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Effect of ear picking rollers on corn stover attitude

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Abstract

In order to increase the precision rate of ear picking and decrease the rate of cob damage, this paper investigates and evaluates the impact of ear picking rollers on corn stalk attitude. It then designs an ear picking roller with a straightforward structure and good ear picking effect. This is because the ear picking process and ear picking attitude are more closely correlated. The front end of the ear picking roller is optimized to be tapered in order to minimize the degree of forward tilt of the stalks. The optimal range of values for the bottom angle of the front end of the ear picking roller is 73.1-81°. To ascertain the relationship curve between the influencing factors that cause plant push back and the stalk forward tilt angle, as well as the optimal value range of the stalk feeding speed and cutting table tilt angle, virtual simulation tests are conducted using ADAMS software. The parameter combination with the least amount of plant forward tilt was found using a response surface optimization test design. At a machine travel speed of 0.85 m/s, the cutting table inclination is 27.5° and the stalk tilting angle is at its lowest, which is roughly 2.5°. Through testing, it was confirmed that the conical ear picking roller's design could successfully lessen cob damage and the forward tilt of the stalk.

Key words: corn harvesting; ear picking roller; response surface test; optimization design.

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Introduction

The kernel of maize is readily destroyed and has little resilience to pressure because of its high water content and thin skin. In addition to detracting from appearance, damaged cob is also challenging to repair (Guan, 2023). Corn stalks are softer and more flexible, but they will tilt forward from the early feeding stage until they are firmly clamped by the stalk pulling rollers, which will increase the rate of cob damage. Therefore, how to reduce stalk forward tilt and decrease the ear damage rate during the ear picking process still requires further research.

To reduce the ear damage rate, relevant scholars have conducted research, analysis, and innovation on various types of ear picking devices for corn harvesters (Kim *et al.*, 2022). Fan (2023) measured the physical and mechanical parameters of fresh corn plants during the harvest period, designed a clamping-type ear picking device, analyzed the ear picking mechanism, and carried out finite element analysis, virtual simulation analysis, and bench tests, which verified the reduction in ear damage rate and harvest impurity rate. Fu *et al.* (2019; 2020) conducted corn ear picking collision tests using plate-type and wheel-type ear picking mechanisms, analyzed collision parameters and grain loss rate, performed force analysis on the ear picking wheels, and designed a rigid-flexible coupled damage-reducing ear picking device, which quantitatively reduced the grain loss rate. Wang *et al.* (2023) proposed using ear picking wheels to simulate the downward force applied manually, effectively avoiding problems such as secondary ear damage and high ear damage rate, which was verified by simulation tests. Li and Du (2023) conducted static force analysis on the stalk pulling roller using finite element analysis and designed a stalk pulling roller with a hexagonal staggered blade structure to enhance the traction capacity of the stalk pulling roller on corn stalks during the ear picking process. Luo *et al.* (2023) proposed a fresh corn harvesting method based on bionic ear picking with staggered baffle rollers and carried out virtual simulation experiments to achieve low-damage picking of fresh corn.

In addition, many scholars have analyzed and optimized the specific parameters of ear picking devices. Yu (2013) studied the influence of the geometric parameters of the ear picking device on the threshing quality of corn ears and carried out optimized design. Khatamov and Temirov (2023) studied and determined the length of the separating part of the ear picking roller of the harvester to optimize the ear picking device of the corn harvester. However, the above studies all focus on the design and optimization of ear picking devices. Although they have reduced ear damage to a certain extent, they have problems such as complex machinery, high processing difficulty, high cost, lack of experimental verification in some cases, and poor actual operation efficiency.

Therefore, this paper aims to design an ear picking roller with a simple structure, easy processing, and experimental verification to reduce corn stalk forward tilt and the ear damage rate. The response surface experimental design method is used to determine the parameter combination of the smallest inclination angle of the plant in front of the front end of the roller. The ear picking roller's structure is optimized, and the original equal-diameter cylindrical form of the roller part behind the helical cone at the front end of the single ear picking roller will be designed as a In order to decrease the rate of cob damage, this section is made to be tapered to realize the little disturbance downward tugging of the plant.

Key component design

The overall structure of the designed two-row cutter is shown in Figure 1, including the cutter frame, churn, grain separator, tine box, chopping device, and so on. The stalk attitude, the harvester's forward speed, the linear speed of the stalk-pulling roller, and the toggle chain's linear speed all affect the cutting platform's pulling down and plucking operation process. In the ideal scenario, the partial speed of the toggle chain's linear speed (v_b) in the horizontal direction during the stalk-feeding stage (stage I) is equal in size and opposite in direction to the forward speed of the implements (v_0). In the stalk-drawn down stage (stage II, stage IV) and the tassel stage (stage III), the partial speeds in the horizontal direction and the forward speed of the implements v_0 are equal in size and opposite in direction; the linear speed of the stalk-pulling roller v_1 is also equal in size and opposite in direction; and the plucking operation quality is high. The corn stalks are always in a vertical position at this moment due to high-quality tasseling operations, and the partial velocity and machine forward speed v_0 size are pointing in the same direction.

However, in reality, the introduction of the coefficient of push to l is unavoidable during the process of plucking the ears of the plant's operation forward and backward due to the field plant growth status, variety, stalk moisture content, and other factors. The following requirements must be met in order to achieve the smooth and excellent operation of the cutting platform plucking operation process of the stalk pulling down:

$$\begin{cases} v_0 = \lambda v_b \cos\theta \\ v_0 = v_l \sin\theta \\ \frac{L_1+L_2+L_3+L_4}{v_l \sin\theta\cos\theta} \geq \frac{h_b-h_s}{v_l\cos\theta} \\ \frac{L_1+L_2}{v_l \sin\theta\cos\theta} \leq \frac{h_m-h_s}{v_l\cos\theta} \end{cases} \quad \text{(Eq. 1)}$$

where: v_0 is the machine's moving speed (m/s); v_b is the paddle chain's linear speed (m/s); v_1 is the ear picking roller's linear speed (m/s); θ is the cutting platform's inclination angle (°); L_1 is the ear picking roller's cone length (mm); L_2 and L_4 are the ear picking roller's cone and tassel section lengths (mm); L_3 is the length of the tassel section of the ear picking roller (mm); h_b is the height of the maize stalks (mm); h_m is the height of the ears (mm); h_s is the distance between the cutting platform and the ground (mm). The plant height h_b in this work is chosen to fall between 1730 mm and 2700 mm in order to accommodate the various types of maize plants with varying growth as much as feasible for harvesting (Gao *et al.*, 2012).

This paper optimizes the design of the idea in order to pull the stalk roller gap changes in the sensitive characteristics and pull the stalk roller adjustment inconvenience. The original equal-diameter cylindrical form of the single pull of the stalk roller front (spiral cone head behind the roller body part) will be replaced with this part of the design for the conical, so that the two pulls of the stalk rollers in front of the formation of a front and back of the small conical area. This helps to reduce the conical area of the design from the plant and pulls the stalk rollers in contact with the stability of the resistance of the clamping process. In addition to increasing the adaptability of different stalk diameters, the conical area's design can lower the resistance of the plant from contact with the ear picking roller to the stable clamping state process, realization of the plant's small perturbation pulling, and guarantee that the angle between the stalks and the ear picking roller is always less than 90°. Figure 2 depicts the pulling roller's tapered section.

The size of the taper of the ear picking roller is regulated by the bottom angle of the front end. The relationship with other parameters is:

$$\begin{cases} \tan\varphi = \frac{2x_0}{d_{max}-\delta} \\ \delta = x - D \\ x_0 = l\sin\theta \end{cases} \quad \text{(Eq. 2)}$$

where: φ is the bottom angle of the front end of the ear picking roller (mm); x_0 is the length of the feeding section of the ear picking roller (mm); d_{max} is the maximum diameter of corn stalk (mm); δ is the ear picking roller gap when the two ear picking rollers are parallel (mm); x is the distance between the centre lines when the two ear picking rollers are parallel (mm); D is the diameter of the ear picking roller, mm; l is the length of stalk from the cone tip of the ear picking roller to the ear position (mm); θ is the inclination angle of the cutting table.

The ear picking roller in the current laboratory was measured, and the median value was taken: D = 118 mm and x = 101.6 mm. According to Eq. 2, the calculated range is 14.3-27.5°. Based on field conditions, d_{max} is set to 28 mm and l to 300 mm. Substituting the known data, the bottom angle of the ear picking roller is 73.3° ≤ φ ≤81°.

Modelling

The simulation model of plant-cutter interactions is established in this research using the system dynamics analysis software ADAMS. The pull-down plucking process of the plucking device is simulated using the stalk forward tilt angle as the evaluation index.

Plant simulation modelling

Since the corn stover and the ear picking roller are constantly in touch during the tassel harvesting process, this article builds a continuous, flexible body of the corn plant using the AtuoFlex module included with the ADAMS software to increase simulation accuracy. First, the established SolidWorks plant model is imported into ADAMS, and the Solid185 solid element is selected.

The model's material properties are then established, including a density of 450 kg/m^3, a Poisson's ratio of 0.33, and a Young's modulus of 1.1E+10 N/ m^2 (Zhang, 2003). Cylindrical pairs and prismatic pairs are added at the centers of mass of the two ear picking rollers. When the ear is blocked by the ear picking plate and detached, relative displacement and relative velocity are generated between the ear and the stalk. Therefore, a bushing force (Zhang, 2015) is added between the corn ear and the stalk, and a sensor is installed at the bushing force position with a monitored value set to 500 N. The ear separates from the stalk when the interaction force between them exceeds the set monitored value. Due to the certain speed of the ear picking rollers, collisions with the stalk occur. This paper defines the collision using the impact function method, with a collision exponent of 1.5, a damping coefficient of 0.2% of the stiffness coefficient, and a maximum penetration depth of 0.1 mm (Wang, 2021).

Cutting table simulation modelling

The purpose of the virtual simulation study in this section is to investigate the forward tilt of the stalk in the ear picking process in relation to various parameters, and the main working part involved is the ear picking device, and in order to reduce the simulation calculations, this paper simplifies the cutting table into the two parts of the tine box, the ear picking roller. Similarly, the flexible body of the above three parts is generated by creating cells, defining material properties, dividing meshes and establishing rigid regions, in which Poisson's ratio is set to 0.3, Young's modulus is 2.06E+11N/m^2 and the density is 7850 kg/m^3.

Simulation script setup

The total simulation time is set to 1 s and the number of simulation steps is set to 1000. The simulation model is shown in Figure 3. Since specific cutting table parameters such as the stalk feeding speed (*i.e.*, the harvester operating speed), cutting table inclination angle, and the distance between the cone tips of the ear picking rollers will affect the degree of plant forward tilt and the state of plants within the cutting table, thereby influencing the working effect of the ear picking rollers, this paper will conduct simulation experiments on the aforementioned influencing factors. The evaluation indexes, operation steps, and specific conclusions of the experiments are as follows.

Evaluation indicators

In this paper, the anterior tilt angle of the stalk during pull-down spike picking is used as an evaluation index, where β is:

$$\beta = \arctan\frac{x}{y} \qquad \text{(Eq. 3)}$$

where: x is the displacement of the centre of mass of the maize stalk in the forward direction of the implement (mm); y is the displacement of the centre of mass of the maize stalk relative to the ground (mm).

One-way test

Effect of stalk feeding rate on picking attitude

The plant's picking attitude is somewhat influenced by the collision force that is determined by the stalk feeding speed when the plant comes into contact with the cutting platform. The cutting platform mounted carrier for the 4LZ-1.6Z rice and wheat harvester is designed in this paper. Its maximum traveling speed is 1.2 m/s. To ensure the machine's harvesting efficiency, the machine's traveling speed should be higher than 0.8 m/s. The selection of the machine's traveling speed of 0.8 m/s, 0.9 m/s, 1 m/s, 1.1 m/s, and 1.2 m/s, the five stalk feeding speeds as the experimental values, the fixed ear picking roller speed 600 r/min, and the cutting table inclination angle 20.9°. Figure 4 displays the test results' regression curve.

Figure 4 shows that as the speed of stalk feeding increases, the 16 mm diameter stalks always maintain an upright spike picking attitude, while the 20 mm and 24 mm diameter stalks gradually increase in inclination and exhibit a poorer spike picking attitude. The change trend of the 24 mm diameter stalks is evident, and this phenomenon is caused by the fact that as the diameter of the stalk increases, the pulling roller's compression and friction on the

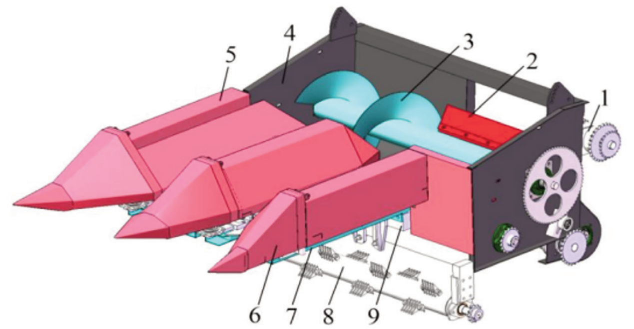


Figure 1. Cutting table 3D model. 1, Power input section; 2, toggle plate; 3, auger; 4, corn header frame; 5, shell casing; 6, grain divider; 7, spike rack; 8, chopping device; 9. gearbox.

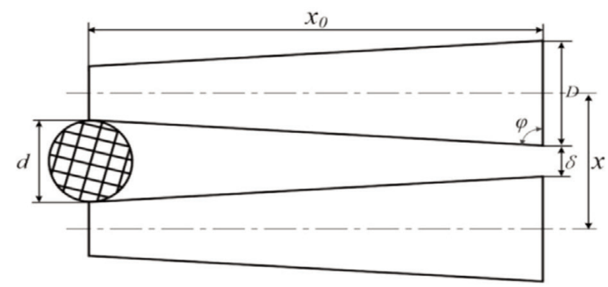


Figure 2. Schematic diagram of the tapered area of the ear picking roller.

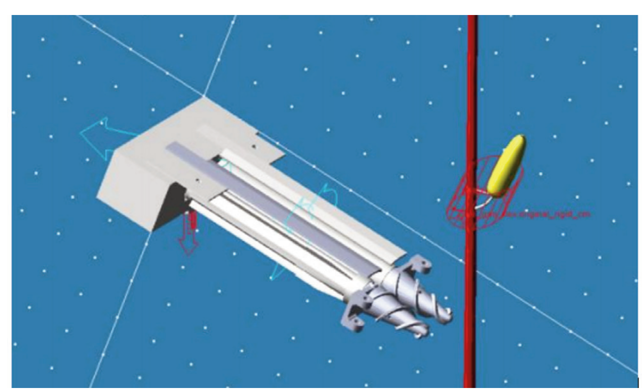


Figure 3. Simulation model.

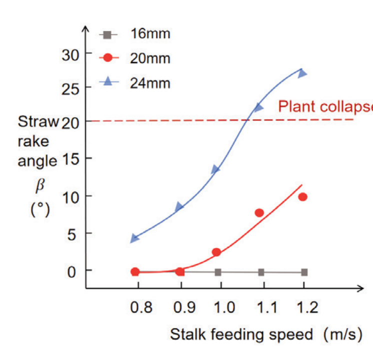


Figure 4. Graph of the results of the one-factor test of stem feeding rate.

stalks increase, and the stalk's resistance to the stable clamping process increases, resulting in poorer contact with the pulling roller. This phenomenon was caused by the fact that as the diameter of the stalks increased, the ear picking roller's compression and friction on the stalks increased as well as the resistance between the stalks' contact with the ear picking roller and the clamping process stabilization. As a result, the stalks tilted forward and the picking attitude deteriorated.

Effect of cutting table inclination on picking attitude

According to the correlation study, the cutting table's inclination angle, which ranged from 14.3° to 27.8°, is a significant factor influencing the condition of the plants within it. In this paper, we fixed the stalk feeding speed at 1 m/s, the ear picking roller speed at 600 r/min, and the spacing between the ear picking roller's cone tips at 103.6 mm. We also chose 14.3°, 17.6°, 20.9°, 24.2°, 27.5°, 27.5°, and the five cutting table inclination angle as the test value. In Figure 5, the test results are displayed.

Figure 5 shows that the selecting attitude improves when the cutting table's inclination angle increases and the inclination angle of the three various stalk diameters gradually lowers. The reason for this phenomenon is that when the inclination angle of the pulling rollers increases, the horizontal component of the pulling roller's force on the uptake of the stalks increases. This results in a larger acceleration and speed of the plant's backward row, a smaller difference between the stalks and the machine's traveling speed, or a smaller relative movement speed, and a smaller compression and friction force of the pulling rollers on the straw, which reduces the forward tilting volume of the stalks and improves the picking attitude. The forward tilt of the stalk decreases and the ear picking attitude improves as a result of the ear picking roller's decreased compression and friction force on the straw.

Effect of ear picking roller cone tip spacing on picking attitude

The front and middle ends of the ear picking device cannot effectively pull down the maize stalks when the cone tips of the ear picking rollers are more than 150 mm apart. All of the ear picking positions are at the back end of the ear picking rollers, indicating that the gap between the ear picking rollers is too great. The minimum distance between the cone tips of the ear picking rollers of the ear picking device used in this test is 101.6 mm. The test values were chosen based on the five spacings of 101.6 mm, 111.6 mm, 121.6 mm, 131.6 mm, and 141.6 mm.

Figure 6 shows that when the distance between the cone tips of the ear picking rollers increases, the stalk inclination angle decreases and the ear picking attitude improves. However, under the same ear picking roller gap, there is a significant difference in the stalk inclination angle between diameters and ear picking attitude. The reason for this is that the ear picking roller's clearance with the ear picking roller cone tip spacing increases. This directly impacts the corn stalks' compression, which decreases, the corn stalk and the ear picking roller's contact to stabilize the resistance process decreases, the stalk forward tilt decreases, and the picking attitude improves.

Virtual simulation experiment

Experimental design

The aforementioned simulation test indicates that the plant inclination angle is less and the picking attitude is better when the machine travelling speed is between 0.8 m/s and 1 m/s and the cutting table's inclination angle is between 20.9° and 27.5°. The range of the bottom angle was found to be 73.3°-81° based on the structural study of the ear picking roller's front end above. The Box-Behnken experimental design was used to perform a virtual simu-

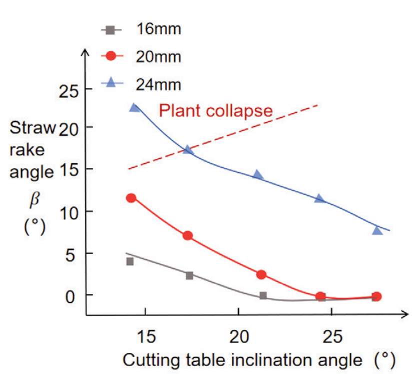


Figure 5. Graph of the results of the one-factor test of cutter inclination angle.

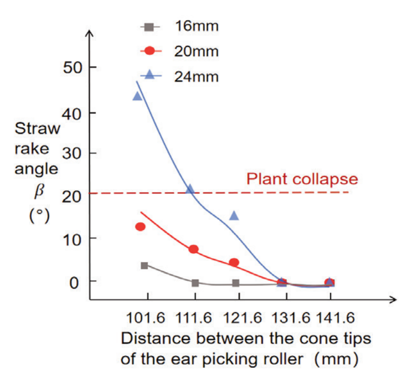


Figure 6. Graph of the results of the one-factor test on the spacing between the cone tips of the ear picking rollers.

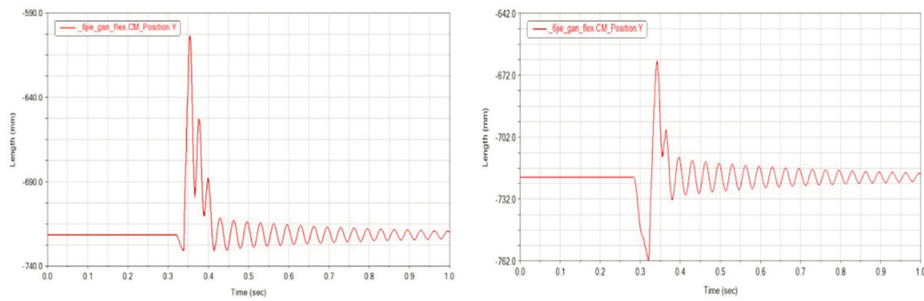
Table 1. Test factor codes.

Encodings	Considerations Machine travelling speed A (m/s)	Cutting table inclination B (°)	Bottom angle of the front end of the stem-drawing roller C (°)
-1	0.8	20.9	73.3
0	0.9	24.2	77.2
1	1	27.5	81

lation test for the aforementioned factors in order to minimize the number of tests and determine the parameter combination with the smallest plant inclination angle. Table 1 displays the codes and experimental factors.

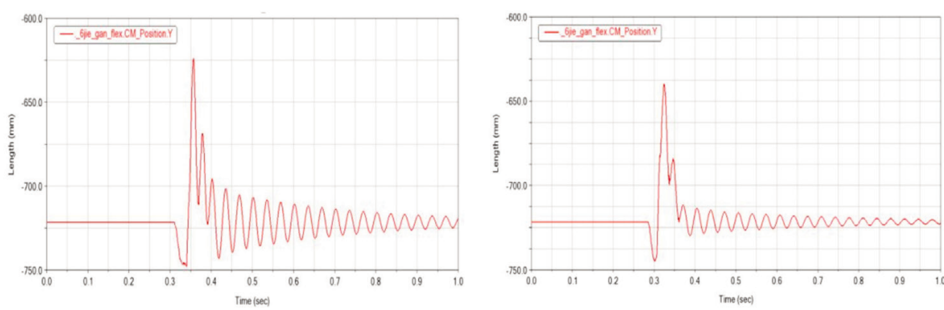
Analysis and optimisation of test results

Figures 7 and 8 show the variation curves of stalk centre-of-mass displacement at 0.9 m/s travelling speed of the implement, with partial cutting table inclination angle and bottom angle of the



(a) Base angle 73.3°   (b) Base angle 81°

Figure 7. Variation curve of stem centre of mass displacement at 20.9° inclination of cutting table.



(a) Base angle 73.3°   (b) Base angle 81°

Figure 8. Variation curve of stem centre of mass displacement at 27.5° cutting table inclination angle.

Table 2. Virtual simulation experiment design scheme and results.

Test number	Experimental factors Machine travelling speed A (m/s)	Cutting table inclination B (°)	Bottom angle of the front end of the stem-drawing roller C (°)	Test indicators Stalk inclination angle β (°)
1	0.9	24.2	77.15	4.5
2	0.8	24.2	73.3	7.8
3	0.8	27.5	77.15	4
4	0.9	27.5	73.3	4.9
5	0.9	27.5	81	2.4
6	1	24.2	81	2.9
7	0.9	20.9	73.3	8.4
8	0.9	24.2	77.15	4.5
9	0.8	24.2	81	3.8
10	0.9	24.2	77.15	4.5
11	1	20.9	77.15	4.9
12	1	27.5	77.15	3.4
13	0.9	24.2	77.15	4.5
14	0.9	24.2	77.15	4.5
15	0.8	20.9	77.15	7.1
16	0.9	20.9	81	6.2
17	1	24.2	73.3	6.4

front end of the ear picking roller. The specific test programme and results are shown in Table 2.

The stalks are initially rowed backward under the action of the stem-pulling roller at approximately 0.35 s when the plant makes contact with the ear picking device, as shown in Figures 7 and 8. Because the stalks' backward rowing speed is marginally greater than the implement's forward speed, their attitude is tilted backward (opposite to the traveling speed of the implement), resulting in the curve initially displaying a slightly concave wave peak. As the cob picking device advances, contact between the stalks and the pulling roller occurs, and the pulling roller clamping process causes the stalks and pulling roller body to move from contact to complete in the forward tilt. This causes the curve to climb quickly and has a first convex wave crest. The second half of the curve displays fluctuating attenuation because the corn stalk resembles an elastic body and will tilt forward following the rebound at the lower end of the stalk-pulling roller clamping stability.

Analysis of variance (ANOVA) was performed on the virtual simulation test results using Design-Expert, and the results are shown in Table 3. The ANOVA of the stalk inclination angle shows that the *p*-value of the regression model of the stalk inclination angle is less than 0.01; this means that the regression model fits well and can be predicted within the range of the test index value. Cutting table inclination angle B and the front bottom angle of ear picking roller C have a *p*-value of less than 0.01 (indicating an extremely significant effect on the stalk forward inclination angle), implement traveling speed A and C^2 have a *p*-value between 0.01 and 0.05 (indicating a significant effect on the stalk forward inclination angle), and the *p*-value of other terms is greater than 0.05 (indicating no significant effect). These findings are based on the *p*-value of each primary term and interaction term.

Multiple regression fitting is used to analyse the test results in Table 2. The regression equation between the stalk forward inclination angle (b) and the implement's traveling speed (A), the cutting table's inclination angle (B), and the bottom angle (C) of the stalk-pulling roller's front end is as follows after terms with little influence were eliminated:

$$\beta = 4.5 - 0.64A - 1.49B - 1.53C + 0.68C^2 \qquad \text{(Eq. 4)}$$

The response surface methodology (RSM) was adopted. By sequentially fixing one factor at the middle level, the effects of the other two factors on the plant forward tilt angle were analyzed to explore the influence law of the two-factor interaction on the plant forward tilt angle. Figure 9 shows the response surface diagrams of the interaction between different factors.

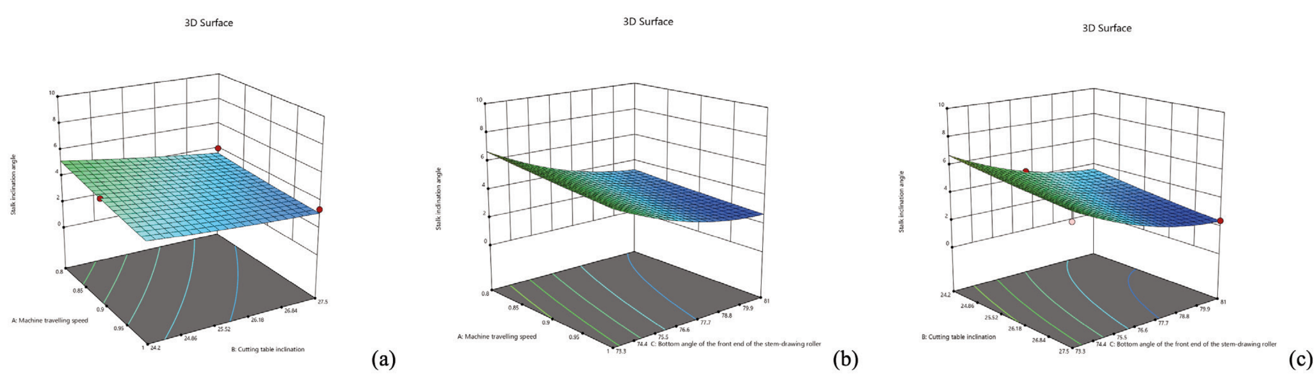


Figure 9. Response surface diagram. **a**) Effect of A and B on stalk inclination angle for C=77.15°. **b**) Effect of A and C on stalk inclination angle for B=25.85°. **c**) Effect of B and C on stalk inclination angle at A=0.9 m/s.

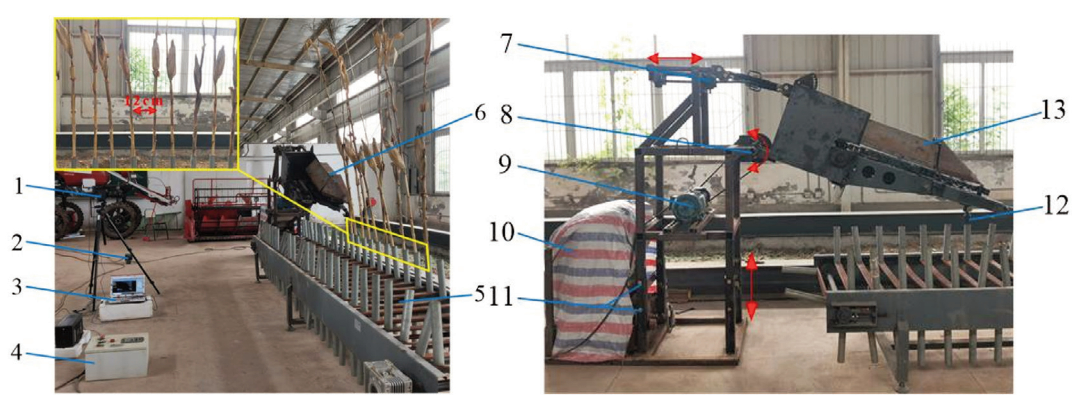


Figure 10. Bench test. **1**, High speed camera; **2**, frequency modulator; **3**, computer; **4**, conveyor belt control box; **5**, conveyor belt; **6**, single row picking test stand; **7**, hand screw lifter; **8**, corn header rotating shaft; **9**, electrical machinery; **10**, counterweight; **11,** locating pin; **12**, front-end support; **13**, single row corn header.

Table 3. Analysis of variance (ANOVA) for stem inclination.

Source of variance	Square sum (*e.g.* equation of squares)	df (physics)	Mean square	F-value	p	Significance
Model	42.72	9	4.75	17.28	0.0005	**
A	3.25	1	3.25	11.84	0.0108	*
B	17.70	1	17.70	64.45	<0.0001	**
C	18.61	1	18.61	67.74	<0.0001	**
AB	0.64	1	0.64	2.33	0.1707	-
AC	0.06	1	0.06	0.22	0.6479	-
BC	0.02	1	0.02	0.08	0.7830	-
A^2	0.01	1	0.01	0.03	0.8503	-
B^2	0.37	1	0.37	1.38	0.2785	-
C^2	1.92	1	1.92	6.99	0.0333	*
Residual	1.92	7	0.27	-	-	-
Lost proposal	1.92	3	0.64	-	-	-
Inaccuracies	0.00	4	0.00	-	-	-
Aggregate	44.64	16	-	-	-	-

Parameter optimisation and validation

A multi-objective variable optimization method was employed with the goal of stem forward inclination angle in order to determine the optimal set of operational parameters (Liu, 2025). The nonlinear planning parameter model was created by combining it with the test factor boundary conditions as follows:

$$\begin{cases} \min\beta(A,B,C) \\ s.t. \begin{cases} 0.8m/s \leq A \leq 1m/s \\ 20.9^\circ \leq B \leq 27.5^\circ \\ 73.3^\circ \leq C \leq 81^\circ \end{cases} \end{cases} \quad \text{(Eq. 5)}$$

The Design-Expert software's multi-objective parameter optimization (Optimization) module was used to solve the problem. Based on the optimization results, a set of parameter combinations was logically chosen from the optimization results, and the predicted stalk inclination angle was 2.4° when the machine travel speed was 0.85 m/s, the cutting table inclination angle was 27.5°, and the bottom angle of the front end of the ear picking rollers was 81°.

A bench verification test was conducted based on the optimization results. The bench setup is shown in Figure 10. The test was repeated three times, and the average value of the stalk forward tilt angle from the three tests was 2.5°, which was basically consistent with the predicted result.

Conclusions

The one-way test determined each factor's influence curve on corn plant forward inclination. The optimal stalk feeding speed (the machine's traveling speed) was 0.8 m/s^{-1} m/s, while the best cutting table inclination angle was 20.9-27.5°. The stalk-pulling roller's front end was modified to lessen stalk forward inclination and promote adaptability to diverse plant sizes. For the cutting table's bottom angle, the stalk-pulling roller's front end had a superior range of 73.1-81°. To reduce stalk forward tilt and adapt to different maize plant diameters, the ear picking roller's front end was conical.

A virtual simulation test using ADAMS' multi-body dynamics analysis program considered the machine's traveling speed, cutting table inclination angle, and ear picking roller front end taper. The machine's moving speed of 0.85 m/s caused the cutting table's inclination angle of 27.5° and the front end of the ear picking roller's bottom angle of 81°, in which the stem inclination angle was lowest.

The optimal data obtained from the test is directly applicable in practice. The optimally designed conical ear picking roller features a simple structure and low processing difficulty, which helps reduce stalk forward tilt. In the future, practical factors such as corn varieties, field soil conditions, and planting density can be incorporated to conduct parameter optimization under multiple scenarios, thereby expanding application scenarios and promoting the overall performance improvement of harvesting machinery.

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