WORKING MECHANISM AND EXPERIMENTAL STUDY OF THE STALK DIVIDING MECHANISM IN CORN HARVESTERS
/
玉米收获机分禾机构的作用机理及试验研究

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ABSTRACT

As the front-end component of the harvesting header in corn harvesters, the smooth feeding of stalks during the operation of the stalk dividing mechanism plays a crucial role in reducing the harvester's operating losses. In this study, the mechanical properties of stalks under the action of stalk division were systematically analyzed, and a kinematic model of the stalk-stalk dividing mechanism was established. The adaptability characteristics between the layout form of the stalk dividing mechanism and single-plant stalk feeding were clarified through experimental statistics and theoretical analysis. Based on the key influencing parameters, an orthogonal test scheme was designed and field validation was conducted. A regression prediction model and a response surface model between the feeding success rate and the parameters were constructed. Validation tests were performed using the optimized parameter combination, and the results showed that the single-plant stalk feeding success rate reached 97.65%±0.08%, with the operating loss in the stalk division stage meeting the expected requirements. This study provides a theoretical basis and technical support for the parametric design and layout optimization of the stalk dividing mechanism.

摘要

分禾机构作为玉米收获机收获割台的前端部件，其作业过程中茎秆的平稳喂入对降低收获机作业损失具有关键作用。本研究系统分析了分禾作用下茎秆的受力特性，建立了茎秆-分禾机构的运动学模型，通过试验统计与理论分析明确了分禾机构布局形式与单株茎秆喂入的适配特性。基于关键影响参数设计正交试验方案并开展田间验证，构建了喂入成功率与参数的回归预测模型及响应曲面模型；采用优化后的参数组合进行验证测试，结果显示单株茎秆喂入成功率达 97.65%±0.08%，分禾环节作业损失符合预期要求。为分禾机构的参数化设计及布局优化提供了理论依据与技术支撑。

INTRODUCTION

As a key link in the whole-chain food loss reduction system, mechanized harvesting loss reduction provides crucial technical support for fortifying the food security line of defense. In the mechanized corn harvesting process, the mechanized harvesting loss rate has decreased from 5% in 2020 to 2.06% in 2024 *(Mao et al., 2025)*. Mechanized harvesting methods are continuously replacing manual harvesting operations *(Szymanek et al., 2025)*. Low-loss harvesting of corn harvesters remains an urgent challenge to overcome in the intelligent development of corn harvesting machinery.

In the mechanized harvesting stage, corn losses can be categorized into indirect losses and direct losses. Indirect losses refer to grain breakage caused by various working processes of the harvester. To address indirect losses, some scholars have reduced harvesting losses by optimizing the control systems of harvesting machinery. An intelligent decision-making system for dynamically adjusting multiple working parameters was proposed to mitigate grain losses resulting from the failure to timely adjust working parameters *(Dong et al., 2025)*. A dual-mode control strategy (manual control and automatic control) was developed for corn harvesting with high moisture content, achieving low-loss threshing of corn with high moisture content *(Zhu et al., 2021)*. Since the harvesting header is the core working component of the corn combine harvester *(Tang et al., 2021)*, measures such as bionic ear picking and optimization of the ear picking structure have been adopted to reduce ear damage *(Zhang et al., 2023; Zhang et al., 2023)*, and a cutting device has been added to the ear picking mechanism to minimize losses during the stalk-ear separation stage *(Li et al., 2023)*.

Direct losses occur when corn plants tilt or break upon initial contact with the harvesting machinery. Unlike crops such as rice and soybeans, corn is harvested using a row-aligned method, which is the first step in corn harvesting.

Typically, a stalk dividing mechanism is installed at the front of the corn harvester to achieve row alignment of corn plants *(Fu et al., 2022)*. For such losses, the key factors lie in whether the stalks can smoothly pass through the stalk dividing mechanism and whether the stalks break within the mechanism. In research on stalk dividing mechanisms, structural parameters of the front-end components of the stalk dividing mechanism have been optimized *(Li et al., 2024; Felipe et al., 2021)*. Scholars from China Agricultural University pointed out that when developing a new type of cutting table for corn stalk and cob combined harvesting machinery, the tip of the stalk divider should be lower than 350 mm, and the height of the operating plane from the ground should be greater than 100 mm *(Zhang et al., 2018)*. Scholars from Shandong Agricultural University evaluated the performance of the stalk divider by analyzing the effects of the operating height of the divider and the forward speed of the harvester on the displacements of corn stalks in the X, Y, and Z directions during harvesting *(Wang et al., 2021)*. A bionic stalk dividing mechanism designed with reference to the mandibles of longhorn beetles was developed to improve the stalk dividing effect during high-speed operations *(Yang et al., 2024)*. Simulation analyses of the stalk dividing mechanism have also been conducted *(Guo et al., 2016; Tai et al., 2020)*. To reduce the loss of fresh corn ears under the action of the stalk dividing device, a new type of stalk divider was designed, which improves the adaptability of the harvesting header to corn plants by combining two types of stalk dividing devices with different lengths and sizes *(Bu et al., 2016)*. Researchers generally analyzed the comparative relationship between the maximum bending angle of stalks under the action of the stalk dividing device and the critical angle at which stalks break, thereby determining the rationality of the designed stalk dividing device *(Du et al., 2014)*.

In summary, only a few scholars have conducted research on stalk dividing mechanisms, and the stalk dividing mechanism and its design parameters have not been thoroughly studied. This study elaborates on the working mechanism of the stalk dividing mechanism, constructs a model of corn stalk movement along the edge of the stalk dividing mechanism under its action, conducts compatibility statistics between the layout form of the stalk dividing mechanism and corn under different planting patterns, selects key parameters and indicators for experimental verification, aims to reduce the mechanized harvesting loss rate of corn harvesters, and provides a theoretical basis for the parametric design of the stalk dividing mechanism.

MATERIALS AND METHODS

Research on the Stalk Dividing Mechanism

Located at the front end of the harvesting header, the stalk dividing mechanism is the first component of the corn combine harvester to come into contact with corn stalks *(Kovács et al., 2018)*. Its core function is to guide the stalks within the target area to smoothly feed backward during the row-aligned harvesting operation of the harvester. When subjected to the action of the stalk divider, the stalks bend relative to their original position while moving backward along the acting edge of the stalk dividing mechanism. At this stage, it is essential to ensure that the stalks bend without direct breakage. To prevent clogging of the rear ear picking mechanism and guarantee the ear picking effect, the feeding of single-plant stalks should be prioritized within the same stalk dividing gap. The stalk dividing gap refers to the area formed between two adjacent stalk dividing mechanisms, where the stalks are subjected to the stalk division action. Typically, the outer surface of the stalk dividing mechanism is designed in a semi-conical shape, which reduces the contact area between the acting edge and the stalks, thereby facilitating the backward transportation of the stalks.

Force Model of Corn Stalks-Stalk Dividing Mechanism

Under the stalk division action, the stalks move backward along the edge of the stalk dividing component, and the mechanical forces acting on the stalks at this time are as shown in Fig. 1.

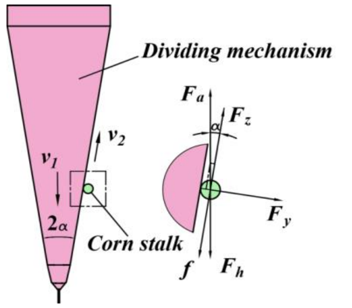


Fig. 1 - Force Analysis of Stalks Under Dividing Action

v_1 is the forward direction of the divider mechanism, v_2 is the moving direction of the stalk along the rear edge of the divider mechanism, the dividing tip angle is 2α, F_a is the acting force of the stalk on the divider mechanism in the direction opposite to the forward direction, F_h is the acting force of the divider mechanism on the stalk in the forward direction, F_y is the acting force of the divider mechanism edge on the stalk, and f is the friction force of the stalk under the dividing action.

The condition for the divider mechanism to satisfy the backward sliding of the stalks is as follows:

$$F_z \geq cos\alpha F_h + f \tag{1}$$

Since all component surfaces are subjected to spray painting treatment, and the value of the rolling friction force exerted by corn stalks on the stalk dividing mechanism is much lower than the force exerted by the stalk dividing mechanism on the stalks, under the condition of ignoring friction, the value of the stalk dividing tip angle is the criterion for determining whether the stalks can slide backward.

Kinematic Model of Corn Stalk-Stalk Dividing Mechanism

The index for evaluating whether stalk breakage occurs is the bending angle of the stalks. By comparing the bending angle of the stalks under the action of the stalk dividing mechanism with the critical value of the bending angle when the stalks break, it is determined whether the stalks will break under the action of the stalk dividing mechanism. A schematic diagram of the kinematic model of the stalk-stalk dividing mechanism is drawn. Taking the projection of the midpoint at the rear end of the stalk dividing mechanism on the ground as the coordinate origin O, the direction perpendicular to the forward direction as the OX axis, the forward direction as the OZ axis, and the direction perpendicular to the ground as the OY axis, a 0-XYZ Cartesian coordinate system is constructed, as shown in Fig. 2.

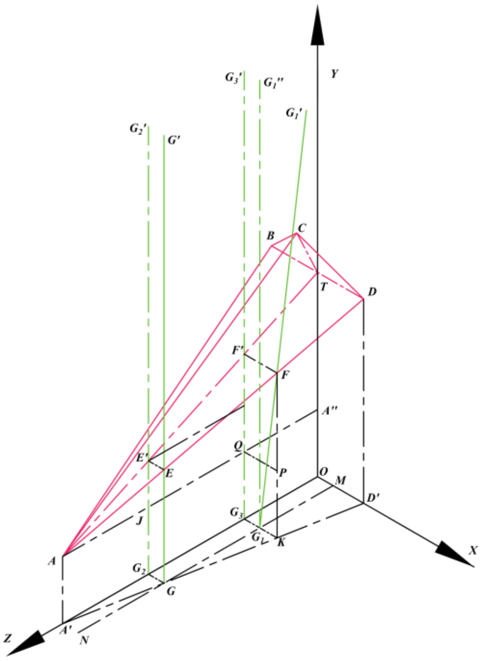


Fig. 2 - Corn Stalk-Divider Mechanism Motion Model

Point A is the lowest point of the divider mechanism, AB and AD are the acting edges of the divider mechanism, $\angle BAD$ is the dividing tip angle, Point T is the midpoint of the rear end of the divider mechanism, and Point C is the highest point of the upper edge of the divider mechanism. Point E is the intersection of the corn stalk and the dividing edge AD. GG' is the initial position when the corn stalk comes into contact with the divider mechanism, and the intersection of the stalk and the dividing edge is Point E.

As the divider mechanism moves along the OZ direction, the stalk moves from Point A to Point D along the dividing edge AD to the position of G_1G_1', and the intersection of the stalk and the dividing edge is Point F at this moment. That is, EF is the moving distance of the stalk along the edge under the action of the divider mechanism after the stalk contacts the divider mechanism. Then the expression of the bending angle of the corn stalk under the action of the divider mechanism is as follows:

$$\begin{cases} arctan\delta = \dfrac{l+sin\frac{\alpha}{2}\cdot S}{h+sin\beta\cdot cot\frac{\alpha}{2}\cdot l+sin\beta cos\frac{\alpha}{2}\cdot S} \quad [°] \\ S = \dfrac{BD}{2sin\frac{\alpha}{2}} - sin\dfrac{\alpha}{2}\cdot l \quad [\text{mm}] \end{cases} \tag{2}$$

where the operating inclination angle is denoted as β, the dividing tip angle as α, the operating height as h, the length of line segment OM as l, the sliding distance of the stalk along the mechanism edge as S, and the stalk bending angle as δ.

Adaptability Analysis of Stalk Dividing Mechanism to Different Planting Patterns

Mechanical sowing is commonly adopted in corn planting (*Duma et al., 2020; Cay et al., 2018*), and the distances between adjacent ridges include 500 mm - 600 mm, 650 mm - 650 mm, 500 mm - 700 mm, and 500 mm - 800 mm (*Wang et al., 2020*). Among these, the planting patterns of 500 mm – 600 mm and 650 mm – 650 mm account for the majority of the planting area in Heilongjiang Province, Jilin Province, and eastern Inner Mongolia. The 500 mm - 600 mm planting pattern is as shown in Fig. 3: two rows of corn are planted on the ridge platform with a spacing of 500 mm, the plant spacing between adjacent ridges is 600 mm, and the height of the ridge platform from the ground is 150 mm. For the 650 mm – 650 mm planting pattern, the distance between adjacent ridges is 650 mm.

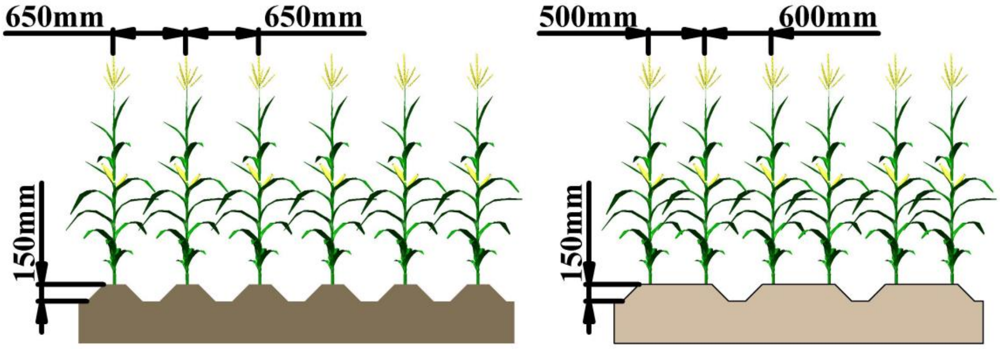


Fig. 3 - Corn Planting Patterns

Theoretical statistical analysis of adaptability was conducted for two planting patterns (500 mm – 600 mm and 650 mm – 650 mm) (*Pargi et al., 2024*). Corn stalk models were placed at the midpoints of ridge spacings, and a kinematic schematic diagram of 6 corn plants was constructed in combination with the layout of the stalk dividing mechanism. The schematic diagram of the 650 mm - 650 mm stalk dividing mechanism and corn planting pattern is shown in Fig. 4. With the stalk dividing mechanism fixed, the first corn stalk on the left along the midline of the stalk dividing gap was selected as the reference target. The corn stalk models were moved integrally to the right with a single movement step of 1 mm. After each movement, the number of corn plants in each ear picking gap was counted until the reference stalk model was tangent to the midline of the stalk dividing mechanism, and the data of each group were recorded.

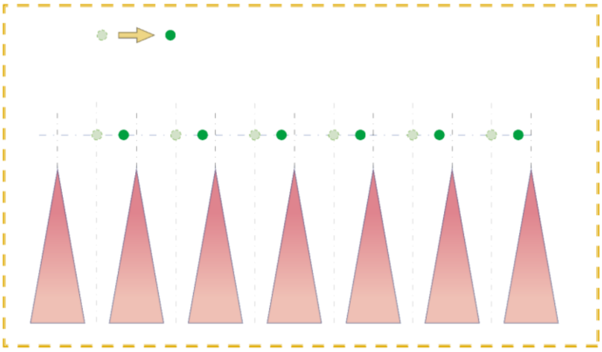


Fig. 4 - Relative Position Between Corn and Divider Mechanism

Two types of stalk dividing mechanisms were sequentially matched and statistically analyzed with two planting patterns to verify their adaptability. For the stalk dividing mechanism corresponding to the 500 mm – 600 mm planting pattern, considering design factors, it was further divided into two subtypes: one arranged symmetrically to both sides with the middle stalk divider as the center at a spacing of 500 mm, and the other at a spacing of 600 mm. During harvesting operations, staggered harvesting is adopted in some plots due to factors such as waterlogging, and some farmers use harvesting headers incompatible with the planting pattern. Therefore, statistical analysis was conducted for the two planting patterns in accordance with the scheme in Table 1, and the results are shown in Fig. 5.

Table 1

Matching scheme

Serial Number	Type of Divider Mechanism	Planting Pattern	Serial Number	Type of Divider Mechanism	Planting Pattern
	mm	mm		mm	mm
1	500-600	500-600	4	650-650	650-650
2	500-600	600-500	5	650-650	500-600
3	500-600	650-650	6	650-650	600-500

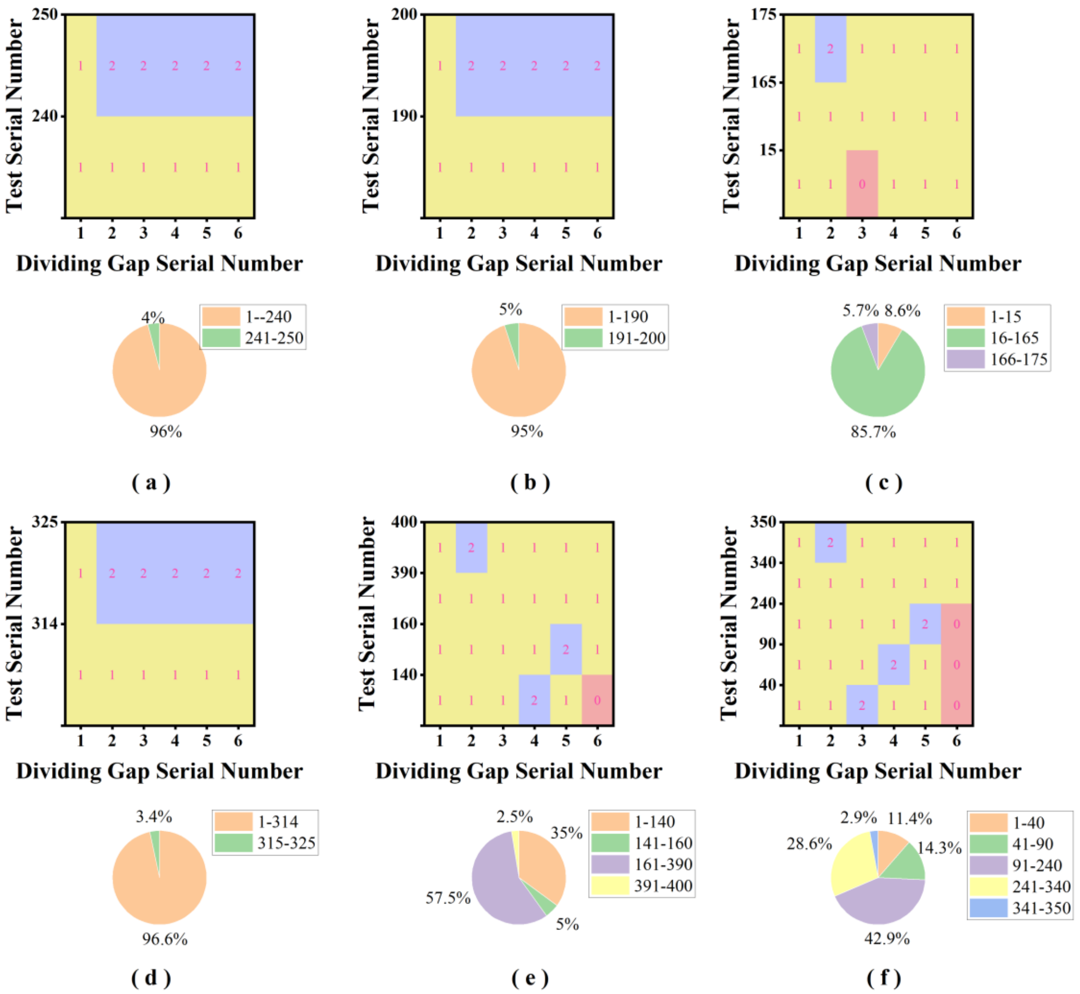


Fig. 5 – Adaptability Statistical Data

Structure and Parameters of the Stalk Dividing Mechanism

The stalk dividing mechanism of the 4YZ-6 type corn combine harvester was optimized and designed in terms of parameters based on the research findings. Its structural configuration is illustrated in Fig. 6. Comprising a flow diversion guide plate, a front-end reinforcement component, a stalk dividing component, and a rear-end fixing component, the stalk dividing device features a modular assembly: the front-end reinforcement component is fastened to the stalk dividing component via bolt-nut connections, and the remaining components are integrated into a single unit through welding.

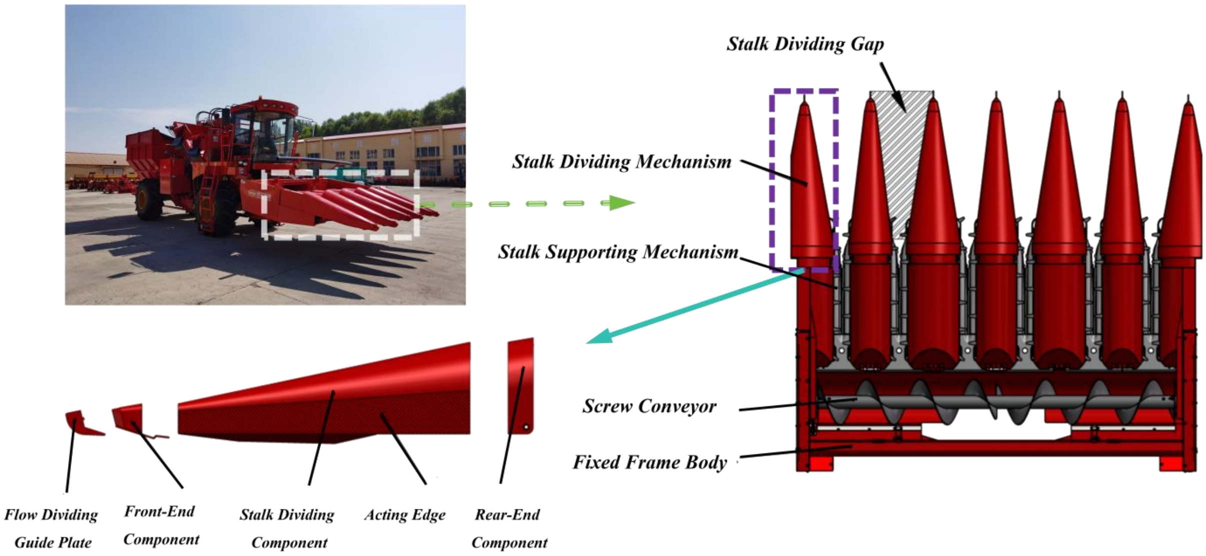


Fig. 6 - The 4YZ-6 Corn Combine Harvester and Its Stalk Dividing Mechanism

The flow dividing guide plate plays a guiding role, directing the corn stalks directly in front of the stalk dividing device to both sides of the device under ideal conditions. The front-end reinforcement component serves a protective function: during the harvesting operation of fresh corn, the stalk dividing device usually needs to be lowered to a position close to the ground to ensure that the working surface of the ear picking device is located below the ears. Therefore, to prevent damage caused by contact between the stalk dividing device and the ground, a front-end reinforcement component is designed at the front of the stalk dividing device. The replacement of this component can be quickly completed by removing and installing bolts, aiming to reduce maintenance time and costs. The stalk dividing components gather the corn plants along the forward direction to the center of two adjacent stalk dividing components, guiding the plants to smoothly feed into the ear picking gap for the separation of ears from stalks. The rear fixing component integrally fixes the entire stalk dividing device above the ear picking device.

Instead of welding, the flow dividing guide plate is installed by inserting it into the front-end reinforcement component and fastening with bolts and nuts. This installation method avoids the flow dividing guide plate tilting to the left or right, which would otherwise affect the stalk dividing effect. To reduce the number of broken stalks, the front-end reinforcement component is specially designed. The key structural parameters of the stalk dividing mechanism are as follows: the total length is 1500 mm. For the 500 mm gap, the rear-end diameter is designed to be 375 mm with a stalk dividing sharp angle of 14.26°; for the 600 mm gap, the rear-end diameter is 475 mm with a stalk dividing sharp angle of 18°; for the 650 mm gap, the rear-end diameter of the stalk dividing mechanism is 525 mm with a stalk dividing sharp angle of 19.86°.

Field Tests

The 4YZ-6 corn combine harvester was selected as the test carrier, and other test materials included a DJI Action 4 sports camera, stopwatch, computer, tape measure, ruler, and so on. The test was conducted at Longmen Farm, Wudalianchi City, Heilongjiang Province, China, with the fresh corn cultivar “Wannuo 2000” as the test crop. The test period was September 17, 2025. For the component design requirement, the front-edge dimension of the component must be smaller than the diameter of the corn stalks. Three 50-meter-long horizontal non-row-aligned plots were randomly selected, with an effective harvesting row spacing greater than 18 meters. Prior to the test, lodged plants, diseased ears, and ears with an ear height lower than 30 cm in the test area were removed (*Li et al., 2024*).

RESULTS

The stalk bending angle was chosen as the evaluation index, while the operating inclination angle, operating height, and relative distance between the stalk and the stalk dividing mechanism were selected as the test factors. The levels of the test factors are shown in Table 2, and the orthogonal test scheme and results are presented in Table 3 (*Wang et al., 2019; Gregor et al., 2023*). The calculation basis for the feeding success rate is as follows [eq. (3)]:

$$C_g = \frac{C_r}{C_z} \times 100\% \tag{3}$$

where:

C_g is single-plant stalk feeding success rate; C_r is number of successfully fed stalks; C_z is total number of stalks.

Table 2

Table of factors and levels

Level	Operating Height	Operating Inclination Angle	Relative Distance
	mm	°	mm
1	400	20	320
0	300	14	155
-1	200	8	10

Table 3

Experimental program and results

Number	Factors			Indicators
	Operating Height [mm]	Operating Inclination Angle [°]	Relative Distance [mm]	C_g [%]
1	400	14	10	94.392
2	200	8	155	96.1905
3	300	8	155	93.594
4	300	14	155	91.6865
5	300	8	320	93.788
6	300	14	155	91.767
7	200	20	155	96.8645
8	300	14	155	92.1965
9	300	20	10	97.9815
10	300	20	320	93.775
11	300	8	10	94.504
12	400	14	320	92.0925
13	200	14	10	95.376
14	200	14	320	93.371
15	300	20	155	96.371
16	300	14	155	91.4655
17	300	14	155	91.701

Regression model construction and testing

Combined with the analysis of experimental data results, multiple regression fitting, and Table 4, it can be seen that x_2、x_3、x_2x_3、x_1^2, and x_2^2 had an extremely significant effect on the single-plant stalk feeding success rate (P<0.01); x_1、x_1x_2、x_3^2 and x_3^2 had a significant effect on the feeding success rate (0.01<P<0.05); while $x_1x_3$had no significant effect on the feeding success rate (P>0.1). After incorporating the regression sum of squares and degrees of freedom of the insignificant interaction terms into the residual term and re-performing analysis of variance (ANOVA), the regression equation describing the single-plant stalk feeding success rate (C_g) was obtained as follows [eq. (4)]:

$$C_g = 91.75 - 0.491x_1 + 1.02x_2 - 1.15x_3 + 0.7412x_1x_2 - 0.8826x_2x_3 + 1.51x_1^2 + 2.86x_2^2 + 0.4794x_3^2 \tag{4}$$

Doing a loss-of-fit test on Eq.4 yields that P=0.1578 is not significant (P>0.1), thus indicating that there are no other major factors affecting the test indicator and that there is a significant quadratic relationship between the test indicator and the test factor.

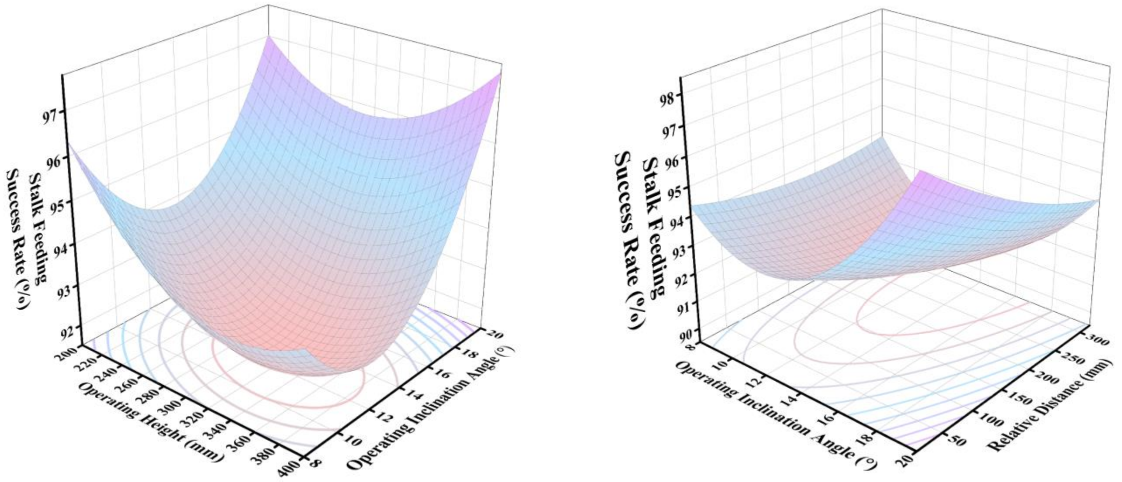
Table 4

ANOVA of stalk feeding success rate

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	65.4	9	7.27	54.63	<0.0001***
x_1	1.04	1	1.04	7.82	0.0267**
x_2	6.25	1	6.25	47.02	0.0002***
x_3	10.64	1	10.64	80.01	<0.0001***
x_1x_2	0.8235	1	0.8235	6.19	0.0417**
x_1x_3	0.0246	1	0.0246	0.1851	0.68
x_2x_3	3.12	1	3.12	23.46	0.0019***
x_1^2	6.27	1	6.27	47.1	0.0002***
x_2^2	28.95	1	28.95	217.63	<0.0001***
x_3^2	0.7655	1	0.7655	5.76	0.0475**
Residual	0.931	7	0.133		
Lack of Fit	0.6449	3	0.215	3	0.1578
Pure Error	0.2861	4	0.0715		
Cor Total	66.33	16			

*Note: *** means highly significant ($P < 0.01$), ** means significant ($0.01 \le P < 0.05$); * means significant ($0.05 \le P < 0.1$).*

Data processing was performed on the experimental results, and the response surface as shown in Fig. 7 were constructed in combination with the regression equation *(Dean et al., 2017)*.



(a) (b)

Fig. 7 - Response Surfaces

As shown in Fig. 7, within the range of test parameters, the feeding success rate exhibits a trend of first decreasing and then increasing with the increase in operating height and operating inclination angle. The operating inclination angle has a greater influence on the feeding success rate than the operating height, and their interaction effect significantly affects the feeding success rate.

The influence intensity of the operating inclination angle on the feeding success rate is significantly greater than that of the relative distance (between the stalk and the stalk dividing mechanism). The feeding success rate first decreases and then increases rapidly with the increase in the operating inclination angle, while it shows a slow linear decreasing trend with the increase in the relative distance. The interaction effect between these two factors also has a significant impact on the feeding success rate.

To obtain the optimal combination of working parameters (*Zhu et al., 2022*), response surface optimization was performed using Design-Expert software:

$$\left\{\begin{array}{c} maxC_g \\ s.t.\left\{\begin{array}{c} 8^\circ \le \beta \le 20^\circ \\ 200mm \le h \le 400 \\ 0mm \le l \le 320 \end{array}\right. \end{array}\right.$$

The theoretical optimal parameter combination of the stalk dividing mechanism was obtained through calculation (*Zhu et al., 2023*): an operating height of 396.932 mm, an operating inclination angle of 19.989°, and a relative distance of 8.569 mm, corresponding to a maximum feeding success rate of 98.73%.

Validation tests were conducted according to the optimal parameter combination. Considering the convenience of debugging in practical applications, the parameter values were rounded. The results of five repeated validation tests showed that the feeding success rate under the adjusted optimal parameter combination was 97.65% ± 0.08%. The absolute error between the measured value and the predicted value did not exceed 0.25 percentage points. Taking into account the existing human operation errors, the measured results were highly consistent with the theoretical optimized values, verifying the reliability of the parameter optimization. According to the requirement for ear loss rate of fresh corn harvesters specified in the national standard GB/T 21962-2020 "Corn Harvesting Machinery", the loss rate in the stalk dividing stage meets the requirement that the total loss rate is less than 3%. Thus, the operational performance indicators of the stalk dividing mechanism comply with the standard requirements.

CONCLUSIONS

This study elaborates on the working mechanism of the stalk dividing mechanism. The force forms of corn stalks under the action of stalk division were analyzed, and a displacement model of the corn stalk-stalk dividing mechanism under stalk division was constructed to explore the adaptability of single-row corn stalk feeding. Orthogonal field tests were conducted to statistically analyze the single-plant stalk feeding success rate of the stalk dividing mechanism. Based on the test results, a regression equation and response surface models were established to verify the operational effect of the stalk dividing mechanism. An optimal parameter combination scheme was developed and subjected to secondary validation tests. The final single-plant stalk feeding success rate reached 97.65% ± 0.08%, and the ear loss rate during the stalk division stage complied with the requirements specified in relevant standards. This research provides a theoretical reference for the parametric design and layout optimization of the stalk dividing mechanism, contributing to the development of low-loss and high-efficiency corn harvesting machinery.

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