DESIGN AND EXPERIMENT OF IMPURITY REMOVAL DEVICE OF POTATO COMBINE HARVESTER
/
马铃薯联合收获机除杂装置的设计与试验

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ABSTRACT
Because of the low impurity removal rate and high damage rate of the potato combine harvester during the working process, a new type of impurity removal device for the potato combine harvester was designed. The device was mainly composed of retaining plates, impurity removal rollers, smooth rollers, and a control system. To determine the best working parameters of the device, the rotational speed of the rollers, the distance between two rollers, and the inclination angle of the device were used as the test factors. The impurity removal rate and damage rate were employed as the evaluation indexes. Then, the single factor test and the second rotation orthogonal regression test were performed. The optimum combination after parameter optimization was determined to be as follows: rotational speed of the rollers was 113.4 r/min, the distance between the two rollers was 97.5 mm and the inclination angle of the device was 10.4°. The corresponding impurity removal rate was 95.12%, and the damage rate was 0.54%. The device can better meet the requirements of impurity removal operations.

摘要
针对马铃薯联合收获机除杂过程中除杂率低、伤薯率高的情况，设计了一种用于马铃薯联合收获机的新型除杂装置。该装置主要由挡土板、除杂辊、光辊、控制系统等组成。为确定装置的最佳工作参数，以辊速、辊距和装置倾角为试验因素，以除杂率和伤薯率为评价指标，进行了二次旋转正交回归试验。获取了最优参数组合为辊速113.4r/min、辊距为97.5mm和装置倾斜角度为10.4°。最优参数下的验证试验结果表明，平均除杂率为95.12%、平均伤薯率为0.54%。该装置能较好地满足马铃薯除杂作业要求。

INTRODUCTION
China is one of the largest potato-producing countries in the world (*Jia et al. 2021; Ji et al. 2020*). In 2021, the total planting area of potatoes in China reached 57,000 hectares and the output exceeded 90 million tons (*Wen et al. 2022; Duan et al. 2022*). The harvested potatoes contain a large number of impurities such as soil and weeds, which cannot be removed well by traditional debris removal devices alone (*Wei et al. 2019; Geng et al. 2021*). At present, there is less research on the impurity removal device in China (*Sun et al. 2017; Zhang et al. 2021*), and the existing impurity removal rollers have a single structure, which has the problems of low impurity removal rate and high damage rate of potatoes.

In recent years, the research on impurity removal equipment mainly had focused on the shape, arrangement, and rotation speed of the rollers (*Wei et al. 2019; Yang et al. 2021*). For example, some scholars changed the arrangement of the rollers and used double rows of rollers to remove impurities (*Yang et al. 2014*). Some scholars chose nylon as the material of the rollers and carried out comparative experiments (*Zhang et al. 2021*). The results showed that the new type of roller has a better effect of removing impurities than the traditional one. In order to improve production efficiency, some scholars designed a machine that can both remove impurities and grade potatoes (*Wang et al. 2017*). Some scholars analyzed the impurity removal process and optimize the design of the rollers based on the analysis results (*Lv et al. 2021*).

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According to the conclusions of the above research and combined with the current research status of the potato combine harvester, a new type of impurity removal device for potato combine harvester was designed in this study. The device adopted the form of an alternate arrangement of impurity removal rollers and smooth rollers, which can effectively remove impurities and reduce the damage rate of potatoes. Then, single factor test and second rotation orthogonal regression test were performed on the device. After several tests, the optimal working parameters were obtained. The research results provide a theoretical basis and reference for the optimal design of the impurity removal device.

MATERIALS AND METHODS

Whole structure and working principle

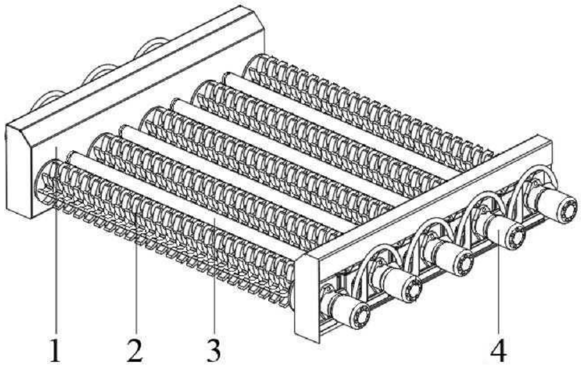

Fig. 1 – Overall structure of the impurity removal device

1. Retaining plate; 2. Impurity removal rollers; 3. Smooth rollers; 4.Control system

As shown in Fig. 1, the device was mainly composed of retaining plates, impurity removal rollers, smooth rollers, and a control system. The rotational speed and direction of rotation of the impurity removal rollers and the smooth roller were the same. The device removed impurities through the frictional collision between the rollers and the potatoes. Smaller clods and weeds fell out of the unit from the gap between the rollers, and cleaned potatoes fall to the conveyor belt. The rotational speed of the rollers, the distance between the rollers, and the inclination angle of the device can be adjusted to meet the needs of the operation under different soil conditions. The main technical parameters of the whole machine are shown in Table 1.

Table 1

Technical parameters of impurity removal device

Parameters	Value
Overall dimensions (Length × Width × Height) [mm]	1630×1295×350
Rated pressure of hydraulic motor [M Pa]	8
Electric motor power of hydraulic power system [kW]	6
Rotational speed of the rollers [r/min]	80~120
Distance between two rollers [mm]	100~160
Inclination angle of the device [°]	8~16

Design analysis of key mechanisms

The design of impurity removal rollers

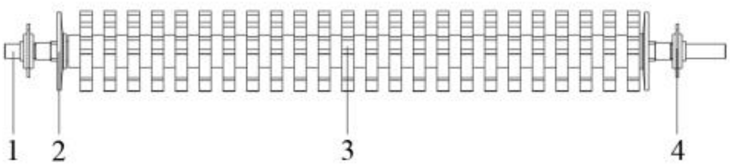

Fig. 2 – Structure of impurity removal roller

1.Axle; 2. Baffle; 3. Rubber sleeve; 4. Bearing blocks

As shown in Fig. 2, the impurity removal roller consists of an axle, baffles, a rubber sleeve, and bearing blocks. To reduce the damage to the potato between the two rollers, referring to the potato damage law of the research, the material of the sleeve is rubber (*Chen et al. 2020*).

To increase the number of contact friction between the impurity removal rollers and the surface of the potatoes, and have a better impurity removal effect, the structure of the rubber sleeve is shown in Fig. 3.

To reduce the rate of potato injury, the edge *1* (shown in Figure 3) in the rubber sleeve was designed as a concave arc, and the edge *2* was designed as an external convex arc. The shape of the potato is ellipsoid, so the edge of the rubber sleeve consists of 4 arcs of tangent transition.

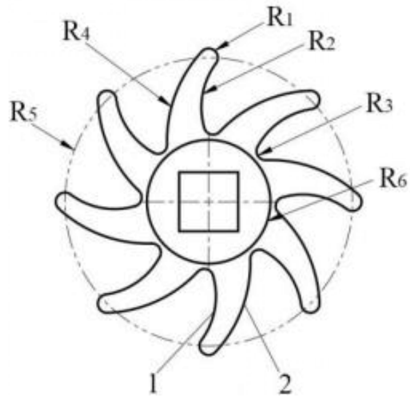

Fig. 3 – Structure of impurity removal wheel

The radii of the arcs are: R1=5 mm; R2=40 mm; R3=10 mm; R4=70 mm. Also, R5=78.5 mm; R6=33.5 mm. To comply with the potato combine harvester, referring to the existing structure and size of the impurity removal roller, the length of the impurity removal roller was designed to be 1200 mm.

The design of smooth rollers

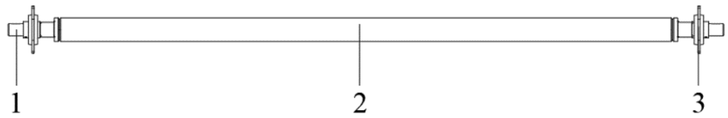

Fig. 4 – Structure of smooth roller

1. Inner shaft; 2. Outer shaft; 3. Bearing blocks

To improve the impurity removal rate, a smooth roller was installed between adjacent impurity removal rollers. Among them, the rotational speed and direction of rotation of the smooth rollers were consistent with the impurity removal rollers. As shown in Fig. 4, the smooth roller consists of an inner shaft, an outer shaft, and bearing blocks. To improve the crushing effect of the clods and reduce the resistance of the potatoes to pass over the smooth rollers, the material of the smooth roller was selected from alloy steel with high strength and low friction coefficient. Referring to the structural parameters of the impurity removal roller, it is determined that the diameter of the outer shaft of the smooth roller is 48 mm, the diameter of the inner shaft is 25 mm, and the length is 1190 mm.

The design of control system

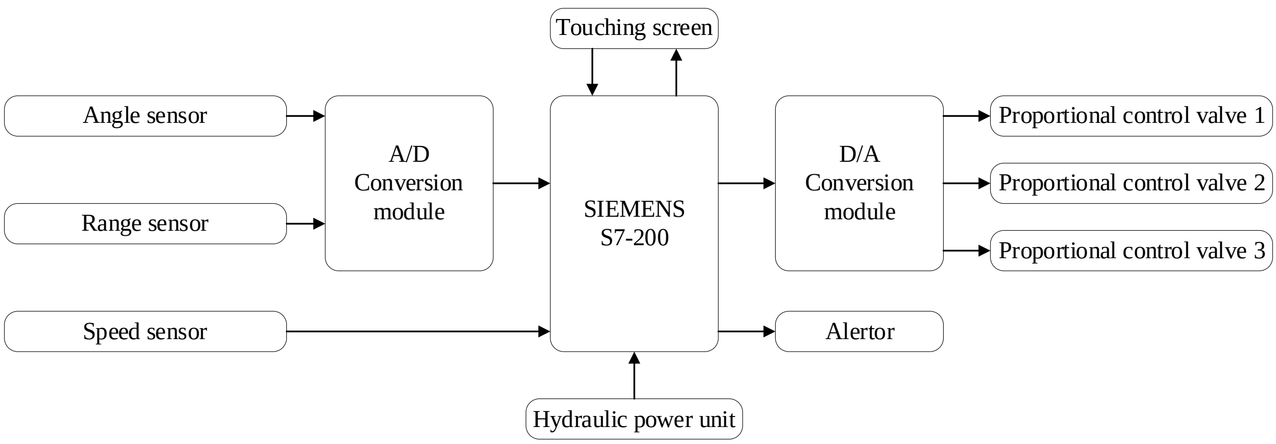

Fig. 5 – Schematic diagram of the control principle

To meet the working requirements of the impurity removal device, the control system for the device was designed. The schematic diagram of the control principle is shown in Fig. 5. It mainly includes detection module, control module, and alarm module.

CBN hydraulic power unit was selected as the power source of the impurity removal device. The speed of the rollers was controlled by BMR-160 hydraulic motor. The distance between two rollers and the inclination angle of the device were controlled by HSG-40 hydraulic cylinder. The main control module of the system was Siemens PLC S7-200. The system hardware was mainly composed of the main controller, TPC7062Ti touching screen, C12-10NO speed sensor, JUB500-30GM-E5-V15 distance sensor, MPU-6050 angle sensor, EFBF-03-160-H proportional control valve, etc. The system controlled the work of each actuator by collecting the rotational speed of the rollers, the distance between two rollers, and the inclination angle of the device.

Experimental design

To obtain the optimal working parameters combination of the impurity removal device, the rotational speed of the rollers, the distance between two rollers, and the inclination angle of the device, which has a great influence on the impurity removal effect, were selected as the test factors, and the influence of the three factors on the performance of the impurity removal device was analyzed. The three factors were adjusted in the following manner:

1. Rotational speed of the rollers: the rotational speed was regulated by the hydraulic motor.
2. Distance between two rollers: the distance was regulated by the distance adjustment device.
3. Inclination angle of the device: the angle was regulated by the hydraulic cylinder.

Fig. 6 – Test prototype

The test contents and methods are as follows. Firstly, the parameter ranges of the rotational speed of the rollers, the distance between two rollers, and the inclination angle of the device were obtained by using single factor tests. Then, the distance between two rollers, and the inclination angle of the device were used as the test factors. And the impurity removal rate and the damage rate were employed as the evaluation indexes. Finally, the orthogonal test of three factors and five levels was carried out.

The test was carried out in Dezhou City, Shandong Province. The test material was the Xisen No. 4 potatoes harvested on the same day. The average diameter of the potatoes was 47.2 mm, the average length was 82.4 mm, the average moisture content was 84.6%, and the average mass was 95.3 g. The test photo is shown in Fig. 6.

Performance evaluation of the impurity removal device

The test indicators were based on the relevant requirements in the Chinese national standards NY/T 648—2015 "Technical Specification for Quality Evaluation of Potato Harvesters"(Wei et al. 2019; Zhang et al. 2020). The selected test response indicators were the impurity removal rate y_1, and damage rate y_2.

The calculation formula is as follows:

$$y_1 = \frac{m_1}{m_1 + M} \times 100\% \tag{1}$$

$$y_2 = \frac{m_2}{m_1} \times 100\% \tag{2}$$

Where:

m_1—is the total potato mass after harvest operation, kg;
M—is the total mass of impurities, kg;
m_2—is the quality of damaged potatoes after harvesting, kg;

RESULTS AND ANALYSIS
Single factor test

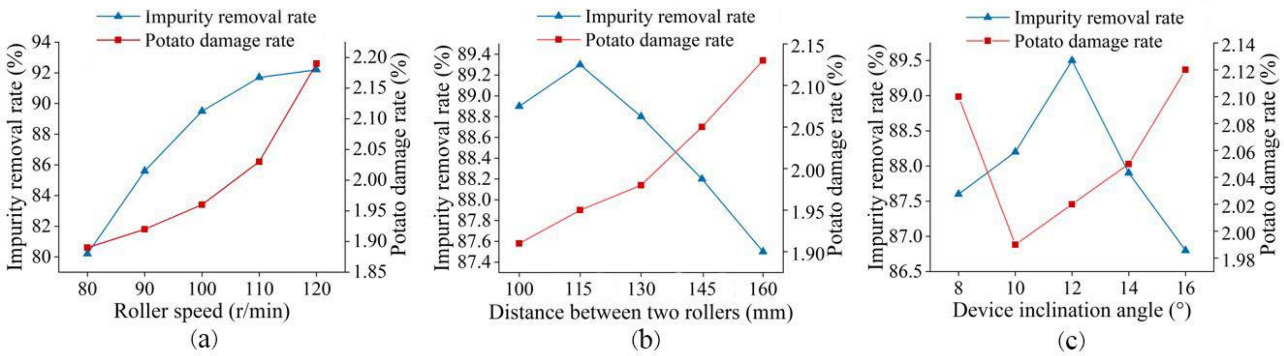

Fig. 7– Impact of rotational speed of the rollers on evaluation indexes

The distance between the two rollers was set to 130 mm; the inclination angle of the device was set to 12°; the rotational speed of the rollers was adjusted to 80, 90, 100, 110, and 120 r/min respectively. It can be seen from Fig. 7a that with the increase of the rotational speed of the rollers, both the impurity removal rate and the damage rate showed an upward trend. When the rotational speed of the rollers reached 110 r/min, the impurity removal rate increased slowly, but the damage rate increased rapidly. Overall, the device worked better when the speed of the rotational speed of the rollers was in the range of 100 to 110 r/min.

The rotational speed of the rollers was set to 100 r/min; the inclination angle of the device was set to 12º; the distance between the two rollers was adjusted to 100, 115, 130, 145, and 160 mm, respectively. It can be seen from Fig. 7b that with the increase of the distance between the two rollers, the impurity removal rate first increased slowly and then decreased rapidly, but the damage rate had been on the rise. When the distance between the two rollers was in the range of 100 to 130 mm, the impurity removal rate was higher than 88%, the damage rate was lower than 2%. It showed that the device works well.

The distance between the two rollers was set to 130 mm; the rotational speed of the impurity removal rollers was 100 r/min; the inclination angle of the device was adjusted to 8, 10, 12, 14, and 16° respectively. As shown in Fig. 7c, when the inclination angle of the device was in the range of 8 to 12°, the impurity removal rate increased with the increase of the inclination angle. When the inclination angle of the device was in the range of 12 to 16°, the impurity removal rate decreased with the increase of the inclination angle of the device, but the damage rate first decreased and then increased. This results in the best overall performance of the device when the inclination angle was 10 to 14°.

Orthogonal experiment results and analysis

Through the single factor test analysis, it was obtained that the range of factors with good performance was that the rotational speed of the rollers was 100 to 110 r/min, the distance between the two rollers was 100 to 130 mm, and the inclination angle of the device was 10 to 14°. The orthogonal test was designed with the ranges obtained by the single factor test. The level of each factor was determined as shown in Table 2.

Table 2

Experimental factors and levels

levels	Factors		
	Rotational speed of the rollers A	Distance between two rollers B	Inclination angle of the device C
	[r/min]	[mm]	[°]
1.68	113.4	140.2	15.4
1	110	130	14
0	105	115	12
-1	100	100	10
-1.68	96.6	89.8	8.6

According to the test scheme, 23 groups of tests were performed, and each group of tests was repeated three times. Take the average value as the test results. And the test results are shown in Table 3.

Table 3

The experiment results

Test number	A	B	C	Impurity removal rate Y_1	Potato damage rate Y_2
	[R/min]	[mm]	[°]	%	%
1	-1	-1	-1	94.21	0.53
2	1	-1	-1	95.94	0.62
3	-1	1	-1	93.95	0.49
4	1	1	-1	96.35	0.95
5	-1	-1	1	95.43	0.74
6	1	-1	1	96.32	1.08
7	-1	1	1	94.71	0.85
8	1	1	1	97.02	1.25
9	-1.68	0	0	94.21	0.53
10	1.68	0	0	96.47	0.84
11	0	-1.68	0	96.13	0.72
12	0	1.68	0	95.28	1.03
13	0	0	-1.68	94.57	0.56
14	0	0	1.68	95.28	1.03
15	0	0	0	96.47	0.97
16	0	0	0	96.41	1.03
17	0	0	0	95.68	1.08
18	0	0	0	95.83	1.01
19	0	0	0	96.24	0.96
20	0	0	0	96.02	0.97
21	0	0	0	96.35	1.02
22	0	0	0	96.41	0.94
23	0	0	0	96.52	1.07

Variance analysis

Analysis of variance (ANOVA) was performed using Design Export 10.0 for the impurity removal rate and damage rate, and the results are shown in Tables 4-5. It can be seen from the two tables that the model terms are all significant (P < 0.01), and the lack of fit terms is not significant (P > 0.1). This indicates that the regression equation fits well and can represent the mathematical relationship between the three factors and the two response indicators.

Table4

Variance analysis results of impurity removal rate

Source	Sum of Squares	DF	Mean Square	F Value	P Value
Model	15.17	9	1.69	14.77	<0.0001**
A	9.07	1	9.07	79.48	<0.0001**
B	0.12	1	0.12	1.08	0.3169
C	1.31	1	1.31	11.45	0.0049**
AB	0.55	1	0.55	4.78	0.0476*
AC	0.11	1	0.11	0.95	0.3482
BC	0.004	1	0.004	0.032	0.8615
A^2	1.10	1	1.19	9.64	0.0084**
B^2	0.29	1	0.29	2.50	0.1377
C^2	2.67	1	2.67	23.38	0.003**
Residual	1.48	13	0.11		
Lack of Fit	0.76	5	0.15	1.67	0.2464
Pure Error	0.73	8	0.091		
Cor Total	16.66	22			

*Note: P < 0.01 (extremely significant, **), 0.01 <P < 0.05 (significant, *).*

It can be seen from Table 4 that A, C, A^2 and C^2 have extremely significant effects on the impurity removal rate (P<0.01), and AB has a significant effect on the impurity removal rate (0.01<P<0.05).

Other factors had no significant effect on the impurity removal rate (P>0.1). After removing insignificant terms, the fitted regression equation is:

$$y_1 = 96.13 + 0.82A + 0.31C + 0.26AB - 0.26A^2 - 0.41C^2 \quad (3)$$

Table5

Variance analysis results of damage rate

Source	Sum of Squares	DF	Mean Square	F Value	P Value
Model	0.92	9	0.10	22.06	<0.0001**
A	0.24	1	0.24	51.66	<0.0001**
B	0.065	1	0.065	13.91	0.0025**
C	0.33	1	0.33	70.79	<0.0001**
AB	0.023	1	0.023	4.97	0.0441*
AC	0.004	1	0.004	0.97	0.3426
BC	1.25×10^{-5}	1	1.25×10^{-5}	2.68×10^{-3}	0.9594
A^2	0.16	1	0.16	35.06	<0.0001**
B^2	0.040	1	0.040	8.55	0.0118*
C^2	0.062	1	0.062	13.31	0.0029**
Residual	0.060	13	4.65×10^{-3}		
Lack of Fit	0.041	5	8.2×10^{-3}	3.38	0.0617
Pure Error	0.019	8	2.42×10^{-3}		
Cor Total	0.98	22			

*Note: P < 0.01 (extremely significant, **), 0.01 <P < 0.05 (significant, *)*

It can be seen from Table 5 that A, B, C, A^2 and C^2 have extremely significant effects on the damage rate (P<0.01), and B^2、AB have a significant effect on the damage rate (0.01<P<0.05). Other factors had no significant effect on the damage rate (P>0.1). After removing insignificant terms, the fitted regression equation is:

$$y_2 = 1 + 0.13A + 0.069B + 0.16C + 0.054AB - 0.1A^2 - 0.05B^2 - 0.062C^2 \quad (4)$$

Response surface analysis

Response surface analysis of impurity removal rate

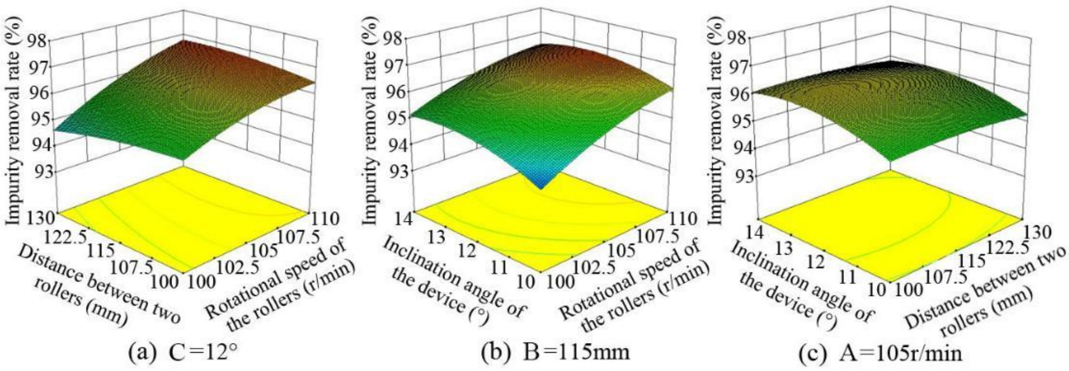

Fig. 8 – Response surface of impurity removal rate

As shown in Fig. 8a, when the inclination angle of the device was 12°, the impurity removal rate decreased with the increase of the distance between two rollers and increased with the increase of the rotational speed of the rollers. As shown in Fig. 8b, when the distance between the two rollers was 115 mm, the impurity removal rate increased with the increase of the inclination angle of the device. However, the impurity removal rate increased and then decreased slowly with the rotational speed of the rollers. As shown in Fig. 8c, when the rotational speed of the rollers was 105 r/min, the impurity removal rate first increased and then decreased slowly with the increase of the inclination angle of the device and the distance between the two rollers.

The overall influence trend of the experimental factors on impurity removal rate was as follows: when the distance between the two rollers and the inclination angle of the device were moderate and the rotational speed of the rollers was high, the impurity removal rate was high. When the distance between the two rollers is larger or smaller, the contact area between the surface of the potatoes and the impurity removal rollers will be reduced, resulting in a decrease in the impurity removal rate. When the rotational speed of the impurity removal roller increases, the number of contacts between the potatoes and the impurity removal rollers increases, so that impurities can be effectively removed.

Response surface analysis of damage rate

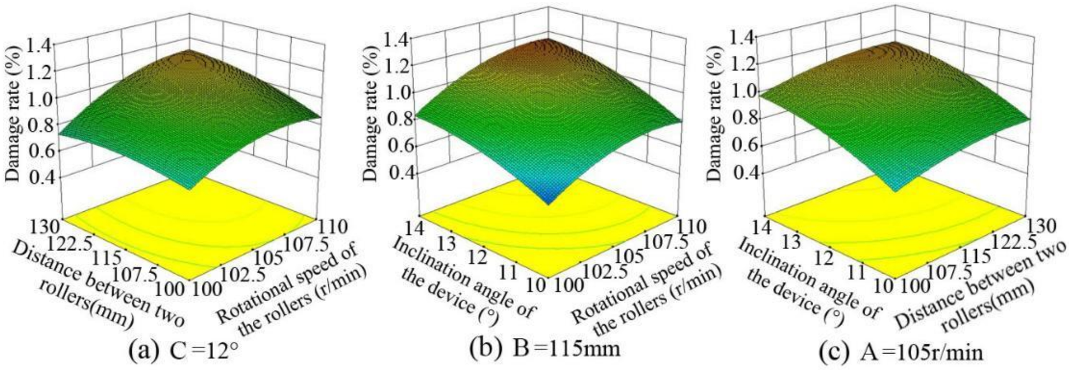

Fig. 9 – Response surface of damage rate

As shown in Fig. 9a, when the inclination angle of the device was 12°, the damage rate first increased and then decreased slowly with the increase of the distance between the two rollers. But the damage rate increased with the increase of the rotational speed of the rollers. As shown in Fig. 9b, when the distance between the two rollers was 115 mm, the damage rate increased with the increase of the device inclination angle and the rotational speed of the rollers. As shown in Fig. 9c, when the rotational speed of the rollers was 105 r/min, the damage rate increased with the increase of the inclination angle of the device and the distance between the two rollers.

The overall influence trend of the experimental factors on damage rate was as follows: when the distance between the two rollers was moderate and the rotational speed of the rollers and the inclination angle of the device were large, the damage rate was high. The main reason is that when the distance between the two rollers is larger or smaller, the number of collisions between the potatoes and the impurity removal rollers will be reduced, resulting in a lower damage rate. And when the speed of the impurity removal rollers increases, the number of collisions between the potato and the impurity removal roller will be increased, resulting in a higher damage rate. In addition, when the inclination angle of the device increases, the height of the potatoes falling to the next-level impurity removal roller will increase, thereby increasing the contact force with the impurity removal roller, resulting in an increase in the damage rate.

Parameter optimization and validation

To obtain the best working parameters of the impurity removal device for potato combine harvester, taking the maximum impurity removal rate and the minimum damage rate as the optimization objectives, the optimization module in Design-Export 10.0.3 was used to solve the optimal parameters.

The objective function and constraints conditions are as follows:

$$\begin{cases} \max\ y_1(A,B,C) \\ \min\ y_2(A,B,C) \\ s.t. \begin{cases} 96.6r/\min < A < 113.4r/\min \\ 89.8mm < B < 140.2mm \\ 8.6° < C < 15.4° \end{cases} \end{cases} \tag{5}$$

After optimization calculation, the optimal working parameters were obtained as follows: the rotational speed of the rollers was 113.4 r/min, the distance between two rollers was 97.5 mm and the inclination angle of the device was 10.4°. The predicted value of impurity removal rate was 95.85%, and the predicted value of damage rate was 0.49%.

Five replicate experiments were carried out with the above optimization parameters, and the test results were averaged. The results showed that the impurity removal rate was 95.12%, and the damage rate was 0.54%, which was consistent with the prediction results of the model, and the prediction errors were less than 3%.

CONCLUSIONS

1. A new type of impurity removal device for potato combine harvester was designed in this study. The device adopted the form of an alternate arrangement of impurity removal rollers and smooth rollers, which can effectively remove impurities and reduce the damage rate of potatoes.

2. To determine the best working parameters of the device, the second rotation orthogonal regression test was carried out with the rotational speed of the rollers, the distance between two rollers, and the inclination angle of the device as the test factors. Furthermore, the impurity removal rate and damage rate are employed as evaluation indexes. Through the response surface analysis of the impurity removal rate and damage rate, the influence of three factors on the two response indicators was obtained.

3. The best working parameters were obtained taking the maximum impurity removal rate and the minimum damage rate as the optimization objectives. The optimal parameters obtained were as follows: the rotational speed of the rollers was 113.4 r/min, the distance between two rollers was 97.5 mm and the inclination angle of the device was 10.4°. At this time, the impurity removal rate was 95.85% and the damage rate was 0.49%. The results of the verification test showed that the relative error between the measured value and the predicted value was less than 3%, which indicates that the regression model was reliable.

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