forward speed reduced in an orderly way, the time of effective cutting, pushing and vibrating for separation of soil and films of the film-soil compounds increased, causing more thorough intermittent interaction between the film-picking component and the film-soil compounds, which was inducive to the rapid falling of soil and stubbles from the residual films and could effectively reduce resistance in film picking and ensure the high quality and effective film-picking operation.

It can be obtained through the interactive response surface of the two factors and the contour plot in Figure 14 that, when cam arrangement angle was 180°, and the rotating speed of the cam shaft reduced from 140 to 120 r/min, the film-picking rate presented an increasing trend, the film-picking rate gradually increased from 90% to 95% (maximum film-picking rate at 94.6%). The reason is that, during the intermittent film-picking operation, with the gradual reduction of rotating speed of the cam shaft (from 140 to 120 r/min), the intermittent interaction frequency between the film-picking component and the soil-film compounds also reduced, and the phenomena of film tearing and stirring were alleviated. At the same time, by effectively reducing the disturbance strength to seedbed films and soil from the film-picking component, the contact time between them increased, the soil and films were effectively separated in an orderly way to ensure the film picking rate.

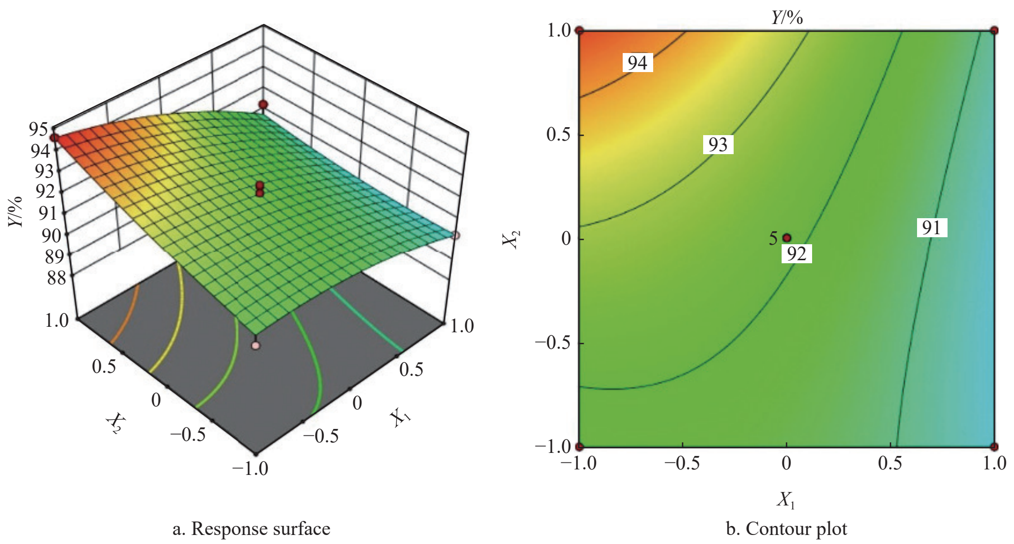


Figure 12 Influence of forward speed and cam arrangement angle on film-picking rate

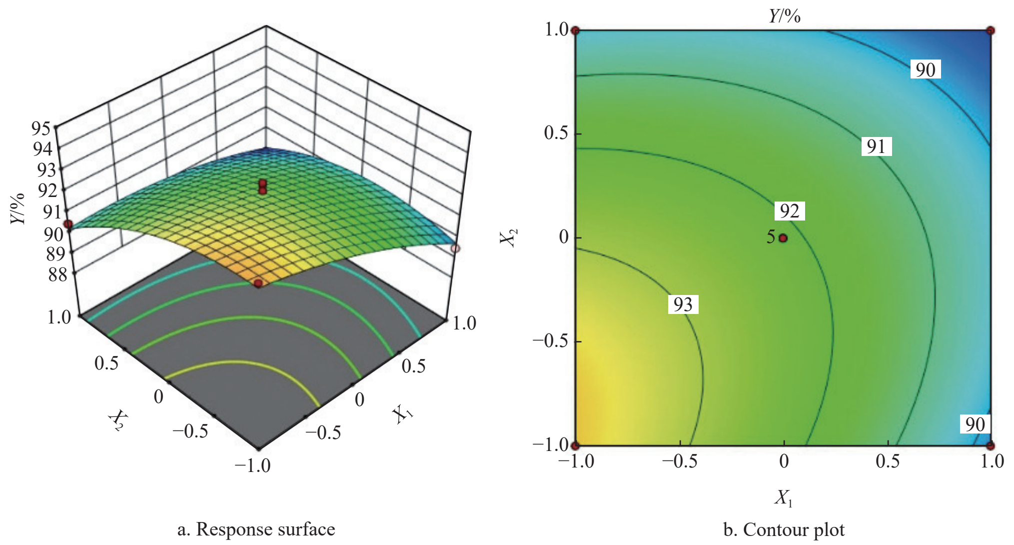


Figure 13 Influence of forward speed and rotating speed of cam shaft on film-picking rate

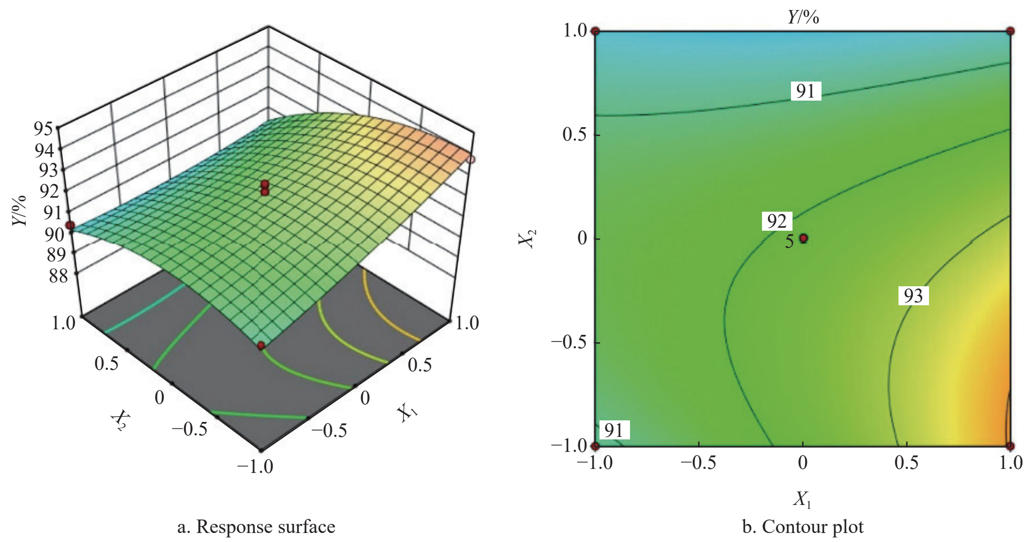


Figure 14 Influence of cam arrangement angle and rotating speed of cam shaft on film-picking rate

4.4 Optimization of the working parameters of the intermittent film-picking component

Taking the 100% film picking rate of the intermittent film-picking component on full-film mulched double ditches as the target, the Optimization-Numerical module in the Design-Expert 13 software was applied in optimization solution on the regression equation model[23], and the optimal parameter combination of the intermittent film-picking component was obtained as follows: the forward speed was 2 km/h, cam arrangement angle was 180°, and rotating speed of the cam shaft was 120 r/min.

To verify the reliability of Model (2), the optimal parameter combination of the intermittent film-picking component was adopted for the simulation tests on the working performance of the film-picking component on the seedbed with full-film mulched double ditches (Figure 15). Results of the verification test showed that, the average film-picking rate was 96.1%, showing a significant increase to that before the optimization. It indicates that, after optimizing the working parameters, the sliding cutting and raking performance of the intermittent film-picking component could be enhanced, and the separation degree of the film-soil compounds could be increased, the disturbance to the seedbed soil could be alleviated, the quality of residual film recycling could be improved, and the technical requirements in mechanized recycling of residual films on double ditches could be met. Therefore, the established regression model was reliable.

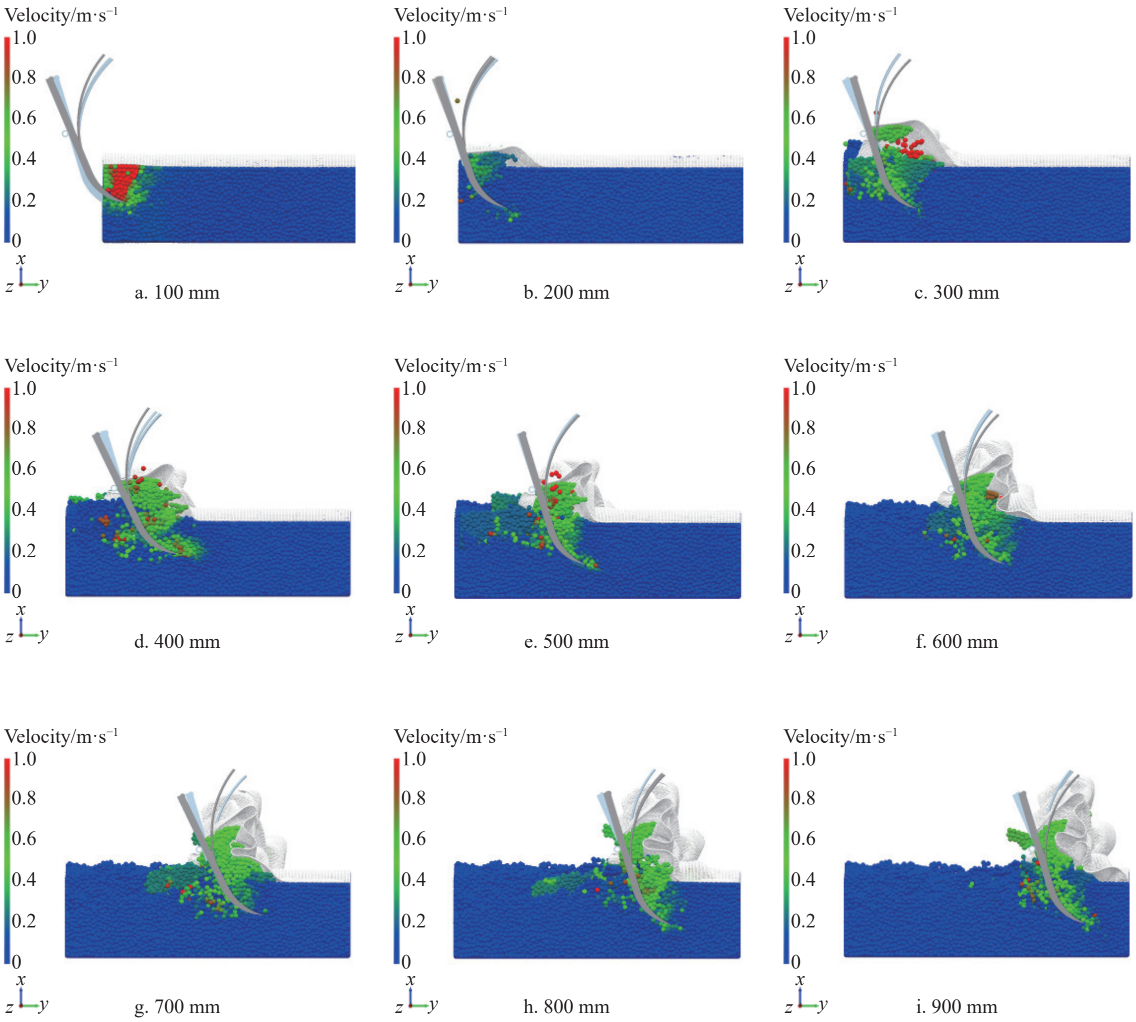


Figure 15 Simulation test on film-picking performance of the intermittent film-picking component under optimal working parameters

5 Field test verification

To further verify the film-picking performance under optimal working parameters of the intermittent film-picking component on full-film mulched double ditches, the verification test was carried out in the test field with whole process mechanization and full-film mulched double ditches in Yuzhong county, Lanzhou of Gansu province, China (Figure 16).

The soil in the test field is loessal soil with a moisture content of 18.60%. The planting pattern of full-film mulched double ditches was adopted for maize planting, with row spacing of 400 mm, and plant spacing of 280 mm. A certain amount of maize stubbles were distributed in the small ridge, and the height of the stubbles was among 75-100 mm. The big and small ridge bodies were laid with while mulching film with a thickness of 0.01 mm and a width of 1200 mm. The test was carried out by referring to GB/T 25412-2021 (Farm waste film-pick up machines), after film picking operation, a seedbed with full-film mulched double ridges 15 m in length was randomly selected and its film-picking effect was measured. Taking the average value of the results of 6 plots, and the average film-picking rate was 95.6%, 0.5% lower than the simulation test result.

It was found in the test that, under the rotation of the cam shaft of the intermittent film-picking component, the motion trajectory of the teeth tip was a sinusoidal curve motion, which could effectively alleviate the congestion of the film-soil compounds to the film-picking component. Therefore, the intermittent film-picking method is conducive to film-soil separation and the picking and delivery operation of the front-mounted eccentric teeth shifting cylinder. The actual working condition of the intermittent film-picking component and the simulation process was basically consistent and could accurately reflect the how the film-picking component efficiently pick up residual films, showing that the established DEM-MBD coupling simulation model was accurate, and the optimal parameter combination of the intermittent film-picking component was reasonable. However, since the parameters of the discrete element soil particles are greatly different from the actual soil aggregation degree in rotary tillage, and the actual soil has a large range of moisture content, by referring to related studies, some contact parameters of the film-mulched seedbed were not calibrated, thus the actual interaction of the intermittent film-picking component, seedbed films and the soil was not fully represented. Therefore, it is necessary to further optimize the model establishment and calibration of related parameters.

a. Field performance test of the intermittent film-picking component

b. Intermittent film-picking c. Effect of intermittent film-picking

Figure 16 Verification test on the field operation performance

6 Conclusions

1) In this study, the key factors affecting the working performance of the intermittent film-picking device on the full-film mulched double ditches were analyzed and determined based on its structure and working principles. The DEM-MBD coupled algorithm was adopted for numerical simulation on the operation process of the intermittent film-picking component on full-film mulched double ditches, and a comparative analysis was carried out on the seedbed disturbance effect and resistance variation characteristics in film-picking by fixed and intermittent film-picking components.

2) By using the response surface analysis method, a quadratic polynomial regression model between the film-picking rate and forward speed, cam arrangement angle and rotating speed of the cam shaft was established. Taking the full film-picking rate as the objective, the optimal parameter combination of the intermittent film-picking device was: the forward speed was 2 km/h, cam arrangement angle was 180°, and rotating speed of the cam shaft was 120 r/min. Under this optimal parameter combination, the average film-picking rate corresponding to simulation verification tests was 96.1%.

3) Field test showed that, the average film-picking rate of the intermittent film-picking component was 95.6%, 0.5% higher than that of the simulation test. The working condition of the sample machine was basically consistent with the simulation process, and can accurately represent the operation mechanism of intermittent film-picking on full-film mulched double ditches, showing that the established discrete element simulation model and its parameters were accurate and reasonable.

In the subsequent research, we will consider that in addition to the interaction between components and film-soil, the stubble could also be taken into account to make the simulation effect and parameters more accurate.

Acknowledgements

The authors acknowledge that this work was financially supported by the National Natural Science Foundation of China (Grant No. 52065005), Outstanding Youth Foundation of Gansu Province (Grant No. 20JR10RA560), Longyuan Youth Innovation and Entrepreneurship Talent Project in Gansu Province (Grant No. 2022LQGR79).

[References]

[1] Dai F, Zhao W Y, Zhang F W, Ma H J, Xin S L, Ma M Y. Research progress analysis of furrow sowing with whole plastic-film mulching on double ridges technology and machine in northwest rainfed area. Transactions of the CSAM, 2019; 50(5): 1–16. (in Chinese)

[2] Zhou L M, Jin S L, Liu C A, Xiong Y C, Si J T, Li X G, et al. Ridge-furrow and plastic-mulching tillage enhances maize-soil interactions: opportunities and challenges in a semiarid agroecosystem. Field Crops Research, 2012; 126: 181–188.

[3] Qin S H, Zhang J L, Dai H L, Wang D, Li D M. Effect of ridge-furrow and plastic-mulching planting patterns on yield formation and water movement of potato in a semi-arid area. Agricultural Water Management, 2014; 131: 87–94.

[4] Wang Z C, Li X Y, Shi H B, Sun M, Ding T, Wang C G. Effects of residual plastic film on soil hydrodynamic parameters and soil structure. Transactions of the CSAM, 2015; 46(5): 101–106, 140. (in Chinese)

[5] Zhang D, Hu W L, Liu H B, Du L F, Xu Y, Cheng Z H, et al. Characteristics of residual mulching film and residual coefficient of typical crops in North China. Transactions of the CSAE, 2016; 32(3): 1–5. (in Chinese)

[6] Hu K, Wang J K, Li B, Jiang P, Ding S S, Li T W. Development and experiment of combined operation machine for cotton straw chopping and plastic film collecting. Transactions of the CSAE, 2013; 29(19): 24–32. (in Chinese)

[7] Yang L, Zhang D X, Hou S L, Xu F. Analysis of structural parameters and experiment of plastic film collector for corn fields during seedling period. Transactions of the CSAM, 2010; 41(12): 29–34. (in Chinese)

[8] Lü Z Q, Zhang L, Zhang G L, Liu S F. Design and test of chain guide rail-type plastic film collector. Transactions of the CSAE, 2015; 31(18): 48–54. (in Chinese)

[9] Zhang J X, Wang X N, Zhang L, Yu C, Jiang Y X, Zhang H C, et al. Effects of mechanical tensile properties of plastic film on plastic recycling method. Transactions of the CSAE, 2015; 31(20): 41–47. (in Chinese)

[10] Dai F, Zhao W Y, Zhang F W, Wu Z W, Song X F, Wu Y F. Optimization and experiment of operating performance of collector for corn whole plastic film mulching on double ridges. Transactions of the CSAE, 2016; 32(18): 50–60. (in Chinese)

[11] Wang J X, Zhao W Y, Liu X L, Dai F, Xin S L, Wu Z W. Improved design and experiment of collector for corn whole plastic film mulching on double ridges. Transactions of the CSAM, 2021; 52(1): 119–128. (in Chinese)

[12] Xin S L, Zhao W Y, Dai F, Wang J X, Liu X L, Wu Z W. Improved design and experiment of collector for corn whole plastic film mulching on double ridges. Transactions of the CSAM, 2018; 49(S1): 311–319. (in Chinese)

[13] Wang X Z, Zhang S, Pan H B, Zheng Z Q, Huang Y X, Zhu R X. Effect of soil particle size on soil-subsoiler interactions using the discrete element method simulations. Biosystems Engineering, 2019; 182: 138–150. (in Chinese)

[14] Hu J P, Pan J, Chen F, Yue R C, Yao M J, Li J. Simulation optimization and experiment of finger-clamping seedling picking claw based on EDEM-RecurDyn. Transactions of the CSAM, 2022; 53(5): 75–185, 301. (in Chinese)

[15] Dai F, Guo W J, Song X F, Shi R J, Zhao W Y, Zhang F W. Design and test of crosswise belt type whole plastic-film ridging-mulching corn seeder on double ridges. Int J Agric & Biol Eng, 2019; 12(4): 88–96.

[16] Ucgul M, Saundersa C, Li P L, Lee S H. Analyzing the mixing performance of a rotary spader using digital image processing and discrete element modelling (DEM). Computers and Electronics in Agriculture, 2018; 151: 1–10.

[17] Dai F, Song X F, Zhao W Y, Zhang F W, Ma H J, Ma M Y. Simulative calibration on contact parameters of discrete elements for covering soil on whole plastic film mulching on double ridges. Transactions of the CSAM, 2019; 50(2): 49–56, 77. (in Chinese)

[18] Guo W S, Hu C, He X W, Wang L, Hou S L, Wang X F. Construction of virtual mulch film model based on discrete element method and simulation of its physical mechanical properties. Int J Agric & Biol Eng, 2020; 13(4): 211–218.

[19] Wang F, Dai F, Zhang F W, Song X F, Shi R J, Zhao W Y, et al. Simulation analysis and test on the effect of picking up the residual film of typical film lifting parts. Agronomy, 2023; 13(2): 488.

[20] Dai F, Song X F, Zhao W Y, Shi R J, Zhang F W, Zhang X K. Mechanism analysis and performance improvement of mechanized ridge forming of whole plastic film mulched double ridges. Int J Agric & Biol Eng, 2020; 13(5): 107–116.

[21] Lai Q H, Yu Q X, Dong J Y. Dynamic analysis of rotary tiller gearbox based on EDEM, ADAMS and ANSYS. Journal of Intelligent & Fuzzy Systems, 2019; 36: 1153–1160.

[22] Tang H, Xu C S, Xu W L, Xu Y N, Xiang Y S, Wang J W. Method of straw ditch-buried returning, development of supporting machine and analysis of influencing factors. Frontiers in Plant Science, 2022; 13: 967838.

[23] Dai F, Guo W J, Song X F, Zhang Y, Shi R J, Wang F, et al. Optimization of mechanized soil covering path based on the agronomic mode of full-film double-ditch with double-width filming. Int J Agric & Biol Eng, 2022; 15(1): 139–146.