DESIGN AND TESTING A CORN COMBINE HARVESTER HEADER FOR HILLS AND MOUNTAINS

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A number of problems exist for corn combine harvesters used in hills and mountains, among which the high rate of cob losing and the low quality of stalk shredding can be mentioned. This paper aims at designing a header to improve the performance of combine harvesters used in hills and mountains. To determine the optimal design parameters of the proposed header, the orthogonal combination experiment of secondary rotation was carried out. Accordingly, while the ear loss rate and qualified rate of the shredding stalk were used as the evaluation indexes, the forward speed, rotation speed and diameter of the picking roller as well as the rotation speed of the cutter shaft were considered as the influencing factors. The results revealed the order of the influencing factors on the ear loss rate as the diameter of picking roller > rotation speed of picking roller > forward speed > rotation speed of cutter shaft. In addition, the order of the influencing factors on the qualified rate of shredding stalk was found to be as the rotation speed of cutter shaft > forward speed > diameter of picking roller > rotation speed of picking roller. Moreover, after carrying out the parameter optimization, the optimum combination was established. Accordingly, the forward speed of the machine, the rotation speed of the picking roller, the diameter of the picking roller, and rotation speed of cutter shaft were determined to be 4.2 km/h, 1450 r/min, 84 mm and 1980 r/min, respectively. Finally, to evaluate the optimum parameter combination, a test was carried out, the results of which revealed the values of 3.26% and 91.10% for the ear loss rate and the qualified rate of shredding stalk, respectively. Hence, as the obtained values were consistent with the predicted results, the design requirements were fulfilled.

Keywords: agricultural machinery, hills and mountains, header, optimization, harvesting header, stalk shredding device

1. Introduction

Corn is one of the three major food crops in China. Accordingly, a planting area of about 4×10^7 hm^2 was allocated to grow this crop in 2022. Moreover, a significant area of hills and mountains, i.e., 1.2×10^7 hm^2, is allocated to planting corn in the country [1]. However, compared with fields and plains, the

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level of mechanization of harvesting corn is far less in hills and mountains [2]. Therefore, improving the level of mechanization of harvesting corn in hills and mountains is of particular importance.

Numerus studies have investigated corn combine harvesters. For example, to design a harvester, the biological characteristics of maize and a model of its mechanical properties have been used by a number of researchers [3]. Yet, other scholars have experimentally applied statistical methods to study such influencing factors as the biological characteristics of corn, its moisture content during harvest, the growth environment and specific parameters of mechanism. Moreover, to analyze, design and improve the working device of the harvester based on the experimental data, the loss rate, impurity content and stalk shredding quality have been considered as the measurement indicators [4-10]. In the majority of mature corn combine harvesters, the principle of horizontal roll ear picking is adopted, and, as a result, the corn stalk is returned to the field [11, 12]. For example, the ear picking mechanism of German corn harvester adopts various forms of stem pulling structure, cancels the field returning machine at the rear part, reduces the engine load, releases the engine power, and makes the header to hold stronger driving power [13].

However, previous studies have mainly investigated the common combine harvester, whose actual working environment is significantly different from that of the hills and mountains. Hence, designing a corn combine harvester, particularly for hills and mountains, is of considerable need and importance.

2. Design of a corn combine harvester header

2.1 Structure and the working principle

The header of a corn harvester is one of its most critical components. More precisely, it determines whether the subsequent parts of the whole harvest process can proceed smoothly [14, 15]. Accordingly, the functional characteristics of hilly and mountainous areas need to be considered when designing the header.

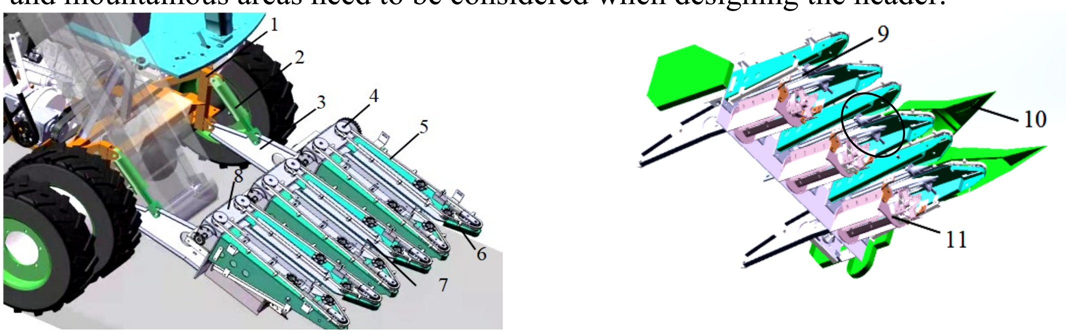


Fig. 1. Overall structure of the header of a corn combine harvester
1. Frame; 2. Hydraulic cylinder; 3. Installing frame of picking platform; 4. Pushing wheel; 5. Poking chain; 6. Reel tooth; 7. Picking plate; 8. Gear box; 9. Picking roller; 10. Splitting device; 11. Stalk chopping device

Fig.1 displays the overall plan of a header. In addition, regarding mountainous areas, Table 1 shows the main performance parameters of the 4YZ-3 corn harvester.

Table 1

Main performance parameters of 4YZ-3 corn combine machine

Performance parameter	Numerical value
Structure	Self- propelled
Engine type	4G33V16
Rated power of engine/KW	88.2
Rated speed of engine/($r\cdot min^{-1}$)	2400
Type of drive	4WD
Size(L×W×H)/(mm×mm×mm)	6445x2700x2900
Vehicle quality/kg	5200
Number of rows	4
Working width /mm	2480
Minimum ground clearance/mm	260
Operational speed/($km\cdot h^{-1}$)	1.4-4.5
Productivity/($hm^{2}\cdot h^{-1}$)	0.36-0.7
Form of stem shredding	Chopped type

2.1.1 Design of ear picking platform lifting hydraulic cylinder

The lifting movement of the ear picking platform is controlled by hydraulic system. So, when the load of the hydraulic cylinder exceeds a certain level, accessories in small size and good stability need to be selected [16]. The installing frame of the ear picking connects the main body of the corn harvester to the header. The header weighs about 800 kg. While one end of the installing frame of the ear picking rotates around the main body, the other end installs the header. The structure of the ear picking is shown in Fig.2.

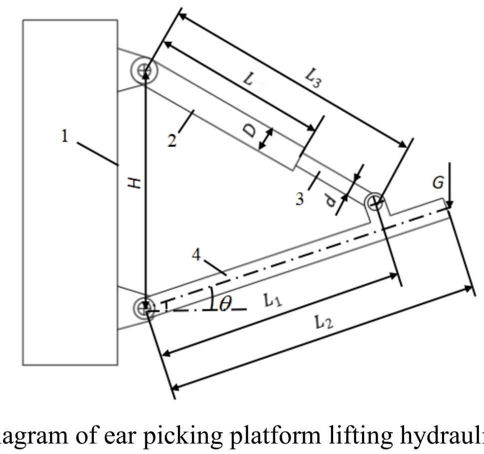


Fig. 2. Schematic diagram of ear picking platform lifting hydraulic cylinder parameters
1. Harvester's main frame; 2. Hydraulic cylinder platform; 3. Piston rod; 4. Installing frame

The height difference (H) between the two fixed ends, the length of the installing frame (L_2), and the distance between the two hinged seats on the installing frame are 386 mm, 510 mm, and 385 mm, respectively. With the expansion of the hydraulic cylinder, the angle, around the fixed end of which the ear picking stage can rotate is about 20°.The hydraulic cylinder dimensions can be calculated using the following formula:

$$D = 1.13\sqrt{\frac{F}{p}} \tag{1}$$

$$d = 0.5D \tag{2}$$

$$\delta = \frac{1}{10}D \tag{3}$$

Where *D* denotes the diameter of hydraulic cylinder block, *d* stands for the diameter of piston rod and *δ* represents the thickness of cylinder wall, all in mm.

The working pressure of the hydraulic cylinder is selected as 1.5 MPa. Moreover, according to the stress analysis and trigonometric function relationship, the hydraulic cylinder can bear the maximum load when positioned horizontally, i.e., 7840 N. Calculations demonstrated that the diameter and the wall thickness of the hydraulic cylinder, as well as the diameter of the piston rod were not less than 81.7 mm, 8.17 mm and 40.8 mm, respectively. In addition, using SolidWorks Motion to simulate the movement process, the length of the hydraulic cylinder was found not to be less than 265 mm.

2.1.2 Design of ear picking device

As the key parts of the header, as shown in Fig.3, every ear picking device has a pair of longitudinal picking rollers, two straw cutters used with the rollers, two picking plates and two ring transport chains.

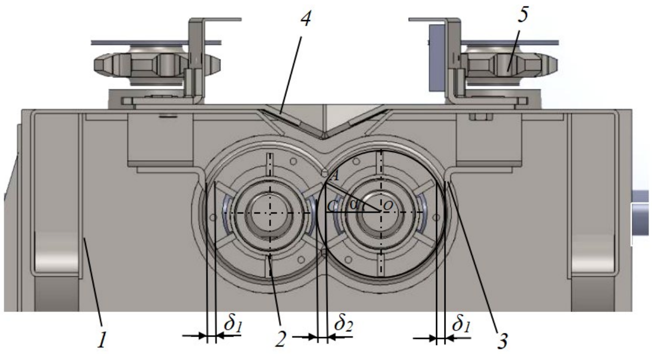


Fig. 3. Structure diagram of the picking device
1. Picking rack; 2. Picking roller; 3.Grass cutter; 4.Picking plate; 5 Pushing stem chain

To avoid poor stem passing ability and squeezing maize during the process of picking, the working process of picking roller was analyzed. To grasp the stem, the starting grasping angle (α) of the picking roller should not be too large. This is calculated as follows:

$$\cos\alpha = \frac{OC}{OA} = 1 - \frac{d - \delta_2}{D_l} \tag{4}$$

Where d stands for the maximum diameter of corn stalk, δ_2 denotes the gap of picking roller, and D_l represents the diameter of picking roller, all in mm.

Due to the friction coefficient between the pulling roller and the stalk $f_0 \geq \tan\alpha$ and $\cos\alpha = \frac{1}{\sqrt{1+\tan^2\alpha}}$,

$$D_l \geq \frac{d - \delta_2}{1 - \frac{1}{\sqrt{1+f_0^2}}} \tag{5}$$

To reduce damage and loss, the diameter of the picking roller was corrected in accordance to the conditions where the corn is not grasped by the picking roller,

$$D_l < \frac{d_{g\min} - \delta_{2\max}}{1 - \frac{1}{\sqrt{1+f_g^2}}} \tag{6}$$

Where d_{gmin} stands for the minimum diameter of the large end of the corn in mm, δ_{2max} denotes the maximum gap between two picking rollers in mm, and f_g represents the scraping coefficient.

For the picking roller made from cast iron, f_g=0.7~1.1 [17]. Applying the formula, the range of the picking roller's diameter is obtained between 60 to 100 mm. Furthermore, the gap between the two picking rollers is generally δ_1= (0.1~0.4) d. Considering hilly corn harvesters, Stem thin, low water content, The gap of picking roller is adjusted smaller, The stem be pulled in the middle of the stem roller is preferred. In order to prevent the entanglement of weeds in the picking roller, the gap between the grass cutter and the picking roller should be kept in 4~6 mm.

The grasping ability of the stalk is greatly influenced by the speed of the picking roller. This is to say that while the high speed of the picking roller can lead the maize to easily fall, its low speed can easily cause the stalk to be accumulated and blocked in the shredding mechanism.

The rotation speed of the picking roller can be calculated using the following formula:

$$n_l = \frac{60v_l}{\pi D_l} \tag{7}$$

Where v_l denotes the linear velocity of picking roller in m/s and

n_l represents its rotation speed in r/min.

Furthermore, the rotation speed of picking roller generally adopts the following data:

$$K = \frac{v_m}{v_l \sin \beta_0} = 0.7 \sim 1 \tag{8}$$

where:

v_m is the running speed of harvester in m/s and β_0 suggests the roll Angle,° .

In addition, while the working velocity of corn harvester is 1.4~4.5 km/h in a mountainous area [18], the circumferential velocity of picking roller is 3-4 m /s.

2.1.3 Design of the Stem shredding device

The stem shredding device is composed of a cutting and a shredding mechanism. As shown in Fig. 5, the former consists of cutting blades, grass cutting blades and tool holders. Four cutting blades are evenly distributed around the tool rest. Fig. 6 displays the size of the blade. Moreover, the blade is made of a 65Mn steel, the wear resistance of which is improved by a heat treatment such as quenching. To ensure the adequate sharpness of the blades in the cutting process, the thickness of 4 mm is determined. Accordingly, the corn stalks are cut off and enter the cutting table from the root. Fig. 7 displays the size of the cutting blade (with the thickness of 3.5 mm) which is located at the front part. The function of the blade is cutting the weeds on the ground, preventing them from being entangled and cutting the blade from affecting the operation effects.

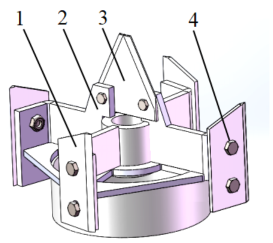


Fig. 5. Structure of the cutting mechanism
1. Cutting blade; 2. Knife rest; 3. Grass cutting blade; 4. Bolt

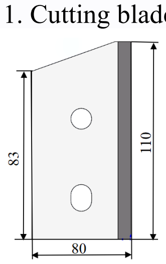


Fig. 6. Cutting blade

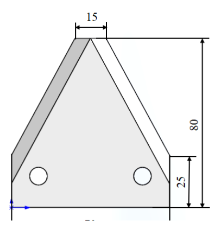


Fig. 7. Grass cutting blade

The shredding mechanism is essential for shredding and crushing the stalks. Being installed behind the cutting mechanism, the two mechanisms rotate in the same direction and at the same speed. As can be seen in Fig. 8, the mechanism is composed of the moving and the fixed blades, spindle, tool holder, etc. Moreover, as shown in Fig. 9, three fixed star frames are designed on the spindle. Around the planetary frame, the area of the six moving blades is evenly divided. Based on the kind of positions, either two, three or six blades are installed. To have a simple structure, processed and low power consumption at work, the moving blade adopts straight knife type. The size of the blade is shown in Fig.10.

To ensure the required stiffness and shredding reliability of the blade, the straight knife is made from a 65Mn steel, with the thickness of 10 mm, and the blade Angle of 40°.

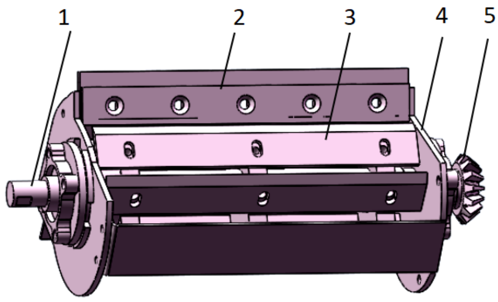
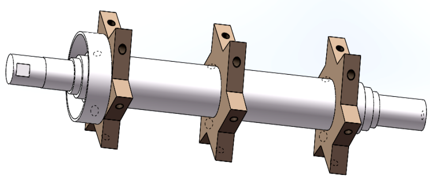


Fig. 8. Structure of shredding mechanism
1. Spindle; 2. Fixed blade; 3. Shredding blade; 4. Knife rest; 5. Bevel gears



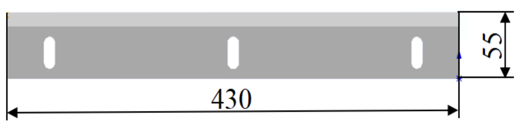


Fig. 9. The spindle of shredding device

Fig.10. The blade of shredding mechanism

2.2 Experiment design

Based on the analysis of the obtained data, the range of the machine's forward speed was determined as 3-5 km/h. Furthermore, the rotation speed of the picking roller, the diameter of the picking roller, and the spindle speed of shredding device were determined as 1200-1600 r/min, 60-100 mm, and 1900-2300 r/min, respectively. Each set of tests was repeated for three times.

Subsequently, the average value of the test results was considered [19]. Table 2 demonstrates the test factors as well as the test levels.

Table 2

Factors and levels

Level	Forward speed of machine x_1/ (km·h^{-1})	Rotation speed of Picking roller x_2/ (r·min^{-1})	Diameter of picking roller x_3/ (mm)	Spindle speed of shredding device X_4/ (r·min^{-1})
+2	5	1600	100	2300
+1	4.5	1500	90	2200
0	4	1400	80	2100
-1	3.5	1300	70	2000
-2	3	1200	60	1900

2.3 Performance evaluation

According to the test method specified in GB/T 21962-2020 and GB/T 24675.6-2009, the performance of the harvester was evaluated based on the calculation of the ear loss rate as well as the qualified rate of stalk shredding using the following formulas:

$$Z_1 = \frac{W_1}{W_2} \times 100\% \tag{9}$$

$$F_1 = \frac{M_z - M_b}{M_z} \times 100 \tag{10}$$

where:

Z_1 is the ear loss rate, in percentage, W_1 denotes the grain mass of landing ear in kg, W_2 stands for the total grain mass of measurement area in kg, F_1 represents the qualified rate of stem crushing length in percentage, M_Z signifies the mass of stem before crushing in kg and M_b suggests the mass of stem with the length of greater than 100 mm in kg.

3 Results

3.1 Test results and analysis

According to the test plan, 30 groups of tests were taken, each of which was repeated for three times. While the average values were taken as the test results, the indexes were calculated using formulas (9) and (10). The obtained results are shown in Table 3.

Table 3

Test design and results

Test No.	Forward speed of Machine X_1	Rotation speed of Picking roller X_2	Diameter of Picking roller X_3	Spindle speed of shredding device X_4	Ear loss Rate Y/%	Qualified rate of shredding stalk Y/%
1	-1	-1	-1	-1	3.4	86.5
2	1	-1	-1	-1	4.8	89.8
3	-1	1	-1	-1	6.0	87
4	1	1	-1	-1	3.5	89.5
5	-1	-1	1	-1	5.4	88.6
6	1	-1	1	-1	5.9	90.6
7	-1	1	1	-1	3.1	89.4
8	1	1	1	-1	4.5	91.3
9	-1	-1	-1	1	5.8	85.7
10	1	-1	-1	1	4.0	86.5
11	-1	1	-1	1	5.5	86.7
12	1	1	-1	1	5.2	85.9
13	-1	-1	1	1	4.3	84.2
14	1	-1	1	1	5.4	85.7
15	-1	1	1	1	3.6	83.6
16	1	1	1	1	2.4	84.8
17	-2	0	0	0	4.1	90.2
18	+2	0	0	0	7.6	91.8
19	0	-2	0	0	3.3	85.6
20	0	+2	0	0	2.2	86.7
21	0	0	-2	0	10.6	80.5
22	0	0	+2	0	8.3	81.7
23	0	0	0	-2	3.5	86.9
24	0	0	0	+2	2.3	88.4
25	0	0	0	0	4.5	85.1
26	0	0	0	0	3.4	88.5
27	0	0	0	0	3.1	85.7
28	0	0	0	0	4.1	86.3
29	0	0	0	0	4.6	87.5
30	0	0	0	0	5.4	90.4

3.2 Analysis of variance and the regression model

The obtained results (Table 1) were analyzed using Design-export 8.0.6 software. The regression models of Y1 and Y2 were obtained using formulas (11) and (12). The analysis of the variance indicates that while the two models were significant ($P<0.01$), the lack of fit was not ($P>0.05$). Accordingly, it can be argued that the influencing factors on the ear loss rate can be ordered as: the diameter of picking roller>rotation speed of picking roller>forward speed>spindle speed of shredding device. Moreover, the influencing factors on the qualified rate of shredding stalk can be ordered as: the spindle speed of shredding device>forward speed >diameter of picking roller>rotation speed of picking roller.

$$Y_1 = 4.18 + 0.23x_1 - 0.31x_2 - 0.34x_3 + 0.31x_1x_3 - 0.6x_2x_3 - 0.37x_3x_4 + 0.03x_1^2 + 0.47x_2^2 + 1.2x_3^2 - 0.44x_4^2 \quad (11)$$

$$Y_2 = 87.25 + 0.65x_1 - 1.11x_4 - 0.44x_1x_4 - 0.85x_3x_4 + 1.06x_1^2 - 1.41x_3^2 + 0.23x_4^2 \quad (12)$$

Where X_1 denotes the forward speed of the machine in km·h^{-1}, X_2 stands for the rotation speed of the picking roller in r.min^{-1}, X_3 represents the diameter of the picking roller in mm and X_4 signifies the spindle speed of the shredding device.

Table 4

Variance analysis table of loss rate

Sources	Squares	FD	MS	F value	P value	Sources	Squares	FD	MS	F value	P value
Model1	79.01	14	5.64	4.94	0.002	Model2	158.03	14	11.29	3.21	0.0159
X_1	1.31	1	1.31	1.14	0.3018	X_1	10.14	1	10.14	2.89	0.1100
X_2	2.28	1	2.28	2.0	0.1780	X_2	0.33	1	0.33	0.093	0.7646
X_3	2.80	1	2.8	2.45	0.1382	X_3	0.38	1	0.38	0.11	0.7484
X_4	0.33	1	0.33	0.29	0.6007	X_4	29.48	1	29.48	8.39	0.0111
X_1X_2	0.90	1	0.9	0.79	0.3882	X_1X_2	0.49	1	0.49	0.14	0.7140
X_1X_3	1.56	1	1.56	1.37	0.2605	X_1X_3	0.04	1	0.04	0.011	0.9164
X_1X_4	0.56	1	0.56	0.49	0.4937	X_1X_4	3.06	1	3.06	0.87	0.3653
X_2X_3	5.76	1	5.76	5.04	0.0403	X_2X_3	0.022	1	0.022	0.006	0.9373
X_2X_4	0.01	1	0.01	0.008	0.9267	X_2X_4	0.49	1	0.49	0.14	0.7140
X_3X_4	2.25	1	2.25	1.97	0.1809	X_3X_4	11.56	1	11.56	3.29	0.0897
X_1^2	2.5	1	2.5	2.19	0.1596	X_1^2	31.09	1	31.09	8.85	0.0094
X_2^2	6.13	1	6.13	5.37	0.0351	X_2^2	0.60	1	0.60	0.17	0.6852
X_3^2	39.63	1	39.63	34.69	<0.0001	X_3^2	54.56	1	54.56	15.53	0.0013
X_4^2	5.20	1	5.2	4.55	0.0498	X_4^2	1.41	1	1.41	0.40	0.5353
Residual	17.14	15	.14			Residual	52.7	15	3.51		
Lack of Fit	13.59	10	1.36	1.92	0.2452	Lack of Fit	33.22	10	3.32	0.85	0.61
Pure Error	3.55	5	.71			Pure Error	19.48	5	3.9		
Cor Total	96.15	29				Cor Total	210.73	29			

3.3 Analysis of the influence of the interaction factors on ear losing rate

Fig. 11a-11c display the response surfaces of the picking roller's diameter, its rotation speed and the spindle speed of the shredding device with the rate of ear loss. As can be seen in Fig. 11a, when the rotation speed of the picking roller was 1400r/min and the Spindle speed of shredding device was 2100r/min, an increase in the diameter of the former led to first an increase and then a decrease in the rate of ear loss. On the other hand, when the diameter of the picking roller remained constant, the rate of ear lose increased slowly when the forward speed of the machine increased (Fig. 11b). Yet, the forward speed of 4km/h of the machine and the rotation speed of 1400r/min of the picking roller led to first an increase and then a decrease in the rate of ear loss, when the Spindle speed of shredding device increased (Fig. 11c).

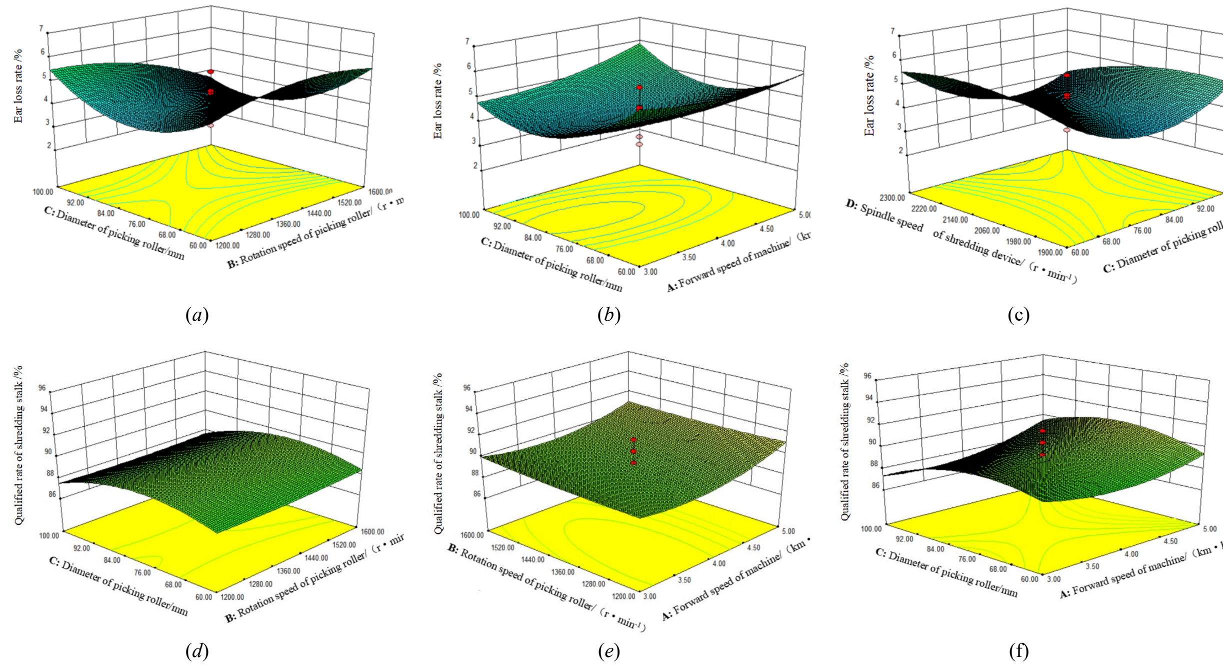


Fig. 11. Response surface of double parameters about experiment index of corn combine harvester for hills and mountains

3.4 Analysis of the influences of the interaction factors on quality of stalk shredding

Fig. 11d-11f show the response surface of the picking roller's diameter, its rotation speed and the forward speed of the machine with quality of stalk shredding. As can be seen in Fig. 11d, when the forward speed of the machine was 4km/h and the Spindle speed of shredding device was 2100r/min, an increase in the rotation speed of the picking roller led to a slow increase in the quality of the stalk shredding. On the other hand, when the rotation speed of the picking roller remained constant, increasing the forward speed of the machine led to first a decrease and then an increase in the quality of the stalk shredding (Fig. 11e). However, when the forward speed of the machine remained constant, with increasing the diameter of picking roller, the quality of stalk shredding first increased and then decreased (Fig. 11f).

3.5 Parameter optimization and validation

To get the optimal design parameters of corn combine harvester header, the regression equation was further solved by using Design-export 8.0.6 software. The objective function and constraints are as follows:

$$\begin{cases} \min Y_1(x_1, x_2, x_3, x_4) \\ \max Y_2(x_1, x_2, x_3, x_4) \\ \text{s.t.} \begin{cases} 4.0 \le x_1 \le 4.2 \\ 1350 \le x_2 \le 1450 \\ 84 \le x_3 \le 90 \\ 1980 \le x_4 \le 2060 \end{cases} \end{cases} \tag{13}$$

Establishing the optimum parameter combination of the header of the corn combine harvester, the forward speed of the machine, the rotation speed of the picking roller, the diameter of the picking roller, and the Spindle speed of the shredding device were determined as 4.2 km/h, 1450 r/min, 84 mm, and 1980r/min, respectively. In addition, the predicted values of the ear loss rate and the qualified rate of the shredding stalk were found as 3.33% and 90.30%, respectively. To confirm the reliability of the predicted values, a validation test was taken, the results of which revealed the ear loss rate of 3.26% and the qualified rate of the shredding stalk of 91.10%. Finally, since the prediction error was less than 2%, the reliability and practicality of the prediction model proposed in the present study were confirmed.

4. Conclusions

(1) In the present project, a corn combine harvester header to be utilized in hills and mountains was innovatively designed. To ensure the rationality and reliability of the header, the design parameters of the proposed corn combine harvester header were studied and analyzed.

(2) The regression models of the ear loss rate and the qualified rate of shredding stalk were set up. Moreover, the primary and secondary factors affecting the performance indexes of the header were determined. The results revealed the order of the influencing factors on the ear loss rate as: the diameter of picking roller>rotation speed of picking roller>forward speed> spindle speed of shredding device. Furthermore, the order of the influencing factors on the qualified of shredding stalk was as: the spindle speed of shredding device>forward speed >diameter of picking roller>rotation speed of picking roller.

(3) After carrying out the parameter optimization, the optimum combination was obtained. Accordingly, the forward speed of the machine, the rotation speed of the picking roller, the diameter of the picking roller, and the Spindle speed of the shredding device were determined as 4.2 km/h, 1450r/min,

84 mm and 1980 r/min, respectively. In addition, based on the optimum parameter combination, a test was taken, the results of which revealed the values of 3.33% and 90.30% for the rate of ear loss and the qualified rate of shredding stalk, respectively. Hence, since the obtained results were coherence with the optimization results, the reliability of the regression model is proved.

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