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DESIGN AND EXPERIMENTAL STUDY OF SORGHUM CUTTING TABLES BASED ON A PUSH AND DIVISION INTEGRATED OUTER DIVIDER

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KEYWORDS

harvester; sorghum; cutting table; outer divider; loss ratio.

ABSTRACT

At present, there are serious problems in sorghum harvesting, such as lodging entanglement and the loss of broken stems due to the lack of an external dividing device for the cutting table and holding device. Based on the physical and mechanical characteristics of sorghum plants, an integrated outer divider was developed. The main structural parameters and working parameters of the outer divider were determined. A comparative test of the working quality of the outer divider was carried out. The results show that the working quality of the cutting table with the outer divider is obviously better than that without the outer divider and that the harvest loss of the cutting table is effectively reduced. The Box–Behnken experimental design method was used to investigate the effects of the forward speed, rotation speed of the grain lifter and dividing angle of the outer divider on the lodging and broken stem loss rates during sorghum harvesting. The regression mathematical model and response surface of the lodging and broken stem loss rates and the analysis factors were established, and the optimal working parameters of the outer divider were determined as follows: the dividing angle of the outer divider was 20°, the forward speed was 0.8 m/s, and the rotating speed of the grain lifter was 330 rpm. Under these parameters, the loss rate of the fall was 1.08%, and the loss rate of broken stems was 1.05%, which met the requirements of sorghum cutting tables.

INTRODUCTION

As one of the main grain crops in China, sorghum has a long planting history and is widely used. In recent years, with the increase in the liquor market, the planting area of sorghum has increased annually (Han et al., 2017; Cao et al., 2020). However, owing to the constraints of the local economy, the planting environment and other factors, research on sorghum harvesting mechanization technology and equipment is still in the initial stage. As one of the important working parts of sorghum harvesters, the cutting table mainly completes the harvesting and feeding of sorghum ears. During the mature harvest period, sorghum plants are prone to skew and lodging, resulting in overlapping and winding among stalks, leaves and ears, which often leads to unclear grain division during cutting table operation, increasing the harvest loss of the cutting table and greatly affecting the working reliability of the cutting table (Al-Zube et al., 2017; Fan et al., 2022; Gomez et al., 2017; Gomez et al., 2018; Kebrom et al.,2017). Therefore, it is highly important to carry out research on dividing and supporting grain during sorghum harvest to reduce the loss of the cutting table.

To solve the problem of cutting table loss caused by plant entanglement and ear overlap during sorghum harvest, scholars and experts at home and abroad have extensively researched this problem (Fu et al., 2022). Domestic sorghum mechanized harvesting technology is relatively rare. Yang proposed a design scheme for the cutting table of a sweet sorghum harvester, but there is a problem of a high gripper chain drop rate, which affects stalk transmission (Yang et al., 2011). Geng reduced the loss of the cutting table within a certain range by lengthening the bottom plate of the cutting table and increasing the diameter of the harvesting wheel, but there was a serious problem of ear loss (Geng et al., 2022). In foreign countries, for example, the sorghum cutting table produced by John Deere Company is equipped with reverse rotating spiral dividing

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devices on both sides of the cutting table, which realizes the effective separation of plants inside and outside the harvest row and achieves good results (Forell et al., 2015). In a cutting table produced by CASE Company, reciprocating cutters are set on both sides of the cutting table so that the plants inside and outside the harvesting line are actively cut, and the efficient separation of the plants inside and outside the harvesting line is realized (Ma et al., 2014; Seegmiller et al., 2020). In addition, to completely solve this problem, foreign countries have also made efforts in variety development, research and development and cultivation of tight ear sorghum, reduced the overlap and winding of ears, and reduced the harvest loss of sorghum (Kashiwagi & Ishimaru, 2004; Lemloh et al., 2014; Liu et al., 2022; Muhammad et al., 2020; Stubbs et al., 2020).

Although the planting area of sorghum in China is large and the yield is high, sorghum is mostly planted in hills and mountains, so it is mainly harvested via artificial harvesting, which is associated with many operation links, high losses, and easily threatened by bad weather. Some enterprises also refer to foreign models and develop reverse rotation augers to divide grains and support grain devices; however, because of the domestic sorghum skew, long leaves and scattered ears make it difficult to solve the problem of sorghum division and support grains (Wang et al., 2020). Therefore, on the basis of foreign technology, the team developed an integrated sorghum splitting and supporting device, which better solved the problem of separation inside and outside the harvesting row of sorghum with long leaves, loose grain ears and multiple tilting or even falling, and reduced the loss of the cutting table during sorghum harvesting.

MATERIAL AND METHODS

Overall structure of the cutting table

To address problems such as thin and tall sorghum plants, narrow and long leaves, scattered and overlapping ears, and skew and falling plants, a sorghum harvesting and cutting table based on push and division integration was developed. Its structure is shown in Figure 1. It is mainly composed of an outer divider rod, a grain lifter, an inner divider, a transverse conveyer, a gripping conveyor chain, a power input system cutter and a frame.

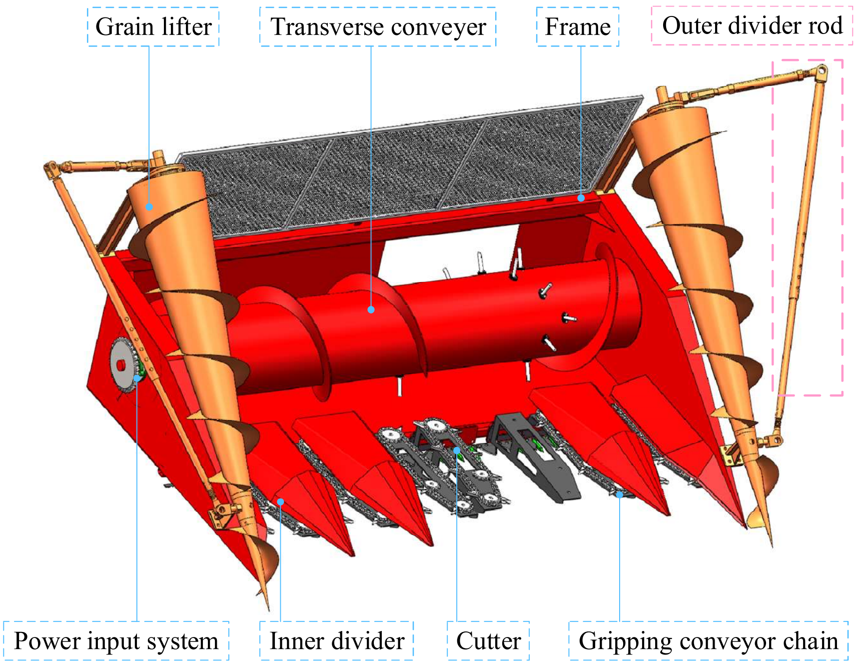


FIGURE 1. Structural diagram of the sorghum cutting table.

During operation, the sorghum cutting table is connected to the front of the harvester. As the harvester advances, the grain lifter located on both sides divides the sorghum to be harvested into two parts inside and outside the cutting width. The sorghum plants at the cutting width are introduced into the gripper conveyer chain under the action of the inner divider. When the gripper conveyer chain transfers the sorghum plants to the cutter, the cutter then cuts the lower part of the plant, and the cut plant is sent to the transverse conveyor auger under the push action of the inertia force and the connecting plant. When the sorghum plant skews and collapses, the inner divider and the front part of the grain lifter are inserted into the lower part of the plant and transported to the cutter under the action of the gripper conveyer chain, where the front part of the side of the grain lifter actively helps the plant avoid the problem that plant leakage causes the tire of the harvester to crush and increases harvest loss. The upper part of the plant lies on the surface of the grain lifter, and the helical blade in front of the grain lifter pushes the plant gradually backward while righting the plant, avoiding the problem that the sorghum plants intertwine with other plants and drag to increase the harvest loss during the clamping and conveying process and preventing the plants from entangling and piling up and blocking the cutting table.

The sorghum plant outside the cut width, if the stalk is upright and does not skew or fall, is pushed outward and backward from the front part of the grain lifter to the position of the outer grain dividing pole. With the advance of the harvester, the plants are gradually pushed to the outside under the action of the outer divider rod, and the grain loss caused by the collision and entanglement between the ear and the leaf of the sorghum plant and the helical leaf of the grain lifter is avoided. If the stalk is skewed, lay down, or even interleaved, the plant is separated by the helical leaf at the front of the grain lifter and is gradually pushed backward to the position of the outer divider rod to avoid the problem of winding and dragging the plant in the cut width with it, resulting in increased grain loss at the ear. With the advance of the harvester, the external harvester pushes the plant to the outside at the same time but also moves upward and backward until reaching the approximate upright state to ensure the smooth passage of the harvester, effectively reducing the drag and winding loss of the ear of the sorghum plant outside the cutting width and improving the reliability of the sorghum cutting table.

Determine the parameters of the outer divider

To solve the problem that the overlap and entanglement of stems, leaves and ears of sorghum during the harvest period affect work reliability and harvest loss and to solve the righting of fallen sorghum, an outer divider rod structure with adjustable arms is adopted to achieve outward separation of the cut outer sorghum. The main structure is shown in Figure 2.

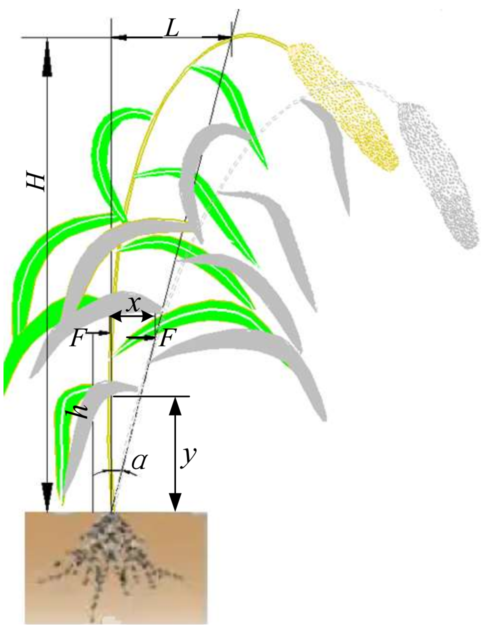


FIGURE 2. Analysis of plant deformation under force *F*.

Rule of influence of the dividing position on the deflection angle

Owing to its height, ear weight, relatively thin stalk and dense planting, sorghum is prone to skew and even lodging during maturity, which increases the risk of mutual interference among the stem, leaf and ear and increases the harvest loss of the sorghum cutting table. For this reason, this study adopted the scheme of separating sorghum with the cut edge through the grain lifter and pushing the stems outside the cut edge through the rod, which improved the reliability of the separation of the stems, leaves and ears of the plants outside and inside the cut edge and reduced the harvest loss on the cutting table.

To reduce the probability of overturning sorghum plants in the working process, the influence laws of the plant deflection angle and lateral offset were investigated by analyzing the plant position (Robertson et al., 2015). Assuming that a force F is applied to a position with a height h from the surface, the stalk is pulled until broken under the action of this force F, where the maximum lateral offset of the application point is represented by x, the maximum angle α of the straight line connecting the application point to the root and the vertical direction is the deflection angle, ignoring the influence of spike gravity on the transverse deviation and deflection angle of the stalk, the stalk is in the state of cantilever beam at this time, and the bending moment of section y from the base is as follows:

$$M(y) = F(h - y) \tag{1}$$

Obviously, $M(y)$ is at a maximum when y=0, that is:

$$M_{\max}(y) = Fh = Fy \tag{2}$$

That is, the maximum bending moment occurs at the base of the sorghum plant, which is consistent with the phenomenon that the sorghum plant is mostly broken from its lower part during harvesting.

Furthermore, the differential equation of the flexible curve is as follows:

$$x'' = -\frac{M(y)}{EI} = \frac{Fy}{EI} \tag{3}$$

The lateral displacement of the stem is obtained from position y measured from the base:

$$x = \frac{Fy^2(3h - y)}{6EI} \tag{4}$$

Where:

F-the maximum bending load that can be borne by the stalk is 88.26 *N*;

E-the elastic modulus of sorghum stalk, 44.60 *MPa*;

I-the moment of inertia of the section with respect to the neutral axis is 0.785.

When $y=h$ (the position of the force application point), the lateral offset clearly reaches its maximum value, which is:

$$x_{\max} = \frac{Fh^3}{3EI} \tag{5}$$

Similarly, the stalk deflection angle is:

$$\alpha_{\max} = \frac{Fh^2}{2EI} \tag{6}$$

As seen from the above equation, the lower the application point of the outer divider rod force is, the smaller the deflection angle and lateral deviation of the stalk, that is, the easier it is to cause the stalk to bend during the dividing process; the higher the application point of the outer divider rod force is, the larger the deflection angle and lateral deviation of the stalk, the more conducive it is to the separation of the stalk and stem and leaf, and the bending problem will not occur.

Determination of the horizontal direction angle of the outer divider rod

As above, the larger the horizontal deviation angle of the outer divider is, the more conducive it is to the separation of sorghum ears and stems and leaves, but too large may lead to bending of the plant, so to avoid bending of the stalk during the grain dividing process, the horizontal angle of the outer divider is equal to the deflection angle of the base of the outer divider (Lee et al., 2020; Li et al., 2018). The cutting height of sorghum during harvest ranged from 30 cm-40 cm. Since the function of the outer divider is to separate the sorghum plants inside and outside the cut width and the maximum lateral displacement of the stalk mentioned above is the lateral displacement of the contact position of the outer divider, the stalk deformation of the plant under the action of *F* is analyzed to determine the spike offset, as shown in Figure 2.

$$L = H\tan\alpha = H \times \frac{x_{\max}}{h} \tag{7}$$

After the relevant data were substituted, the offset distance of the ear was 55~115 cm, which was greater than the length of the sorghum ear, meeting the separation conditions of the wrapped sorghum ear.

Determination of vertical direction angle of the outer divider rod

To realize the gradual upward movement of stem separation, the outer divider rod of the sorghum cutting table is tilted upward, as shown in Figure 3.

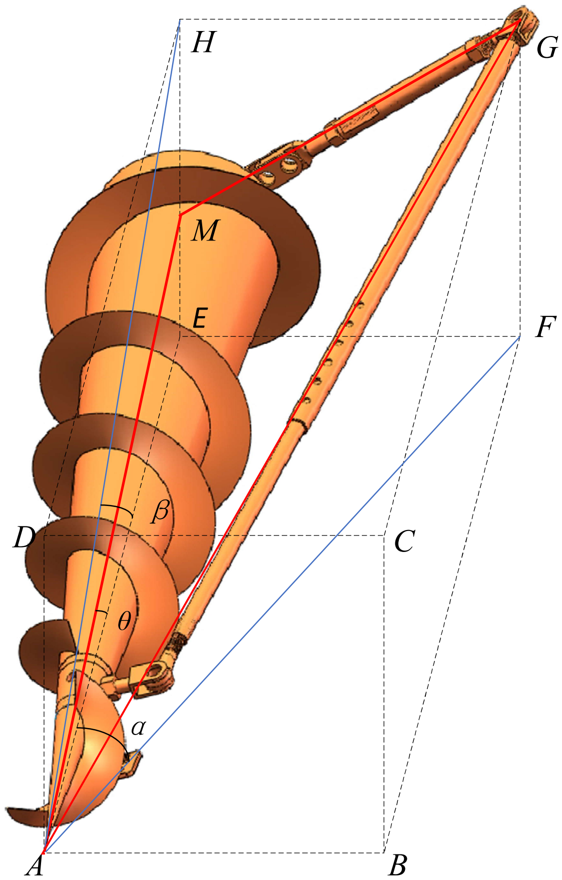


FIGURE 3. Determination of the position of the outer divider rod.

We assume that the angle between the horizontal plane and the forward direction is $\angle EAF=\alpha$ and that the angle between the vertical plane and the forward direction is $\angle HAE=\beta$; then, the actual position of the outer divider rod is *AG,* and the position of the grain lifter is *AM*. The angle between it and the horizontal plane is $\angle MAE=\theta$, and the minimum distance between the outer stalk and the inner stalk when the sorghum plant is pushed to the end position of the outer stalk is *MG* (because, as the sorghum plant is pushed by the outer stalk, the stalk will only move away from the grain lifter the action of gravity at the ear). Obviously, to ensure a reliable separation effect, then:

$$MG_{\min} \geq \max(l_p, l_l) \tag{8}$$

Where:

l_p- length of sorghum ear (stem skin hard and not easy to bend), *cm*;

l_l- the maximum length of sorghum leaves, *cm*.

The length of the grain is $AM= l$, and the angle between it and the horizontal plane is $\angle MAE=\theta$; then,

$$MG_{\min} \geq \max(l_p, l_l) \tag{9}$$

As previously known, the angle between the projection of the outer divider rod on the horizontal plane and the direction of advance is $\angle EAF=\alpha$, so:

$$EF = AEtan\alpha = lcos\theta tan\alpha \tag{10}$$

$$AF = \frac{AE}{\cos\alpha} = \frac{l\cos\theta}{\cos\alpha} \tag{11}$$

In $\triangle HMG$:

$$HM = \sqrt{MG_{\min}^2 - HG^2} = \sqrt{MG_{\min}^2 - EF^2} = \sqrt{MG_{\min}^2 - AE^2\tan^2\alpha} \tag{12}$$

In $\triangle AHE$:

$$\begin{aligned}\beta &= \arctan(\frac{HE}{AE}) = \arctan(\frac{HM+ME}{AE}) = \arctan(\frac{\sqrt{MG_{\min}^2 - AE^2\tan^2\alpha} + l\sin\theta}{l\cos\theta}) \\ &= \arctan(\frac{\sqrt{MG_{\min}^2 - l^2\cos^2\theta\tan^2\alpha} + l\sin\theta}{l\cos\theta})\end{aligned} \tag{13}$$

The substituted relevant data are as follows: β=15.77°.

Determination of the length and angle of the outer divider rod

As shown in Figure 3, the length of the outer divider rod AG is as follows:

$$\begin{aligned}AG &= \sqrt{AF^2+FG^2} = \sqrt{(\frac{lcos\theta}{cos\alpha})^2 + HE^2} = \sqrt{(\frac{lcos\theta}{cos\alpha})^2 + (HM+ME)^2} \\ &= \sqrt{(\frac{lcos\theta}{cos\alpha})^2 + (\sqrt{MG_{\min}^2 - (lcos\theta)^2\tan^2\alpha} + l\sin\theta)^2}\end{aligned} \tag{14}$$

The dividing angle before the outer divider rod and the grain lifter apparatus is γ, and the relevant data are as follows:

$$\gamma = \arctan(\frac{MG_{\min}}{AM}) = \arctan(\frac{MG_{\min}}{l}) \tag{15}$$

AG=190.92 cm, and γ=20.56°.

Test scheme

The experiments were divided into comparison experiments, field orthogonal experiments and field verification experiments.

Test conditions

Considering that the inner divider is the function of the harvest line and that the plant will be lifted by it and introduced into the gripper conveyer device, the operation performance of the outer divider is only verified and analyzed here. The experiment was carried out in the experimental field of Zhu tai town farm, Linzi District, Zibo city, Shandong Province, from September 26 to 29, 2023. The sorghum variety used was "Liang nuo No. 1", with 10 plants per square meter. The plants were crooked and disordered, and the lodging rate ranged from 20--30%. The specific material characteristics are shown in Table 1.

TABLE 1. Physical characteristics of sorghum plants (Variety: Liang nuo No 1).

Project	unit	Minimum value	Maximum value	Mean value
Plant height	*cm*	206.23	231.44	224.06±9.28
Blade length	*cm*	28.82	38.46	32.72±5.60
Ear length	*cm*	41.2	68.6	58.66±25.60
Ear weight	*g*	42.63	105.98	62.78±17.10
Stem moisture content	*%*	34.86	52.63	45.15±4.63
Grain water content	*%*	17.71	27.83	22.11±2.76

The equipment used in the test is shown in Figure 4. The test equipment includes a harvesting machine, a cutting table, a Vernier caliper, an electronic balance, a tape measure and so on.

FIGURE 4. Outer divider field test.

According to the above analysis of the structural parameters and working parameters of the outer divider, the loss rate of sorghum fall and the loss rate of broken stems are the result of the comprehensive action of the forward speed of the harvester, the rotational speed of the grain lifter and the dividing angle of the outer divider rod. Therefore, to grasp the influence law of the above parameters on the performance of the cutting platform, the optimization parameters that are conducive to improving the cutting platform performance should be determined, and orthogonal tests should be carried out.

According to the physical characteristics of the sorghum plants and the field test environment, the forward speed of the sorghum harvester was selected to be in the range of 0.8~1.2 m/s. During harvest, the size of the dividing angle directly affects the cutting operation effect. In this study, the dividing angle range of the outer divider rod was 15~25°; the rotation speed of the grain lifter had a great influence on the lifting of fallen plants. In this study, the rotation speed range of the grain lifter was 300~360 rpm; therefore, the forward speed X_1, the rotation speed of the grain lifter X_2 and the dividing angle of the outer divider rod X_3 were set to carry out three-factor and three-level orthogonal tests, and the test factor levels are shown in Table 2.

TABLE 2. Factors and levels of test.

Forward speed/v_m(m/s)	**Rotation speed of the grain lifter/*n(rpm)***	**Dividing angle of the outer divider rod /γ (°)**
0.8	300	15
1.0	330	20
1.2	360	25

Evaluation indicators

To evaluate the effects of cutting table operation, the GB8231-87 sorghum harvester and GB/T8097-2008 combine harvester were tested, and the loss rates of sorghum and broken stems were measured (State Food Administration, 2007; China Machinery Industry Federation, 2008). Three test areas were randomly selected in the test field, and each test area was divided into a preparation area, test area and parking area (Teixeira et al., 2017). The preparation area is 10 m, the test area is 50 m, the parking area is 5 m, and the width of the test area is the full width of the cutting table (Bai et al., 2021; Du et al., 2018). In the test area, the sorghum ears that were leaked due to broken stems falling outside the machine and falling during harvesting were manually threshed, and the impurities were removed and then weighed and averaged.

Lodging of sorghum is one of the main reasons for the high harvest loss, and lodging loss mainly includes the loss of grain caused by crooked plants, which are difficult to lift when lodging on the ground. The lodging loss rate of sorghum is calculated according to [eq. (17)]:

$$R_{wl} = \frac{w_l}{w_l + w_d + w_h} \tag{16}$$

The loss of broken stems mainly includes grain loss caused by broken stems and ears in the process of dividing and supporting crops. The loss rate of broken stems of sorghum was calculated according to [eq. (18)]:

$$R_{wd} = \frac{w_d}{w_l + w_d + w_h} \tag{17}$$

Where:

R_{wl} - lodging loss rate of sorghum, *%*;

R_{wd} - sorghum stem loss rate, *%*;

w_l - weight of seed lost due to lodging, *kg*;

w_d - grain mass resulting in ear loss due to stem breakage, *kg*;

w_h - total grain mass in the harvester and granary, *kg*.

RESULTS AND DISCUSSION

Comparative analysis of the experimental results

To check the working quality of the external divider on the cutting table, the methods of disassembly (without an outer divider) and installation (with an outer divider) were used to carry out a comparative test of the outer divider on lodging loss and broken stem loss. The results are shown in Figure 5 below.

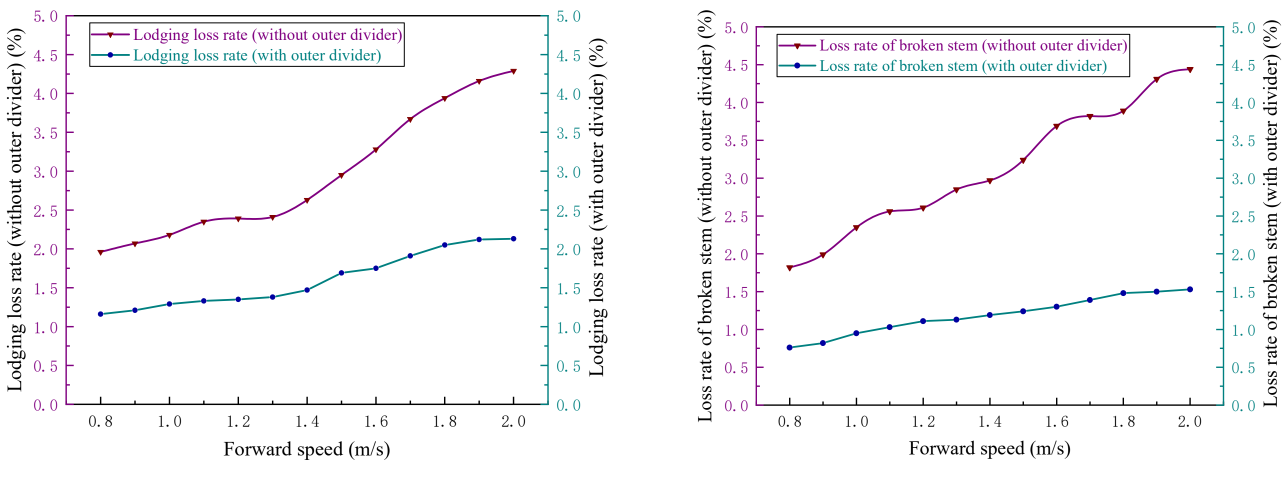


FIGURE 5. **(a)** Comparative analysis of the lodging loss rate; **(b)** comparative analysis of the loss rate of broken stems.

Results and analysis of the field orthogonal experiment

The experimental scheme design and data analysis were carried out according to the Box–Behnken Center combination design theory in Design-Expert 13 software, taking the lodging loss rate of the sorghum head and the loss rate of the broken stem as assessment indices, and the test was carried out 17 times, in which 12 groups were taken as analysis cause points and 5 groups were taken as zero points. Multiple tests were carried out at zero points to estimate the test error. The test scheme and results are shown in Table 3.

As shown in Figure 5, lodging loss and stem breaking loss occur to a certain extent even with or without an outer divider, and with increasing harvester operation speed, the lodging loss rate and stem breaking loss rate both increase within a certain range; however, in the test involving the installation of an outer divider, the loss rate of the fall and the loss rate of the broken stem clearly decrease, especially with increasing harvester operation speed, and the loss rate of the fall and the loss rate of the broken stem clearly decrease. In other words, installing an outer divider on the outside of the harvester can effectively reduce lodging loss and stem breaking loss during sorghum harvesting.

TABLE 3. Test plan and results.

No	Forward speed X_1	Rotation speed of the buttress X_2	The outside branch points the corner X_3	Lodging loss rate/%	Loss rate of broken stem/%
1	1.2	360	20	1.53	1.15
2	1	300	15	1.38	1.18
3	0.8	360	20	1.15	1.09
4	1.2	300	20	1.44	1.29
5	1	330	20	1.12	1.03
6	1	360	15	1.32	1.09
7	1	300	25	1.39	1.76
8	0.8	300	20	1.08	1.22
9	1	330	20	1.11	0.96
10	1.2	330	25	1.6	1.42
11	1	330	20	1.14	0.97
12	1.2	330	15	1.43	1.01
13	0.8	330	15	0.97	0.96
14	1	330	20	1.17	1.01
15	0.8	330	25	1.16	1.35
16	1	360	25	1.56	1.42
17	1	330	20	1.15	1.02

X_1, X_2 and $X3$ are the level values of forward speed, rotation speed of the grain lifter and the dividing angle of the outer divider, respectively.

Lodging loss rate variance analysis

The variance analysis of the lodging loss rate in the test is shown in Table 4, and a quadratic polynomial regression equation was established for influencing factors such as the sorghum lodging loss rate Y_1 at forward speed X_1, the rotation speed of the grain lifter X_2, and the angle of the outer divider rod X_3, as shown in [eq. (18)]:

$$Y_1 = 1.13+0.203X_1+0.033X_2+0.076X_3+2.500\times10^{-3}X_1X_2\text{-}5.000\times10^{-3}X_1X_3 \\ +5.750\times10^{-2}X_2X_3+2.250\times10^{-2}X_1^2+0.145X_2^2+1.375X_3^2 \tag{18}$$

TABLE 4. Analysis of variance of wound loss rate and results.

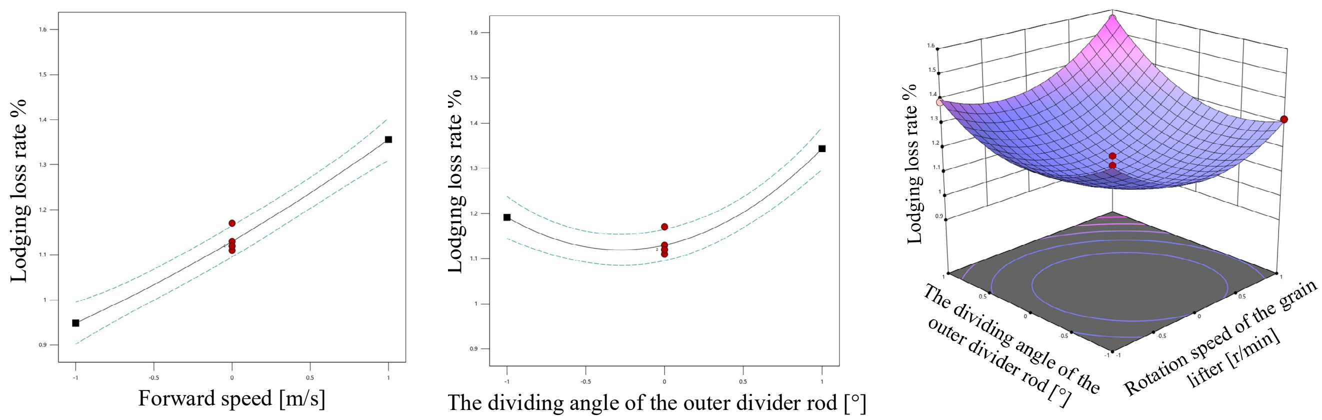
Sources	Lodging loss rate				
	Sum of squares	**Degree of freedom**	**Mean square**	***F* value**	***P* value**
Model	0.5841	9	0.0649	60.37	< 0.0001**
X_1	0.3321	1	0.3321	308.94	< 0.0001**
X_2	0.0084	1	0.0084	7.86	0.0264*
X_3	0.0465	1	0.0465	43.27	0.0003**
X_1X_2	0	1	0	0.0233	0.8831
X_1X_3	0.0001	1	0.0001	0.093	0.7692
X_2X_3	0.0132	1	0.0132	12.3	0.0099**
X_1^2	0.0021	1	0.0021	1.98	0.2019
X_2^2	0.0885	1	0.0885	82.35	< 0.0001**
X_3^2	0.0796	1	0.0796	74.05	< 0.0001**
Residual	0.0075	7	0.0011		
Lack of fit	0.0053	3	0.0018	3.23	0.1437
Pure error	0.0022	4	0.0005		
Correct total	0.5916	16			

P<0.01 (highly significant, **); *P*<0.05 (significant, *).

According to the test of the *F* value, the factors affecting the loss rate of sorghum ranged from the largest to the smallest: the forward speed of the harvester, the dividing angle of the outer divider rod and the rotation speed of the grain lifter. To further optimize the regression model, nonsignificant regression items in the model were removed, and after the lodging loss regression model was optimized, the optimized regression equation was as follows:

$$Y_1 = 1.13+0.203X_1+0.033X_2+0.076X_3+5.750\times10^{-2}X_2X_3+0.145X_2^2+1.375X_3^2 \tag{19}$$

The analysis of the significance test results reveals that the forward speed of the harvester and the dividing angle of the outer divider rod significantly affect the lodging loss rate, and the relationship between the lodging loss rate and the variables is shown in Figure 6(a) and (b). In the range of the given factor level, the forward speed of the harvester is positively correlated with the lodging loss rate; that is, the greater the forward speed of the harvester is, the greater the lodging loss rate. With an increasing dividing angle of the outer divider rod, the lodging loss rate decreases slowly at first and then increases sharply.



(a) $Y_1 = f(x_1、x_2、330)$ **(b)** $Y_1 = f(x_1、28、x_3)$ **(c)** $Y_1 = f(1.0、x_2、x_3)$

FIGURE 6. Winding loss rate in relation to variables.

The significant influence of the interaction on the loss rate is only X_2X_3 when the forward speed of the harvester is set to 0; that is, the forward speed of the harvester is 1.0 m/s, and the response surface is shown in Figure 6c. The lodging loss rate can be maintained at a lower level when the rotation speed of the grain lifter and the angle of the outer rod divider increase or decrease at the same time. When the rotation speed of the grain lifter is 315~345 rpm and the dividing angle of the outer divider rod is 17.5~22.5°, the lodging loss rate is the smallest.

Analysis of variance of the stem loss rate

The variance analysis of the interrupted stem loss rate in the test is shown in Table 5, and a quadratic polynomial regression equation was established for influencing factors such as the sorghum grain broken stem loss rate Y_1 on the forward speed X_1, the speed of the grain puller X_2, and the dividing angle of the external grain dividing rod X_3, as shown in [eq. (20)]:

$$\begin{aligned}Y_2 &= 1.00{+}0.031X_1{+}0.086X_2{+}0.214X_3{-}2.500\times10^{-3}X_1X_2{+}5.000\times10^{-3}X_1X_3\\&-6.250\times10^{-2}X_2X_3+6.000\times10^{-3}X_1^2+0.184X_2^2+0.181X_3^2\end{aligned} \tag{20}$$

TABLE 5. Analysis of variance of stem loss rate and results.

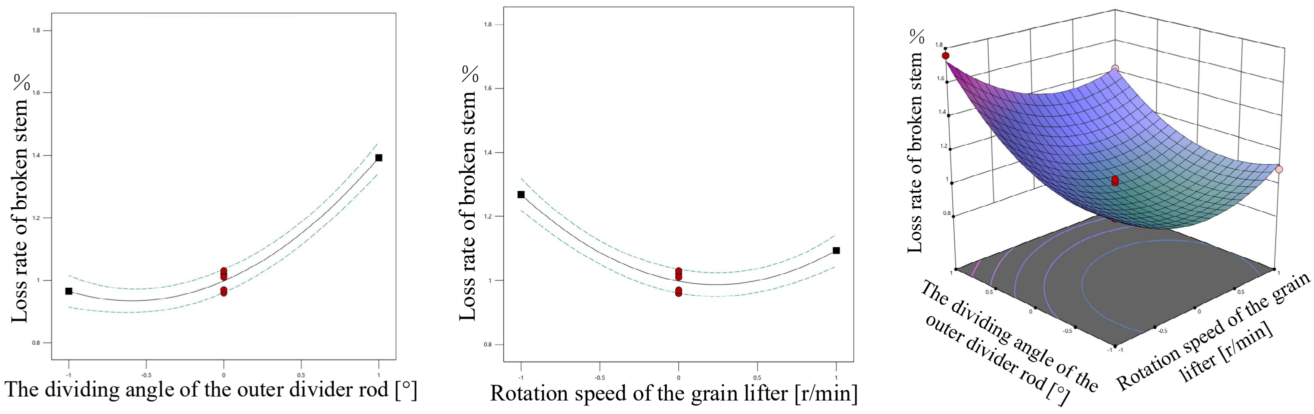
Sources	Loss rate of broken stem				
	Sum of squares	**Degree of freedom**	**Mean square**	***F* value**	***P* value**
Model	0.7485	9	0.0832	67.65	< 0.0001**
X_1	0.0078	1	0.0078	6.36	0.0398*
X_2	0.0613	1	0.0613	49.83	0.0002**
X_3	0.3655	1	0.3655	297.34	< 0.0001**
X_1X_2	0	1	0	0.0203	0.8906
X_1X_3	0.0001	1	0.0001	0.0813	0.7837
X_2X_3	0.0156	1	0.0156	12.71	0.0092**
X_1^2	0.0002	1	0.0002	0.1233	0.7358
X_2^2	0.1418	1	0.1418	115.33	< 0.0001**
X_3^2	0.1379	1	0.1379	112.21	< 0.0001**
Residual	0.0086	7	0.0012		
Lack of fit	0.0047	3	0.0016	1.62	0.3179
Pure error	0.0039	4	0.001		
Correct total	0.7571	16			

P<0.01 (highly significant, **); *P*<0.05 (significant, *).

According to the test of the F value, the factors affecting the loss rate of broken stems of sorghum ranged from the largest to the smallest, including the dividing angle of the outer divider rod, the rotation speed of the grain lifter and the forward speed of the harvester. To further optimize the regression model, the nonsignificant regression terms in the model were removed, and the broken stem loss regression model was optimized and fitted again. The reconstructed regression model had a high degree of fit, and its optimized regression equation was as follows:

$$Y_2 = 1.00{+}0.031X_1 - 0.086X_2{+}0.214X_3{-}6.250\times10^{-2}X_2X_3 + 0.184X_2^2 + 0.181X_3^2 \tag{21}$$

An analysis of the significance test results reveals that the dividing angle of the outer divider rod and the rotation speed of the grain lifter significantly influence the loss rate of broken stems. The relationships between the loss rates of broken stems and the variables are shown in Figures 7(a) and 7(b). For a given range of factors, the dividing angle of the outer divider rod is positively correlated with the lodging loss rate; that is, the lodging loss rate increases slowly with increasing dividing angle of the outer divider rod and then increases sharply. With increasing rotation speed of the grain lifter, the lodging loss rate first decreases sharply and then increases slowly.



(a) $Y_2 = f(x_1、x_2、330)$ **(b)** $Y_2 = f(x_1、28、x_3)$ **(c)** $Y_2 = f(1.0、x_2、x_3)$

FIGURE 7. Relationships between the stem loss rate and variables.

The significant influence of the interaction on the loss rate of broken stems was X_2X_3. When the forward speed of the harvester is set to 0, that is, when the forward speed of the harvester is 1.0 m/s, the response surface is shown in Figure 7c. The loss rate of the broken stem can be maintained at a lower level when the rotation speed of the grain lifter and the dividing angle of the outer divider rod increase or decrease at the same time. When the rotation speed of the grain lifter is 315~345 rpm and the dividing angle of the outer divider rod is 15~20°, the lodging loss rate is the smallest.

Parameter Optimization

To obtain the best parameter combination, combined with the boundary conditions of the test factors, the above regression model was optimized and solved with the goal of minimizing the lodging loss rate and the broken stem loss rate, and a parametric mathematical model was established. The objective and constraint functions are shown in [eq. (22)]:

$$\begin{cases} \min Y_1(x_1, x_2, x_3) \\ \min Y_2(x_1, x_2, x_3) \\ \text{s.t.} \begin{cases} 0.8 \le x_1 \le 1.2 \\ 300 \le x_2 \le 360 \\ 15 \le x_3 \le 25 \end{cases} \end{cases} \tag{22}$$

The results are as follows: when the forward speed of the harvester is 0.8 m/s, the rotation speed of the grain lifter is 330 rpm, the dividing angle of the outer divider rod is 20°, the loss rate of the fall is 1.03%, and the loss rate of the broken stem is 1.01%.

Verification test

To verify the results of the optimization analysis, a field verification test was carried out in the experimental field of Zhutai town, Linzi District, Zibo city, Shandong Province, in October 2023, as shown in Figure 8. The test conditions and test indices were consistent with those in Section 2.7. The forward speed of the harvester was controlled to 0.8 m/s, the rotation speed of the grain lifter was adjusted to 330 rpm, and the dividing angle of the outer divider rod was adjusted to 20°. To eliminate random error, the experiment was repeated three times, as shown in Table 6.

TABLE 6. Results of field validation test.

Item	Operating parameter	Lodging loss rate/%	Loss rate of broken stem/%
1	0.8m/s	1.12	1.05
2	330 rpm	0.95	1.01
3	20 °	1.17	1.09

The statistical test results were averaged; the lodging loss rate was 1.08%, and the stem loss rate was 1.05%. The verified test values are close to the theoretical optimization values and meet the relevant technical requirements.

FIGURE 8. Validation test.

CONCLUSIONS

(1) In view of the problems of lodging and winding leading to severe lodging and broken stem loss during sorghum harvest, the physical and mechanical characteristics of sorghum stalks and ears were studied. The lower the application point of the stalk to the sorghum plant is, the smaller the deflection angle generated by the stalk and the more conducive it is to the separation of the sorghum ear, which can provide a decision-making basis for the design and development of the outer divider.

(2) The push division integrated outer divider was developed to provide technical support for reducing the winding loss of the lodging sorghum cutting table; according to the working principle and operation requirements of the divider, the design method of the main parameters of the outer divider is established, which provides a theoretical basis for the subsequent design and development of the outer divider.

(3) A field comparison experiment on the working quality of the outer divider was carried out to verify the effectiveness of the structural parameters and working parameters of the outer divider for reducing lodging losses and stem breakage losses; the Box–Behnken response surface method was used to investigate the effects of the forward speed of the harvester, rotation speed of the grain lifter and dividing angle of the outer divider rod on fall loss and stem break loss. The factors affecting the fall loss rate and stem break loss rate in the process of sorghum harvesting were, from the largest to the smallest, the dividing angle of the outer divider rod, the forward speed of the harvester and the rotation speed of the grain lifter. The results revealed that when the dividing angle of the outer divider rod was 20°, the forward speed of the harvester was 0.8 m/s, the rotation speed of the grain lifter was 330 rpm, the loss rate of the cutting table was 1.08%, and the loss rate of the broken stem was 1.05%.

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