Experiments and modeling of mechanism analysis of maize picking loss

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Abstract: Maize picking is the main form of maize harvest in China. Maize picking loss accounts for a large proportion of the current maize harvest loss. An experimental study and a theoretical analysis were conducted to explore the influencing factors and rules of maize picking loss. First, the boundary conditions, established by analyzing the mechanism of maize picking, determined the influences of maize picking loss. Then, single-factor experiments and a central composite design (CCD) method were used to determine the influence of various factors and their interactions on maize picking loss. Finally, the models of kernel loss and ear loss were set up to determine the optimal parameter combination of maize picking harvest. Field experiment verification was conducted. The results indicated that the optimal parameters of the maize picking harvest were the rotational speed of pulling rollers of 1120 r/min, operating speed of 1.94 m/s, the inclination of the header of 18° and clearance between the picking plates of 30 mm. By establishing these optimal parameters, the kernel loss rate was 0.065%, and the ear loss rate was 0%. The obtained experimental results and regression models could be used to predict the performance of the maize picking harvest, guide the adjustment of header working parameters, and provide a theoretical basis for reducing the mechanical loss of maize harvesting.

Keywords: maize picking harvest, kernel loss rate, ear loss rate, maize picking platform, response surface analysis

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1 Introduction

Maize is the primary animal feed grain and serves as critical feedstock for a multitude of food and industrial products including starch, sweeteners, ethanol, etc[1]. In 2016, the comprehensive mechanization rate of maize cultivation and harvesting in China was 83.08%. Among them, the machine tillage rate was 94.81%, the machine seeding rate was 83.85%, and the machine yield showed a low efficiency with only 66.68%[2,3]. In 2017, the Chinese maize planting area and total production were the second in the world, with 42.399 million hm^2 and 259.0707 million t respectively, and mechanized maize harvesting in China reached 69% at the end of 2017[4,5]. The maize harvester must be promoted for the good development of maize cultivation, sufficient supply of maize for industry animal husbandry and daily consumption for people, and Chinese food security[6]. Besides, good-quality maize is also essential for the processing and feed industries[7]. The various models of maize cultivation and maize varieties and the different plant spacing in China, however, cause the adaptation between agricultural machinery and agronomy, and it is difficult to popularize mechanized maize harvest. There were still some problems such as high maize harvest loss rate, low stability, and poor adaptability of the maize harvester[8].

Currently, maize picking is still the main method of maize harvest in China[9-11]. The main source of the total loss in the operation of the maize combined harvester is the loss of ear and kernel falling, directly caused by ear loss and ear damage. In 2017, the Shandong Academy of agricultural machinery science measured the total loss rate, header loss rate and kernel loss rate of 13 maize varieties by ear harvest, and grain harvest, respectively. The experimental results showed that the header loss rates accounted for 75.28% (ear harvest) and 54.53% (grain harvest) of the total loss rates which were the main components of the loss[2]. Maize loss and damage levels in any given situation will depend on machine design, adjustment, and operation, field conditions, weather, and crop morphological, physical and mechanical properties[12-14]. The performance of maize picking mechanisms directly affects the harvesting quality and working efficiency[15]. This research focuses on improving its working performance to realize the mechanization of the maize harvest.

Regarding research on the loss of maize harvest, domestic and foreign scholars mostly explored the mechanical properties of maize and how to optimize the working parameters of the maize harvester during experiments. The impact experiment and mechanical property analysis of maize were conducted to study the mechanical damage mechanism of maize, which analyzed the impact characteristics of ears in different directions and moisture contents[16,17]. The stress resistance characteristics and the rupture mechanism of ear have also been discussed. The study showed that the rupture of maize ear was a progressive process from the inside to outside. There was also grain shedding during the compression process of ear[18]. Under the impact load, the shear strength of maize is inversely proportional to moisture content and directly proportional to impact velocity[19]. Balastreire et al.[20] measured the critical value of maize toughness at fracture. Xu et al.[21,22] quantitatively analyzed the threshing damage of rice

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according to the energy principle and the angle of elastic collision. And the mathematical model of threshing damage was given. Through experimental platform and field experiments, many scholars analyzed the effects of the maize picking form, height of header, the rotational speed of pulling rollers, moisture content of kernel, clearance between the picking plates, and the operating speed of the maize harvester of ear loss rate, kernel loss rate, and stem breaking rate. The ear damage rate and loss rate decreased with the increase of the rotational speed of the pulling rollers and the transmission shaft. When the pulling rollers and the transmission shaft work at high speed, the larger clearance between the picking plates makes the lower damage rate and loss rate of the ear[23]. According to the response surface design and analysis of the loss rate and broken stem rate of three factors, i.e., the rotational speed of the pulling rollers, the height of the header and the operating speed of the maize harvester, the regression model determination coefficients of the loss rate and broken stem rate are 0.84 and 0.90, respectively. Among them, the rotational speed of the pulling rollers has the most significant effect on the loss rate[24]. Fan et al. analyzed that for the index of kernel breaking rate, the moisture content of grain had the greatest influence on it, followed by the form of picking plates and rotational speed of pulling rollers, but less affected by operating speed; for the index of grain loss rate, the rotational speed of pulling rollers was the most important, followed by the form of picking plates. At the significant level of T=0.10, the effects of moisture content and operating speed on it were not significant[25].

The experimental factors and ranges of them, however, are mostly obtained by the harvest experiences of experts. Due to the poor theoretical analysis, most tests only obtained the influence rules of factors and the optimal parameter range, the reasons for these trends were not analyzed in detail. Moreover, they did not determine the predictable model of kernel loss and ear loss. Some scholars established the mathematical model of grain loss by combining theoretical analysis with experiments. Voicu[26] established the mathematical model of grain loss in the cleaning system by using dimensional analysis. Glancey[27] established the mathematical model of green pea's header loss by using the dimensional analysis method, which provided a theoretical basis for loss control of header. The research on maize harvest loss, however, mainly focuses on the threshing and clearing process. Little work has been done in the theoretical analysis of the maize picking process, and there are rarely researches analyzing the stress of ear and the mechanism of maize picking.

The plate-picking mechanism has the characteristics of high harvesting efficiency, and, therefore, is widely used[15,28,29]. The moisture content of the maize harvest in China is relatively high, in general, greater than 25%. This paper, therefore, researches high-moisture content maize and plate-type maize picking. Through the stress analysis of the process of maize picking, the boundary conditions of maize picking will be established, and the main influencing factors of maize picking loss will be obtained. Combined with the experiment of the maize picking platform, the influence rules of the rotational speed of pulling rollers, the operating speed, the inclination of the header, the clearance between the picking plates on the maize picking loss, and the interaction among the factors on the maize picking loss will be clarified. The loss models of the kernel loss rate and ear loss rate during the maize picking harvest will be obtained, providing theoretical guidance for reducing the loss of the maize picking harvest.

2 Theoretical analysis of factors of maize picking loss

2.1 Analysis of the mechanism of maize picking

To facilitate the analysis, the process of maize picking is simplified as follows:

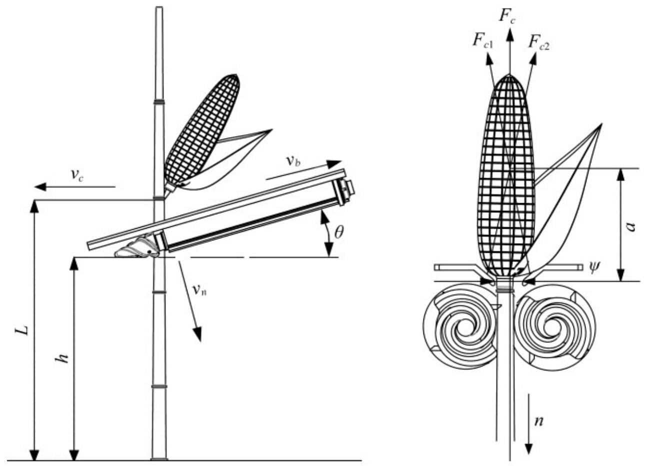
1) At the moment of maize picking, the ear bumps on the picking plates, are unaffected by the action of the conveying chain;

2) The collision between the ear and the picking plates is a head-on collision and the combined impact force F_c is positive along the y-axis;

3) When the ears are in contact with the picking plates, the ear is subjected to the same force from the two picking plates, namely $F_{c1}=F_{c2}$;

4) Object displacement is negligible due to the short time of the collision process;

5) The impact force rapidly increases to the maximum value in a short period and then decays. Due to the large impact force, the impulse of gravity, and elastic force are ignored[30].



a. Movement analysis of maize picking process

b. Force analysis of impact process

Figure 1 Mechanism analysis of maize picking process

Under the action of the guide cone of the divider, conveying chain, and pulling rollers, the maize plant enters between the picking plates to the stalk-pulling section of the pulling rollers. The stem is clamped and pulled downward by the relative rotating blades on the pulling rollers. When the ear is clamped by the picking plates, the maize picking process is realized. As shown in Figure 1, in the direction perpendicular to the picking plates (y-axis direction), when the ear and stem of maize are pulled down by the high-speed pulling rollers, the pull force F_L from the pulling rollers affects them to obtain the initial speed equal to the linear speed of the pulling rollers v_n. When the ear makes contact with the picking plates, the impact forces F_{c1} and F_{c2} from the picking plates affect the ear. In the time Δt, the speed of the ear decreased from v_n to zero, and the speed of the ear springing on the picking plates is v_1. The ear is picked when the pull force F_L is greater than the resistance of stem advance, i.e., the resultant force F_c of the impact force of the picking plates on the ear and the connecting force R of ear and stem.

According to the expression of the energy balance principle ($\delta U_i=\delta U_w+\delta U_k+\delta U_t$), the energy balance formula of grain crack caused by mechanical damage is ($\iint_B \frac{\delta U_i}{\delta A}dA=\iint_B \frac{\delta U_w}{\delta A}dA+\iint_B \frac{\delta U_k}{\delta A}dA+\iint_B \frac{\delta U_t}{\delta A}dA$)[31,32]. At the beginning of maize picking, the kinetic energy of the ear is δU_i, and $\delta U_i = \frac{1}{2} m v_n^2$, where m is the ear mass, kg; v_n is the linear speed of the pulling rollers, m/s; $v_n=\pi dn/60$, where n is the rotational speed of the pulling rollers, r/min; d is the diameter of the pulling roller, mm.

After the collision between the ear and the picking plates, part of the energy is converted into the energy dissipated in the irreversible process, that is, the energy dissipates in the process of ear breaking and kernel breaking. δU_t is the energy of the ear at the end of the maize picking process, and $\delta U_t = \frac{1}{2} m v_1^2$, where v_1 is the speed of ear springing, m/s, $v_1=e\cdot v_n$, e is the recovery coefficient, $0<e<1$. According to Equation (1), the energy dissipated in the maize picking process δU_w is related to the rotational speed of the pulling rollers.

$$\delta U_w = \delta U_i - \delta U_t = \frac{1}{2} m v_n^2 (1-e^2) = \frac{1}{2} m (\frac{\pi dn}{60})^2 (1-e^2) \tag{1}$$

$$\Delta W = \Delta P \cdot \Delta t = \Delta P \cdot \frac{L-h}{v_n \cos\theta} \tag{2}$$

where, δU_w is the energy dissipation in the maize picking process, J; δU_i is the kinetic energy of the ear, J; δU_t is the energy of the ear at the end of the maize picking process, J; m is the ear mass, kg; v_n is the linear speed of the pulling rollers (m/s), $v_n=\pi dn/60$, where n is the rotational speed of the pulling rollers, r/min; and d is the diameter of the pulling roller, mm; e is the recovery coefficient, $0<e<1$.

Equation (2) shows the work consumed by the pulling rollers in the process of maize picking, where ΔP is the power difference consumed by the pulling rollers before and after maize picking, kW; Δt is the time required from the beginning to the end of the maize picking process, s; $\Delta t=(L-h)/v_n\cos\theta$, where θ is the inclination of the header, (°); L is the height of the maize, mm; h is the header height, mm. Besides, header height is a function of the inclination of the header, that is, $\theta=G(h)$. It can be seen that the energy loss of maize and kernel breaking is mainly affected by the rotational speed of the pulling rollers and the inclination of the header.

As shown in Figure 1b, at the moment of impact between the ear and the picking plates, the impulse theorem is as follows:

$$F_c=m\cdot v_n/t' \tag{3}$$

where, F_c is the reaction force of the ear to the impact force of the picking plates, N; t' is the moment when the ear collides with the picking plates, s.

$$F_c = 2F_{c1} \frac{a}{\sqrt{a^2+(\varphi/2)^2}} \tag{4}$$

$$F_{c1} = \frac{m\pi dn}{60t'} \cdot \frac{\sqrt{a^2+(\varphi/2)^2}}{2a} \tag{5}$$

where, a is the distance from the center of gravity of the ear to the end face of the picking plates, mm; F_{c1} is the impact forces of the ear from the picking plates, N; φ is the clearance between the picking plates, mm.

Equation (5) is obtained by combining Equation (3) and Equation (4). According to Equation (5), the impact force of the ear is mainly affected by the rotational speed of the pulling rollers and clearance between the picking plates.

2.2 Analysis of boundary conditions in the maize picking process

Based on the above analysis of the mechanism of maize picking, the boundary conditions of maize picking were established. When feeding the maize, the stalks should keep upright or lean forward in the feeding direction, which could reduce the ear loss, that is,

$$v_b\cdot\cos\theta \geq v_c \tag{6}$$

where, v_b is the speed of the conveying chain, m/s; v_c is the operating speed, m/s.

The transmission ratio of the conveying chain speed and pulling rollers speed in the header gear box are set as i, where z_1 is the number of sprocket teeth of the conveying chain driving wheel; p is the pitch, mm. Equation (6) can be converted into Equation (7)

$$\frac{n}{v_c} \geq \frac{60\times1000}{iz_1 p\cos\theta} \tag{7}$$

The time for the single maize plant to move downward is $T_1=(L-h)/v_n\cdot\cos\theta$, and the time for the single maize plant to move backward is $T_2=S\cdot\cos\theta/v_c$, where S is the length of pulling roller, mm. When $\frac{T_2}{T_1}\geq 1$, a single maize plant reaches the end of the pulling rollers, the ear is plucked, and the maize picking process is completed; when $\frac{T_2}{T_1}<1$, a single maize plant reaches the end of the pulling rollers, the ear is not yet plucked, and, at this time, the stalk is forced to break, which easily causes a broken stem and blocks the header. It, therefore, is necessary to ensure $\frac{T_2}{T_1}\geq 1$, which is

$$\frac{n}{v_c} \geq \frac{L-h}{\pi dS\cdot(\cos\theta)^2} \tag{8}$$

when $F_L-F_c>R$, the ear is picked, that is,

$$\frac{2\times4950P}{n} - \frac{m\pi dn}{60t'} > R \tag{9}$$

where, F_L is the pulling force of the pulling rollers in the y-axis direction, N; and $F_L=2T_L/d$, where T_L is the torque of the pulling rollers, N·m; and $T_L=4950P/n$, where P is the motor power driving the pulling rollers, kW; R is the connecting force between the ear and the stalk, N.

2.3 Factors affecting the loss of maize picking

The impact force on the ear directly affects the loss of maize picking. Equations (1), (2) and (5) show that the irreversible energy dissipation generated during the maize picking process, in other words, the kernel loss rate, and ear loss rate, is affected by the rotational speed of the pulling rollers, the inclination of the header, and the clearance of picking plates. Furthermore, the main impact factor of the impact force on the ear is the rotational speed of the pulling rollers. The impact force increases with the increase of the rotational speed of the pulling rollers, which easily causes kernel breakage, kernel loss, and ear loss. According to Equations (7) and (8), to reduce the occurrence of ear leakage and header blocking during the maize picking process, the rotational speed of the pulling rollers should match the operating speed, and the inclination of the header also affects the maize picking loss. According to the analysis of the maize picking mechanism and the establishment of maize picking boundary conditions, it can be concluded that the main factors affecting the maize picking loss are the rotational speed of pulling rollers, operating speed, the inclination of header, and clearance between the picking plates, which is also consistent with empirical data.

3 Materials and methods

3.1 Materials

The maize variety used in the experiment is ZD 958. Fifty maize plants are randomly selected from the samples, and the main parameters of the maize plants are repeatedly measured. See Table 1 for the natural state of the maize plants. The moisture content of the experiment maize ranges from 28% to 32%. The maize was cut before the experiment to determine whether the moisture content of the maize met the experiment's requirements. Three maize were randomly selected, and the moisture content of the kernels was measured with an LDS-1H grain moisture analyzer, obtaining the average value.

Table 1 Physical properties of maize

Parameter	Value
Moisture content/%	28-32
Row spacing/mm	200
Height of maize/mm	1040-1350
Stalk diameter/mm	17.90
Diameter of maize bottom/mm	52.54
maize length/mm	177

3.2 Experiment methods

From the conclusion of the above theoretical analysis, the maize picking platform was designed to further explore the influence of the four main factors in the process of maize picking on the maize picking loss, namely the rotational speed of the pulling rollers, operating speed, the inclination of header and clearance between the picking plates, and to get the models of kernel loss, and ear loss. A single factor experiment, and four factors, five levels, central composite design (CCD) were conducted on the maize picking platform.

3.2.1 Experimental equipment

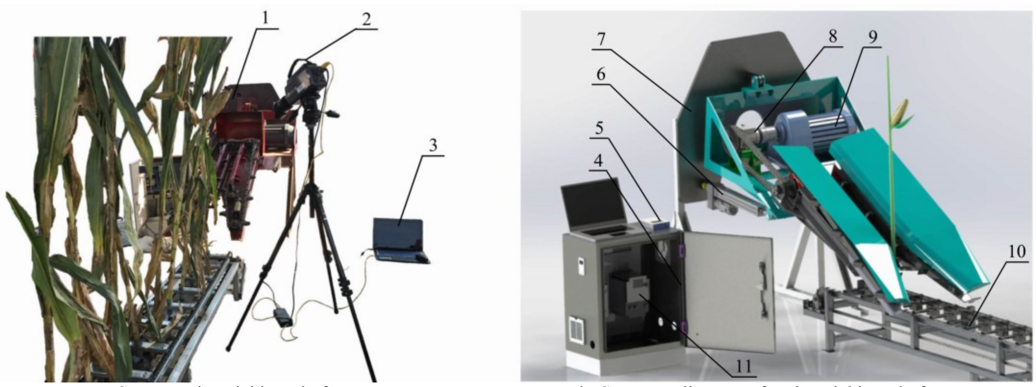
As shown in Figure 2, the equipment needed for the maize picking experiment includes the maize picking platform, electronic scale (ZG-TP10, with a range of 2 kg @ 0.01 g), LDS-1H grain moisture tester, high-speed camera system with a high-speed camera (Phantom v. 9.1, York Technology), notebook PC, data acquisition card (NI-USB6431), and torque-speed sensor (JSC4).

The maize picking platform is a self-designed and self-adjusting plate-type maize picking platform, and its structure is shown in Figure 2b. The maize picking platform consists of a frequency converter, drive motor, servo-electric cylinder, plate-type ear picking header, frame, feeding device, and control cabinet. Table 2 shows the structural parameters of the maize picking platform. The rotational speed of the pulling rollers and operating speed can be changed by adjusting the frequency of the two motors. The controller outputs the pulse signal to the servo-electric cylinder to lift the header and change the inclination of the header (header height). The second part of this article mentions that the height of the header is a function of the inclination of the header (θ=G(h)). According to Figure 3, the functional relationship between header height and header inclination is as follows:

$$h=1457-923.41\cos(70.78°-\theta)-868.57\cos(100.05°-\theta) \quad (10)$$

Table 2 Equipment and material parameters

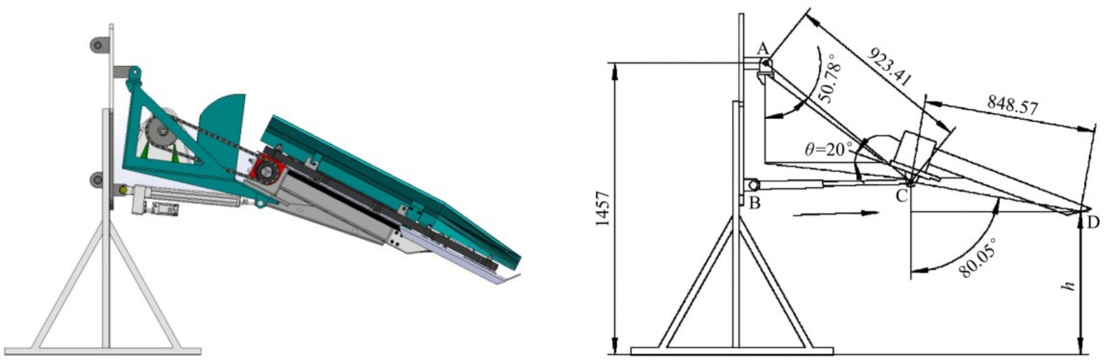
Parameter	Value
Picking motor power/kW	5.5
Feeding motor power/kW	0.75
Rotational speed/r·min^{-1}	0-1500
Maize stalk feed rate/m·s^{-1}	0-2.50
Inclination of the header/(°)	12-25
Clearance between the picking plates/mm	20-40
Overall dimension/mm	2627×1060×1682
Quality of platform/kg	272.6



a. Set up maize picking platform b. Structure diagram of maize picking platform

1. Maize picking platform 2. High-speed camera 3. Notebook PC 4. Control cabinet 5. Data acquisition card 6. Servo electric cylinder 7. Frame 8. Torque speed sensor 9. Drive motor 10. Feeding device 11. Frequency converter

Figure 2 Composition of maize picking platform



a. Left view of the maize picking platform b. Dimensions of the maize picking platform

Figure 3 Functional relationship between header height and header inclination

3.2.2 Experimental design

The experiments include a single factor experiment and CCD experiment. According to different test requirements, adjust the working parameters of the maize picking platform accordingly. The experiment with the same working parameters is a group of experiments, and each group of experiments is repeated three times. In each experiment, twenty maize plants were selected, and the maize picking process was completed on the maize picking platform. After each experiment, the kernel loss rate, and ear loss rate were calculated by weighing, and the average value of the three tests was taken as the experiment result of each group.

To clarify the influence of each factor on the loss rate of maize picking and the selection range of orthogonal test parameters, twenty groups of single-factor experiments were first conducted on four factors. Then, twenty-nine groups of the CCD experiment were conducted. By using the kernel loss rate and ear loss rate as evaluation indicators, and the response surface experiment analysis of four factors and five levels, the effect of the parameter interaction on kernel loss and ear loss was studied. Table 3 shows the coding of the experiment factors.

Table 3 Factor-level coding of experiment

Code	Factor			
	Rotational speed of pulling rollers n /r·min^{-1}	Operating speed v_c /m·s^{-1}	Header inclination θ/(°)	Clearance between picking plates φ/mm
−2	700	1.38	12.00	22
−1	900	1.66	15.25	26
0	1100	1.94	18.50	30
1	1300	2.22	21.75	34
2	1500	2.50	25.00	38

3.2.3 Evaluation index

Maize picking performance depends on the damage caused by the impact force to the ears, the loss of ears caused by rolling off the header and the breakage, and the loss of kernel[33]. The loss of maize picking, therefore, includes two parts: kernel loss and ear loss. Figure 4 shows the loss caused by the maize picking process.

Figure 4 Loss during the maize picking process

(1) Kernel loss rate y_1

In the test area, collect all the dropped kernels and the broken ear less than 5 cm long. After they are removed, weigh them. At the same time, pick out the broken and damaged kernels. Calculate the kernel loss rate using Equation (11).

$$y_1 = \frac{W_L}{W_Z} \times 100\% \tag{11}$$

where, y_1 is the rate of kernel loss, %; W_L is the mass of dropped and broken kernels, g; W_Z is the total mass of sample kernels, g.

(2) Ear loss rate y_2

In the test area, the ears that were missed or have fallen to the ground and the ear segments over 5 cm were collected, and the ears were weighed after being removed. The ear loss rate was calculated using Equation (12).

$$y_2 = \frac{W_U}{W_Z} \times 100\% \tag{12}$$

where, y_2 is the ear loss rate, %; W_U is the kernel mass after threshing the missed ears, g.

4 Results and discussion

4.1 Effects of different operating parameters on maize picking performance

(1) Effect of the rotational speed of the pulling rollers

Set the working parameters of the maize picking platform: the operating speed is 1.94 m/s, the inclination of the header is 20°, the clearance between the picking plates is 30 mm, the rotational speed of the pulling rollers within the range of 700-1500 r/min. Figure 5a shows the effect of the rotational speed of the pulling rollers on kernel loss and ear loss. When the rotational speed of the pulling rollers is equal to or below 900 r/min, the ear loss is high. This could be because the feeding speed does not match the rotational speed of the pulling rollers due to the low rotational speed of the pulling rollers, which causes the stems to be jammed at the front of the picking plate. Consequently, the stalks behind cannot be fed, which easily causes the missing ears and header blocks. When the rotational speed of the pulling rollers is about 1500 r/min, both the kernel loss rate and ear loss rate are high. This is because the high rotational speed of the pulling rollers will produce a large impact force when picking ears, which makes the ears bounce high and in different directions. When the ears collide on the header, it is easy to produce broken ears and broken kernels.

(2) Effect of operating speed

Set the working parameters of the maize picking platform: the rotational speed of the pulling rollers is 1100 r/min, the inclination of the header is 20°, the clearance between the picking plates is 30 mm. Change the operating speed within the range of 1.38-2.50 m/s. Figure 5b shows the effect of operating speed on kernel loss and ear loss. When the operating speed is equal to or below 1.66 m/s, the ear loss rate is high. This could be due to the slow feeding speed of stalks causing the maize picking position forward, causing header congestion and missing ears. Furthermore, the ears cannot be continuously fed into the ear collection box by the conveying chain, which causes the ears to jam between the picking plates and produce broken ears. When the operating speed is about 2.50 m/s, both the kernel loss rate and ear loss are high, which could be because with higher operating speed, the gathering chain does not have enough time to pull the stalks in, so the stalks are pushed and the ears are knocked off. When the moisture content is high, the stalk is thick, and cannot break easily, which is more likely to cause header congestion.

(3) Effect of the inclination of header

Set the working parameters of the maize picking platform: the rotational speed of the pulling rollers is 1100 r/min, the operating speed is 1.94 m/s, the clearance between the picking plates is 30 mm. Change the inclination of the header within the range of 12°-25°. Figure 5c shows the effect of the inclination of the header on kernel loss and ear loss. When the inclination of the header is lower than around 15.25°, the kernel loss rate and ear loss rate are high, because when the height of the header is too high, the position of maize picking will also be brought forward, and the stalks will be pushed down easily, resulting in the loss of maize picking. When the inclination of the header is around 18.50°, the position of picking is close to the middle of the picking plate, and both the ear loss rate and kernel loss rate of picking are the lowest. When the inclination of the header is about 25°, the kernel loss rate and ear loss rate are also high because the height of the header is too low, which will cause the picking plates to be far away from the ears, and the ears will easily pop out of the header, causing the ear to fall.

(4) Effect of the clearance between picking plates

Set the working parameters of the maize picking platform: the rotational speed of the pulling rollers is 1100 r/min, the operating speed is 1.94 m/s, the inclination of the header is 20°, and change the clearance between the picking plates within the range of 22-38 mm. Figure 5d shows that there is a direct relationship between the picking plates clearance and the size of the ears. When the clearance is equal to or less than 26 mm, the loss of maize picking is high. This could be because the stalks and leaves cannot pass through the gap between the picking plates smoothly, causing congestion between the picking plates. The maize ears cannot be sent into the ear collection box by the reeling chain, and more broken stems will be produced at the same time. When the clearance between the picking plates is about 38 mm, the loss of maize picking is also high, because the ears stuck between the plates causes ear loss.

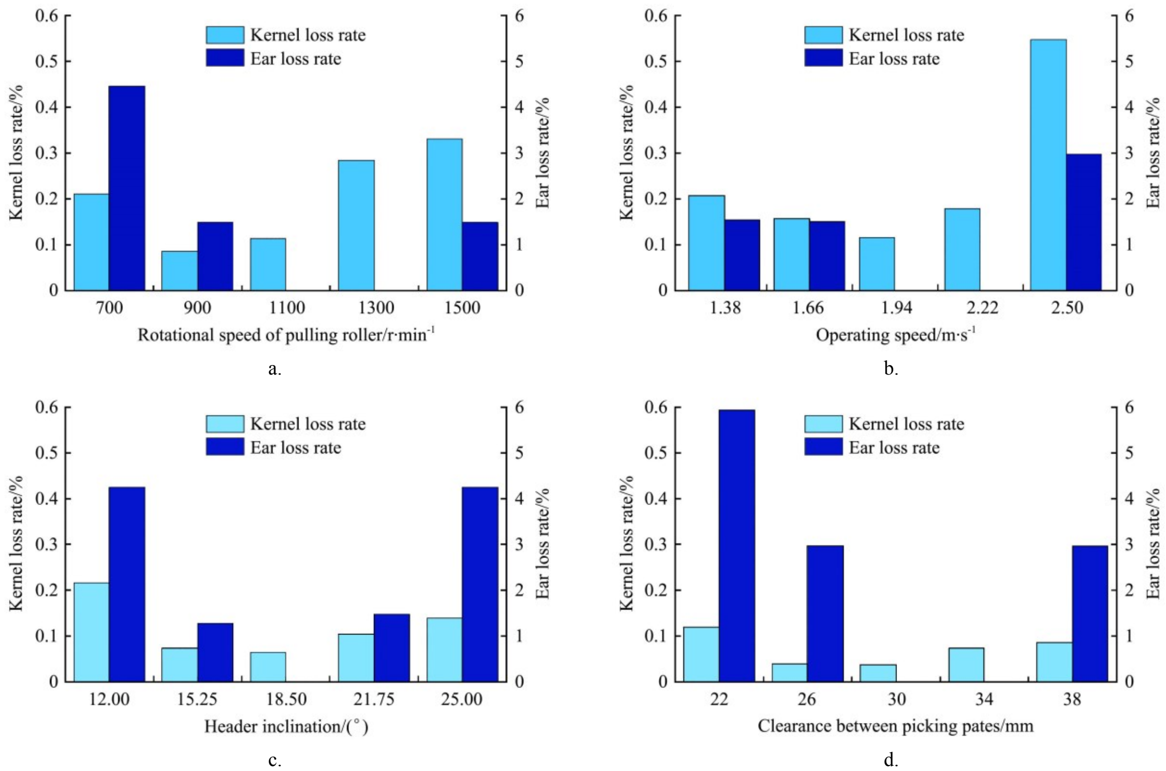


Figure 5 Effects of different operating parameters on maize picking performance

4.2 Response surface for evaluating the influence of the factors on maize picking performance

4.2.1 Statistical analysis and regression model establishment

Design-Expert software was used to design the experimental scheme, and the CCD method in the response surface method was selected. Twenty-nine groups of parameter combinations were obtained, of which twenty-four groups were taken as factorial points, five groups were taken as zero points for error estimation. Table 4 shows the experiment scheme and results, in which X_1, X_2, X_3 and X_4 are the factor coding values. Among them, X_1 represents the rotational speed of the pulling rollers, X_2 represents the operating speed, X_3 represents the header inclination, and X_4 represents the clearance between the picking plates. Table 5 shows the results of the variance analysis of the kernel loss rate and ear loss rate.

Table 4 Analysis of response surface experiment

Number	X_1/r·min^{-1}	X_2/m·s^{-1}	X_3/(°)	X_4/mm	y_1/%	y_2/%
1	−1	−1	−1	1	0.068	6.531
2	1	−1	1	1	0.312	1.486
3	1	−1	−1	1	0.221	1.486
4	0	0	0	2	0.170	0.000
5	−1	−1	1	−1	0.167	0.000
6	−2	0	0	0	0.129	3.838
7	1	1	−1	1	0.185	0.000
8	1	−1	−1	−1	0.078	0.000
9	0	0	0	0	0.081	0.000
10	1	1	−1	−1	0.185	0.000
11	0	0	−2	0	0.095	2.765
12	0	0	0	0	0.137	0.000
13	0	−2	0	0	0.121	1.484
14	2	0	0	0	0.280	2.693
15	−1	1	1	−1	0.085	2.558
16	1	1	1	1	0.279	1.279
17	−1	−1	1	1	0.124	0.000
18	−1	1	−1	1	0.317	3.838
19	0	0	2	0	0.172	2.765
20	1	−1	1	−1	0.186	0.000
21	0	2	0	0	0.171	0.000
22	1	1	1	−1	0.211	2.765
23	0	0	0	0	0.098	0.000
24	0	0	0	0	0.071	0.000
25	−1	1	−1	−1	0.208	2.558
26	0	0	0	−2	0.229	1.486
27	0	0	0	0	0.056	0.000
28	−1	1	1	1	0.107	1.279
29	−1	−1	−1	−1	0.059	2.763

Table 5 Variance analysis result of regression models

Response variable	Model	R^2	p-value Prob>F
y_1	y_1=5.09−2.65×10$^{-3}x_1$−0.06x_3+4.80×10$^{-4}x_1x_2$+2.83x_1x_4+5.44×10$^{-7}x_1^2$+0.23x_2^2+1.19×10$^{-3}x_4^2$	0.7256	0.0397*
y_2	y_2=77.49−0.07x_1−4.61x_3+1.53×10$^{-3}x_1x_3$+0.74x_2x_3−0.37x_2x_4+1.95×10$^{-5}x_1^2$+0.06x_3^2	0.8785	0.0003***

Note: * was significant (p<0.1), ** was very significant (p<0.01), *** was extremely significant (p<0.001).

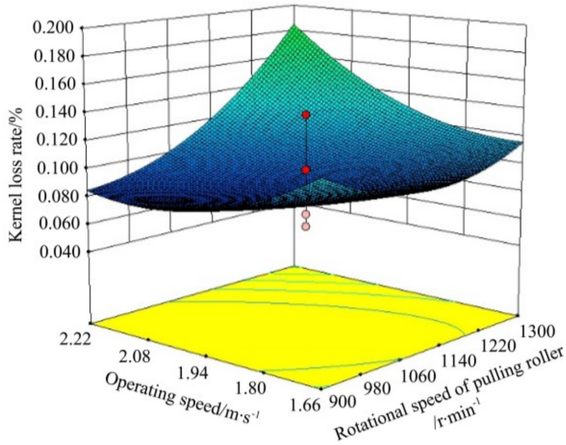
According to the analysis of the variance of the kernel loss rate, within the 90% confidence interval, the factors that significantly affect the kernel loss rate are X_1, X_3, X_1X_2, X_1X_4, X_1^2, X_2^2, and X_4^2. It seems that the rotational speed of the pulling rollers influences the kernel loss more remarkably than the other factors. The p-value of the model obtained by performing multiple regression fitting analysis is less than 0.05, the determination coefficient R^2 is 0.7256. It indicates that the regression model of the kernel loss rate is significant and fit, and the test error has little effect on the test results. Table 5 shows the regression equation of kernel loss obtained by removing insignificant terms.

According to the analysis of the variance of the ear loss rate, within the 90% confidence interval, the factors that significantly affect the ear loss rate are X_1, X_3, X_1X_3, X_2X_3, X_2X_4, X_3X_4, X_1^2 and X_3^2. The p-value of the model obtained by performing multiple regression fitting analysis is less than 0.001, the determination coefficient R^2 is 0.8785, meaning the regression model of the ear loss rate is significant, and the regression equation could accurately predict the relationship between the ear loss rate and the independent variables. Table 5 shows the regression equation of ear loss obtained by removing insignificant terms.

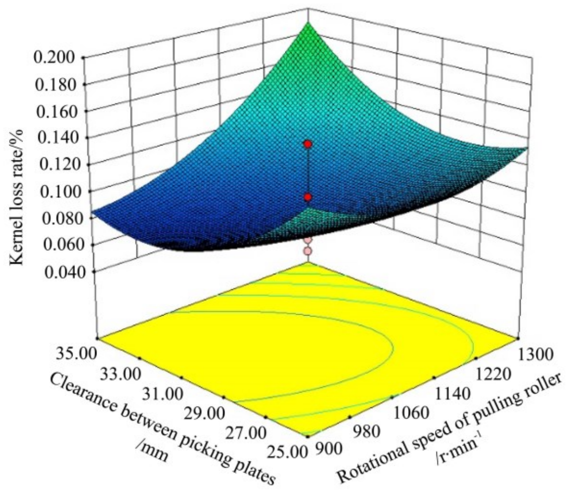
4.2.2 Response surface analysis

The significance analysis (Table 5) of the kernel loss rate showed that only the interaction of X_1X_2, X_1X_4 had significant effects on the kernel loss rate. The plot of the regression surface in Figure 6a shows that when the inclination of the header and the clearance between the picking plates are fixed at zero, the maximum kernel loss rate is around the parameter combination of the operating speed of 2.22 m/s, and the rotational speed of the pulling rollers of 1300 r/min, which is about 0.160%-0.183%. This could be due to the blockage of the header caused by too much feeding. At the same time, the high rotational speed of the pulling rollers will increase the impact force on the ear, so the kernel loss is serious; the too low or too high rotational speed of the pulling rollers will lead to a high kernel loss rate. This could be because when the rotational speed of the pulling rollers is lower than 900 r/min, the speed of pulling the stalks is slow, while the rotational speed of the pulling rollers is higher than 1300 r/min, the impact force on the ear is large. Similar results were found by the researchers in earlier attempts for performance tests on the corncob separator[34].

From Figure 6b, when the operating speed and header inclination are fixed at zero, the kernel loss rate decreases first and then increases with the increase of the clearance between the picking plates. When the clearance between the picking plates is small, the kernel loss rate decreases first and then increases with the increase of the rotational speed of the pulling rollers. When the clearance between the picking plates is large, the kernel loss rate increases with the increase of the rotational speed of the pulling rollers. The combinations of two sets of parameters with high kernel loss rates are around (1300 r/min, 35 mm) and (900 r/min, 25 mm). This could be because the large impact force on the ear caused by the high rotational speed of the pulling rollers and large clearance between the picking plates can easily cause the ears to jam between the ear picking plates and cause kernel loss. When the rotational speed of the pulling rollers, however, is too low and the gap between the picking plates is small, the maize stalks and leaves cannot easily pass through, causing the header to block.



a. Interaction of rotational speed of pulling roller and operating speed



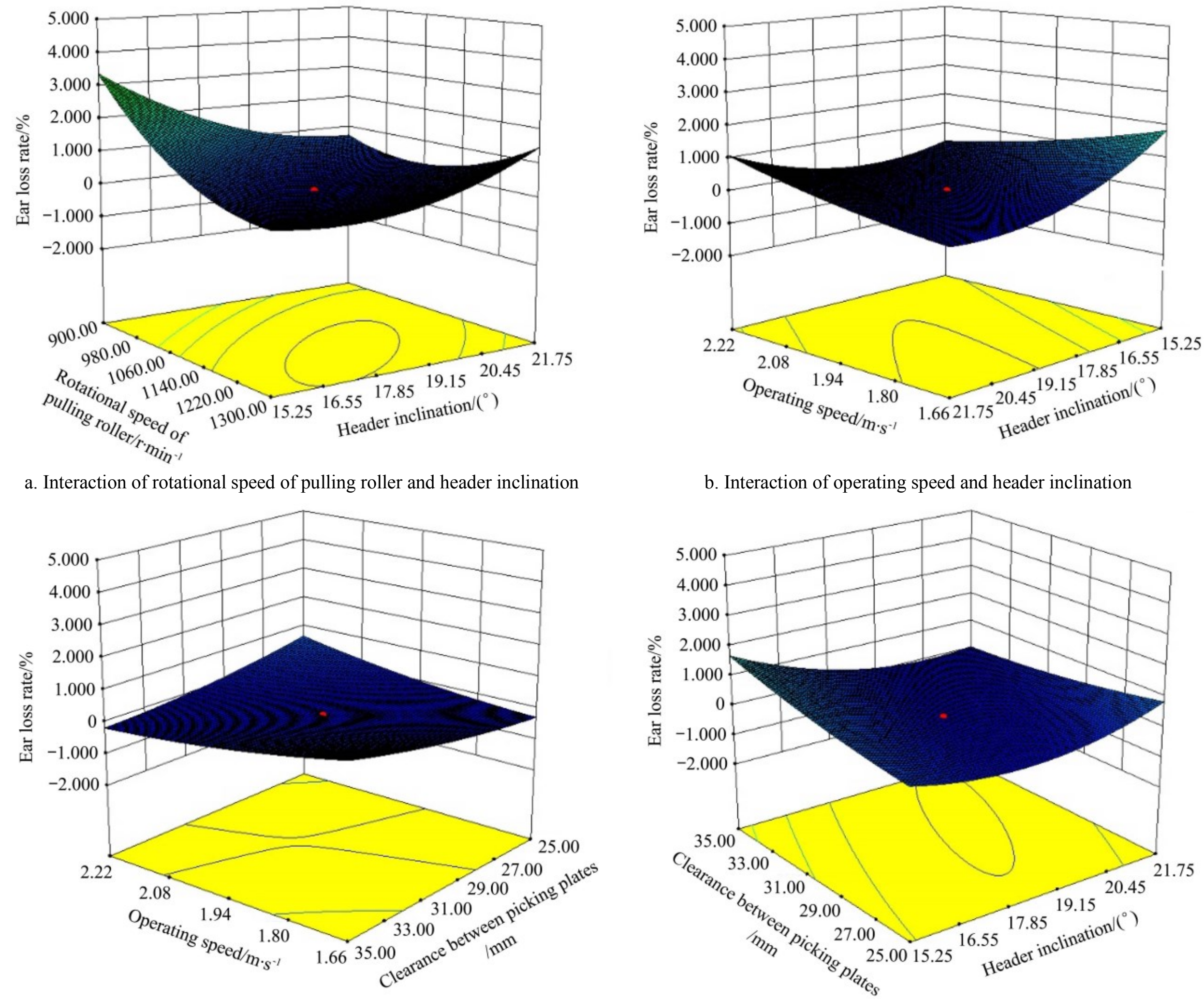
b. Interaction of rotational speed of pulling roller and clearance between picking plates

Figure 6 Effects of interaction of factors on kernel loss rate

The significance analysis (Table 5) of the ear loss rate showed that the interaction of X_1X_3, X_2X_3, X_2X_4, and X_3X_4 significantly affected the ear loss rate. The plot of the regression surface in Figure 7a shows that the combinations of two sets of parameters with high ear loss rates are around (900 r/min, 15.25°) and (1300 r/min, 21.75°). This could be because the small inclination of the header and the rotational speed of the pulling rollers will lead to the picking position moving forward, blocking the header. With the increase of the inclination of the header, the position of maize picking moves backward, although it will move the picking plates far away from the ear. The low rotational speed of the pulling rollers will make the impact force on the ear small, so the ear cannot easily fall from the header. But when the rotational speed of the pulling rollers increases, the impact force will increase, and the larger inclination of the header will make the ear spring up, and fall from the header.

From Figure 7b, it can be seen that when the rotational speed of the pulling rollers and the clearance between the picking plates are fixed at zero, the combination of two sets of parameters with high ear loss rates are around (1.66 m/s, 15.25°) and (2.22 m/s, 21.75°). It is possible that the feeding quantity is too large due to the high operating speed. The ear picking position is too far ahead due to the low operating speed and the small inclination of the header, which will also easily lead to header congestion.

As shown in Figure 7c, when the clearance between the picking plates is large and the operating speed is low, the ears cannot be fed continuously, which results in the ears becoming stuck between the picking plates. When the clearance between the picking plates is small and the operating speed is high, it is easy to block the header because the feeding amount is increased. As shown in Figure 7d, the maximum ear loss rate is around the parameter combination of the clearance between the picking plates at 35 mm and the inclination of the header of 15.25°. This could be because that the clearance between the picking plates is too large and the header inclination is small, which causes the ears to get stuck at the front of the picking plates, causing blockage of the header.



a. Interaction of rotational speed of pulling roller and header inclination

b. Interaction of operating speed and header inclination

c. Interaction of operating speed and clearance between picking plates

d. Interaction of clearance between picking plates and header inclination

Figure 7 Effects of the interaction of factors on ear loss rate

4.2.3 Optimal values of the parameters

According to the response surface analysis, the rotational speed of the pulling rollers, the operating speed, the inclination of the header and the clearance between the picking plates had significant interaction with the kernel loss rate and the ear loss rate. The optimal combination of the parameters was obtained by optimizing the parameters of the model of kernel loss rate and ear loss rate: the rotational speed of the pulling rollers is 1119.55 r/min, the operating speed is 1.91 m/s, the inclination of the header is 17.94°, and the clearance between the picking plates is 29.39 mm, the predicted kernel loss rate is 0.086%, and the ear loss rate is 0%. By rounding the parameters, the rotational speed of the pulling rollers is 1120 r/min, the operating speed is 1.94 m/s, the inclination of the header is 18°, and the clearance between the picking plates is 30 mm. The optimized parameters were set as the working parameters of the maize harvester experiment, and three repeated experiments were conducted to obtain the average value. The experiment results showed that the kernel loss rate was 0.065%, and the ear loss rate was 0%. The experiment results were close to the predicted values, indicating that the model was in line with the performance requirements of ear picking.

5 Conclusions

(1) By analyzing the mechanism of the maize picking process, the boundary conditions of maize picking were established, and the main influencing factors of the loss of maize picking were obtained, which were the rotational speed of the pulling rollers, operating speed, the inclination of header and the clearance between the picking plates, which provided the theoretical basis for the study of the maize picking mechanism.

(2) In this study, an effort was made to determine the effect of the rotational speed of the pulling rollers (700-1500 r/min), operating speed (1.38-2.50 m/s), the inclination of header (12°-25°) and the clearance between the picking plates (22-38 mm) on maize

picking loss. To this aim, single-factor experiments and a CCD experiment were carried out on a self-designed and self-adjusting maize picking platform. The rotational speed of the pulling rollers, the inclination of the header and the clearance between the picking plates, the interaction of the rotational speed of the pulling rollers and operating speed, the interaction of the rotational speed of the pulling rollers and the clearance between the picking plates have a significant effect on the kernel loss rate, which is also consistent with the analysis of the picking mechanism. The rotational speed of the pulling rollers, the inclination of the header, the interaction of the rotational speed of the pulling rollers and the inclination of the header, the interaction of the rotational speed of the pulling rollers and the clearance between the picking plates, the interaction of the inclination of the header and the clearance between the picking plates have a significant effect on the ear loss rate. In accordance with the results, it is suggested to adjust the working parameters properly, in order to reduce the maize picking loss rate.

(3) The models of kernel loss rate and ear loss rate were established by a CCD experiment, and the models optimized the parameters. The results of the significance analysis show that the loss models are correct. And the optimal combination of parameters is as follows: rotational speed of the pulling rollers is 1120 r/min, operating speed is 1.94 m/s, the inclination of the header is 18°, and clearance of the picking plates is 30 mm. The optimized parameter combination was used for the maize picking experiment. The kernel loss rate is 0.065% and the ear loss rate is 0%. The test results are close to the predicted values, indicating that the obtained regression model could predict maize picking performance indicators and could be used to control working parameters to reduce the maize picking loss rate.

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