Design and Experiment of Grain Lifter for Sorghum Harvester

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Abstract: In order to solve the problems of grain lifter in sorghum harvesting, such as ear loss and serious crop leakage loss, combined with the physical and mechanical characteristics of sorghum, the segmented and reverse spiral grain lifter for sorghum harvesting and cutting table was developed, and the design method of the main structural parameters of the grain lifter was determined. The comparative test of the working effect of the clasp showed that the working effect of the cutting table with the clasp was better than that without the clasp, which effectively reduced the harvest loss of the cutting table. By using Box–Behnken experimental design method, the influence law of forward speed, tilt angle, and rotation speed of grain lifter on the rate of ear loss and harvest loss in sorghum harvesting was investigated. The regression mathematical model and response surface of the rate of ear loss and harvest loss and analysis factors were established, and the optimal working parameters of the grain lifter were determined. The forward speed was 0.8 m/s, the tilt angle of the grain lifter was 28°, and the rotation speed of the grain lifter was 330 r/min. Under these conditions, the spike loss rate was 2.01, the leakage loss rate was 2.19, and the error with the theoretical value was less than 3%, which proved the rationality of the optimized combination parameters. In the harvest of crooked and fallen sorghum, the grain lifter can effectively reduce the loss of sorghum head drop and lodging leakage, ensure the reliability of the cutting table, and achieve low loss and efficient harvest of sorghum.

Keywords: sorghum harvest; harvester; cutting platform; a straw helper; loss rate

1. Introduction

Sorghum is the main raw material for making liquor and plays an important role in our national economy [1,2]. Especially in recent years, driven by the rapid development of the liquor industry in 2020, China’s sorghum planting area has reached 635,000 hm² and the output reached 2.97 million tons, it is the fifth largest food crop in the country [3,4], but constrained by many factors, China’s sorghum harvesting mechanization is still in its infancy [5]. One of the main tasks of the harvester is to cut off and transport sorghum plants. However, due to the inconsistency of sorghum row spacing, dense plant spacing, easy lodging, and soft and loose ears, the plants skew and are difficult harvest [6–10]. Sorghum stems and leaves easily appear and the ears overlap, which increases the difficulty of harvesting sorghum, increases the harvest loss of cutting table, and even causes cutting table blockage in serious cases [11–14].

In order to solve this problem, domestic and foreign experts have conducted various studies on it [15]. For example, in order to reduce the influence of overlap and entanglement of sorghum ears, stems, and leaves on mechanical harvesting operations, John Deere adopted the edge supporting technology to cut the active separation of sorghum plants...
sticking inside and outside the cutting table; on the basis of improving varieties (changing loose ear sorghum varieties to tight ear and medium tight ear varieties), CASE Company (New Delhi, India) adopted the method of increasing the range of pulling wheel to achieve low loss harvest of high stalk sorghum [16–18]. Domestic research on sorghum harvesting technology started late. Zhang et al. [19] reduced the loss of the cutting table during sorghum harvest by lengthening the bottom plate of cutting table and enlarging the range of action of the plucking wheel. Feng et al. adopted the cutting method of stem and ear to reduce the loss of cutting table in sorghum harvest. There are also reciprocating knives to cut the overlapping plants and reduce the adhesion of sorghum, which improves the reliability of the cutting table.

Obviously, the sideline of the sorghum harvester is the key to affecting the reliability of the whole machine and reducing the harvest loss of the cutting table [19–24]. Although the predecessors have carried out some research on it, the ideal effect has not been achieved. In order to achieve low loss and high efficiency harvest of sorghum, this paper designed a kind of crop support device that is suitable for sorghum and skew and fall harvest.

2. Sorghum Harvesting and Cutting Table and Working Principle

Aiming at the problems of high stalk, long leaf, and droopy ear of sorghum, which affect the reliability of sorghum mechanized harvest, on the basis of the existing research on sorghum harvesting and cutting tables, we developed a new type of sorghum harvesting and cutting platform in conjunction with Bin Zhou Wan long Agricultural Machinery Manufacturing Co., LTD., (Binzhou, China), as shown in Figure 1. It is mainly composed of dividers (1); gripper conveyor chain (2); cutter (3); transverse conveyor (4); barrier net (5); frame (6); grain lifter (7); power input system (8). This paper mainly carries out the research on the grain lifter.

![Figure 1. Structural diagram of sorghum harvesting header. 1. dividers. 2. gripper conveyor chain. 3. cutter. 4. transverse conveyor. 5. barrier net. 6. frame. 7. grain lifter. 8. power input system.](image)

When working, the sorghum cutting table is connected to the front of the harvester. As shown in Figure 1, as the harvester moves forward, the sorghum located in front of the cutting table is divided into two parts, inside and outside, under the action of the grain lifters (7) on both sides of the cutting table. The sorghum in the cut width is transferred to the gripper conveyor chain (2) by the divider (1); when the sorghum plant is transported to the position of the reciprocating cutter (3) located below the gripper conveyor chain (2), it is cut by the reciprocating cutter (3). The subsequently cut plants are sent to the transverse conveyor (4) by inertia and the push action of subsequent plants. When the sorghum in the cut area appears to be lodging, the grain lifter (7) and the divider (1) are inserted from the lower part of the sorghum plant so that the lower part of the sorghum is gripped by the gripper conveyor chain (2) to the cutter (3) transport, the upper part lies on
the surface of the grain lifter (7), it is gradually pushed backward by the helical blade at the front of the grain lifter (7), the loss increase caused by the dragging of the fallen plants in the process of sorghum clamping transportation is avoided, and the accumulation and blockage of the fallen plants in the cutting table is also prevented. When the upper part of the plant (including the ear) moves to the rear of the grain support, the ear of sorghum waits at the mouth of the row until the lower part is grabbed by the transverse conveyor (4), then the upper part is dragged away from the mouth of the row, so as to avoid the grain loss caused by the ear slipping at the corner of the grain support and the barrier net (5); if the upper part of the plant falls to the end of the grain lifter (7) due to other accidental factors, in order to avoid the loss of grain loss caused by the pulling of sorghum ears in this position, a reverse spiral blade is provided at the end of the grain lifter (7), which can reverse transport the upper part of the sorghum plant to the discharge port to reduce the loss of grain shedding in the sorghum ear. Sorghum located outside the cutting width, if its stalk does not have skew or lodging, it is directly moved by the grain lifter (7) to the outside to realize the separation of sorghum inside and outside the cutting width and ensure the reliable work of the sorghum cutting table; if the stalk is skewed or even collapsed, the plants will be transported upward and backward along the grain lifter (7) while separating, it can be discharged from the head of the row in an almost upright state, which effectively reduces the dragging loss of external sorghum and the influence of falling plants on the reliability of the cutting table.

3. Research on Structure and Parameters of Grain Lifter

The function of the grain lifter is to realize the gradual lifting of the fallen sorghum, and the sorghum in front of the cutting table is divided into two parts that do not interfere with each other so as to ensure the reliability of the cutting table and reduce the loss of the cutting table. In order to avoid the problem of increasing the loss caused by the gathering of plant ears at the dead corner formed by the grain lifter and the barrier net, the reverse spiral structure is added at the end of the grain lifter to ensure the smooth and stable discharge of the righting sorghum ears from the grain lifter. Its structure is shown in Figure 2. It shall include: front bearing seat (1); grain lifter base (2); blade (3); discharge opening (4); rear bearing seat (5); drive shaft (6); frame; (7) and other components. Among them, the front blade (3) of the grain lifter will straighten the crooked and fallen sorghum plants and then gradually transport them backward, while the rear blade (3) of the grain lifter will transport the sorghum plants forward at the dead corner of the barrier net, and the sorghum ears will be discharged at the ear of the discharge opening (4) by the transverse conveyor to the cutting table.

![Figure 2. Structure and motion distribution of the grain lifter. 1. front bearing seat. 2. grain lifter base. 3. blade. 4. discharge opening. 5. rear bearing seat. 6. drive shaft. 7. frame.](image-url)
3.1. The Diameter of the Ear of the Grain Lifter Is Determined

Considering that all the lifted sorghum ears should be discharged from the head of the row, it must be ensured that the head of the row of the straw holder is not entangled by the sorghum ears and stems and leaves, that is, ensure that the minimum girth $c_{\text{min}}$, at the head of the row is greater than the length of sorghum ear $l_p$ (the stalk skin is hard and not easy to bend) and the maximum length of sorghum leaves $l_l$. Namely:

$$c_{\text{min}} = \pi D \geq \max(l_p, l_l)$$

(1)

There is:

$$D \geq \frac{\max(l_p, l_l)}{\pi}$$

(2)

According to the measured data of sorghum, after calculation, $D \geq 18.68$ cm.

3.2. Determine the Length of the Grain Lifter

Since this divider is a segmented structure, that is, it includes the front (lifting section), the middle (discharge opening), and the back (reversing section), the length of the holding apparatus is the sum of the length of the front, the middle, and the back.

3.2.1. Determine the Front Length of the Grain Lifter

The front part of the grain lifter is used to straighten the fallen sorghum so as to reduce the leakage loss during the sorghum harvest. Obviously, the smaller the angle between the grain lifter and the horizontal direction, the more conducive to the righting of the lodging sorghum. However, this may lead to the increase in the length of this section of grain lifter; on the contrary, if the angle of the grain lifter is larger, although the length of the grain lifter can be reduced, it will increase the difficulty of righting the lodging sorghum plants, and even lead to the accumulation and break of the lodging sorghum plants in severe cases. Considering the righting process of lodging sorghum, the stalk has been sliding backward on the surface of the grass lifter with the push of the spiral blade. Therefore, in order to ensure the stable post-sliding of the stalk, the angle between the upper surface of the straw holder and the horizontal plane (equal to the sum of the angle between the axis of the straw holder and the horizontal plane and the half of the cone angle of the straw holder), that is, $\theta + \beta$ is less than the friction angle $\phi$ between sorghum stem and centralizer, that is:

$$\theta + \beta \leq \phi$$

(3)

Considering that although sorghum plants are relatively tall, their stem structure is a columnar structure with hard skin outside the stem pith, so in the righting process, only half of the height of the stem should be held. It can ensure the stem upright state requirements, therefore, when designing the grass aid, the position height of the row head should only exceed 1/2 height of the stalk. If the front length of the centralizer is $l_1$ and the height of the sorghum plant is $h$, then:

$$\frac{l_1}{\cos \beta} \sin(\theta + \beta) \geq \frac{1}{2} h$$

(4)

Namely:

$$l_1 \geq \frac{h \cos \beta}{2 \sin(\theta + \beta)}$$

(5)

After substituting the relevant measured data, there is $l_1 \geq 146.63$ cm.

3.2.2. The Length of the Row Head of the Grain Lifter Is Determined

As shown in Figure 2, the discharge opening (4) is the exit where sorghum plants falling on the grain lifter fall off after being righted. The longer the length is, the more favorable it is to the discharge opening (4) of sorghum, but it also increases the total length of the grain lifter; on the contrary, the shorter its length, the more the helical blade interferes with the outer row of ears, therefore, considering the natural drooping state of the ear
of sorghum plants, the width of the ear \( b \) is 4~10 cm, and the length of the discharge opening (4) of the grain lifter \( l_2 \) is:

\[
l_2 = k b_{\text{max}}
\]  

(6)

Here \( k \) is the ear efflux coefficient, for loose ear sorghum, the value is generally 1.5~2. In this study, the quality of sorghum was Liang Nuo No 1, and the measured value of ear width was brought in, \( l_2 \) was 15~20 cm.

3.2.3. The Rear Length of the Grain Lifter Is Determined

The reverse spiral structure is adopted at the back of the grain lifter, mainly to prevent the grain loss caused by the sorghum plants falling on the surface of the grain lifter from the dead angle formed by the grain lifter and the barrier net. Therefore, the length of the back of the grain lifter \( l_3 \) is taken as the length of a spiral distance (ignoring the change of pitch caused by the conical grain lifter structure), so there is:

\[
\left(l_1 + l_2 + \frac{l_3}{2}\right) \tan \beta \tan \alpha = l_3/2
\]  

(7)

After simplification:

\[
l_3 = \frac{2(l_1 + l_2) \tan \alpha \tan \beta}{1 - \tan \alpha \tan \beta}
\]  

(8)

After substituting the measured data, the length of the back of the grain lifter is 21.83~30.82 cm.

Therefore, the total length of the grain lifter \( l \) is:

\[
l = l_1 + l_2 + l_3
\]  

(9)

After plugging in the relevant data, there is \( l \geq 183.46 \) cm.

3.3. Parameter Determination of Helical Blade on the Surface of the Grain Lifter

Considering that the stalk is close to the surface of the centralizer under the action of gravity and is gradually righted by the spiral leaves, the straightening point of the plant is the contact position between the stalk and the surface of the grain lifter. Assuming that the section radius of the grain lifter is \( r(x) \) at the distance from the tip \( x \), the absolute motion speed of the contact point between the stalk and the grain lifter in this section is \( v(x) \), and the angular velocity of the rotation of the grain lifter is \( \omega \), then:

\[
v(x) = \omega r(x) = \omega x \tan \beta
\]  

(10)

Further, the contact point velocity is decomposed into sliding velocity \( v_f \) along the spiral blade and velocity \( v_n \) perpendicular to the spiral blade, then:

\[
v_n = v(x) \sin \alpha = \omega x \tan \beta \sin \alpha
\]  

(11)

Here, only the backward push motion of sorghum plants is considered, so the speed is projected to the axis of the grain lifter, then:

\[
v_z = v_n \cos \alpha = \omega x \tan \beta \sin \alpha \cos \alpha = \frac{1}{2} \omega x \tan \beta \sin(2\alpha)
\]  

(12)

Here,

- \( x \)—distance from the tip of the grain lifter, cm;
- \( \omega \)—the angular velocity of the grain lifter during operation, rad/s;
- \( \beta \)—half of the cone angle of the grain lifter, °;
- \( \alpha \)—helix angle of a spiral blade, °.
Since the grain lifter is installed at a tilt and the machine moves in a horizontal direction, the speed is further decomposed into a horizontal speed $v_h$, then:

$$v_h = v_2 \cos \theta = \frac{1}{2} \omega x \tan \beta \sin(2\alpha) \cos \theta$$  \hspace{1cm} (13)

Considering that the walking process of the machine is a uniform motion, in order to ensure the stable righting of the sorghum stalk, the speed of the sorghum plant is required to be approximately equal to the speed $v_m$ of the machine, namely:

$$v_h = \frac{1}{2} \omega x \tan \beta \sin(2\alpha) \cos \theta = v_m$$  \hspace{1cm} (14)

So, the spiral angle of the grain lifter is:

$$\alpha = \frac{1}{2} \sin^{-1} \left( \frac{2v_m}{\omega x \tan \beta \cos \theta} \right)$$  \hspace{1cm} (15)

Obviously, for the grain lifter, it is necessary to ensure that the stalk is in a stable state of motion during the lifting process, that is, the partial speed of the plant push speed in the horizontal direction is equal to the speed of the machine, the spiral angle of the helical blade varies with the distance $x$ from the end of the grain lifter, and with the increase in the distance from the front of the grain lifter, the spiral angle gradually decreases.

In order to reduce the risk of breaking the stem in the process of lifting the plant, the lifting speed should not be too high, so the size of the pitch $s$ also changes along the axis, then:

$$\tan \alpha = \frac{s}{2\pi x \tan \beta}$$  \hspace{1cm} (16)

So, the pitch of the grain lifter is:

$$s = 2\pi x \tan \beta \tan^{-1} \left( \frac{1}{2} \sin^{-1} \left( \frac{2v_m}{\omega x \tan \beta \cos \theta} \right) \right)$$  \hspace{1cm} (17)

It can be seen that in order to ensure that the conical spiral centralizer does not damage the plant during operation and the stalk is stably transported backward, the pitch of the grain lifter gradually changes from the front end to the end, so the initial speed of the plant is slow and then gradually accelerates to prevent the plant from squeezing and blocking in the process of lifting.

Further, the size of the pitch is determined by the speed of the grain lifter and the distance from the tip of the grain lifter [25]. When the distance from the tip of the grain lifter is the maximum, that is:

$$x_{\text{max}} = l_1$$  \hspace{1cm} (18)

When the pitch reaches the maximum, taking into account the larger impact force generated when the grain lifter contacts with the plant during the operation process, it is easy to cause the loss of grain dropping. The speed of the harvester should not be too high, combined with the forward speed of the harvester and the speed of the grain chain, take 300–360 r/min, and substitute the relevant data, there are $s \leq 35$ cm.

4. Field Experiment and Analysis
4.1. Test Materials and Test Devices

In order to test the correctness of the theoretical analysis of the sorghum harvester and the effect of this device in field operation, field trials were conducted in Zhu Tai Town, Linzi District, Zibo City, Shandong Province, in October 2022. The test sorghum variety was “Liang Nuo No 1”, the planting density was 12 plants per square meter, the plants were dense and disorderly, and the lodging rate was about 20–30%. The material characteristics are shown in Table 1.
Table 1. Physical characteristics of sorghum plants (Variety: Liang Nuo No 1).

<table>
<thead>
<tr>
<th>Project</th>
<th>Unit</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Mean Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant height</td>
<td>cm</td>
<td>206.23</td>
<td>231.44</td>
<td>224.06 ± 9.28</td>
</tr>
<tr>
<td>Blade length</td>
<td>cm</td>
<td>28.82</td>
<td>38.46</td>
<td>32.72 ± 5.60</td>
</tr>
<tr>
<td>Ear length</td>
<td>cm</td>
<td>41.2</td>
<td>68.6</td>
<td>58.66 ± 25.60</td>
</tr>
<tr>
<td>Ear weight</td>
<td>g</td>
<td>42.63</td>
<td>105.98</td>
<td>62.78 ± 17.10</td>
</tr>
<tr>
<td>Stem moisture content</td>
<td>%</td>
<td>34.86</td>
<td>52.63</td>
<td>45.15 ± 4.63</td>
</tr>
<tr>
<td>Grain water content</td>
<td>%</td>
<td>17.71</td>
<td>27.83</td>
<td>22.11 ± 2.76</td>
</tr>
</tbody>
</table>

The test equipment includes a set consisting of a harvester with a developed cutting table (developed by United Wan long Agricultural Machinery Manufacturing Co., Ltd., (Binzhou, China)), as shown in Figure 3. Other measuring instruments include tape measures, electronic balances, vernier calipers, etc.

![Figure 3. Sorghum harvester with grain lifter.](image)

4.2. Experimental Design and Method

4.2.1. Experimental Design

Firstly, in order to verify the effectiveness of the function of the grain lifter, a comparative test of ear loss and harvest loss was carried out with and without the grain lifter; secondly, in order to verify the correctness of the above analysis results and explore the best parameter combination to ensure the optimal operation effect, the tilting angle, forward speed and rotating speed of the harvester, which had a great influence on the effect of the harvester operation, were selected as the test influence factors, and the orthogonal test of 3 factors and 3 levels was carried out with the loss rate of ear shedding and the loss rate of missing harvest as the assessment index. The levels of each test factor are shown in Table 2.

Table 2. Factors and levels of test.

<table>
<thead>
<tr>
<th>Levels</th>
<th>Forward Speed/vm (ms(^{-1}))</th>
<th>Inclination of Grain Lifter/θ (°)</th>
<th>Rotation Speed of the Buttress/n (rmin(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>−1</td>
<td>0.8</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
<td>28</td>
<td>330</td>
</tr>
<tr>
<td>1</td>
<td>1.2</td>
<td>36</td>
<td>360</td>
</tr>
</tbody>
</table>

4.2.2. Test Methods

According to the test method of GB8231-87 [26] sorghum harvester and GB/T8097-2008 [27] harvester, 3 test areas were randomly selected in the test field [28]; each test was divided into preparation area, test area, and parking area, in which the preparation area was 10 m long, the test area was 50 m long, the parking area was 5 m long, and the width of the test area was the full working width of the cutting table, the comparison test and three-factor and three-level orthogonal test were carried out, and the response values of ear loss rate and missing loss rate were selected as assessment indexes. The leakage loss and ear loss...
of each test area were calculated separately, and the average value of the three test areas was taken.

The loss rate of ear shedding is the percentage of the weight of ear shedding grains caused by plant break during the lifting process and the yield of sorghum in the test section, namely:

$$R_{w_{ed}} = \frac{w_{d}}{w_{l} + w_{d} + w_{h}} \times 100\%$$ (19)

The loss rate of leakage is the percentage of the weight of sorghum grains that the plant falls to the surface without lifting and the yield of sorghum in the test section, namely:

$$R_{w_{el}} = \frac{w_{l}}{w_{l} + w_{d} + w_{h}} \times 100\%$$ (20)

Here,

$$w_{l}$$—Weight of sorghum grains that lie on the ground without lifting, kg;

$$w_{d}$$—The weight of sorghum grains whose ears fell off due to plant break, kg;

$$w_{h}$$—Grain quantity of the grain bin of the harvester, kg.

4.3. Comparison of Test Results and Analysis

In order to verify the effectiveness of the grain lifter on the operation effect, the method of cutting off (without grain lifter) and connecting power (with grain lifter) was preferred, and the comparative test of the grain lifter on the loss of ears and the loss of leakage was carried out. The results are shown in Figure 4 below.

![Comparison of ear loss rate](image)

(a) Comparative analysis of ear loss rate; (b) Analysis of comparative results of loss rate of leakage.

As can be seen in Figure 4, although there are certain loss of ear shedding and loss of harvest with or without the grain lifter, and with the acceleration of operation speed, the loss rate of ear shedding and loss rate of harvest leakage will increase to a certain extent, but after the installation of the grain lifter, the loss rate of ear shedding and loss of harvest will decrease significantly, in particular, with the increase in operation speed, the loss rate of ear shedding and crop leakage decreased more significantly, that is, adding grain supports on both sides of the cutting table could effectively reduce the loss rate of ear shedding and crop leakage during sorghum harvesting.
4.4. Orthogonal Test Results and Analysis

4.4.1. Test Scheme and Results

In order to explore the optimal working parameters of the grain lifter, the tilt angle of the grain lifter, the rotation speed of the grain lifter, and the working speed of the machine, which have the greatest influence on the harvest loss of the cutting table, were selected as the test factors, and the loss rate of ear shedding and side row leakage was taken as the test index, the response surface analysis method in Design-Expert software (Version:13.0.1.0) was used to carry out the operation parameter optimization test of the grain lifter-holding device. A total of 17 tests were conducted, of which 5 groups were taken as zero points and 12 groups were taken as analysis factors. The test scheme and results are shown in Table 3.

Table 3. Test plan and results.

<table>
<thead>
<tr>
<th>No</th>
<th>Forward Speed X1</th>
<th>Tilt Angle of Grain Lifter X2</th>
<th>Rotating Speed of Grain Lifter X3</th>
<th>Loss Rate of ear/%</th>
<th>Loss Rate of Missing Collection/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>−1</td>
<td>3.89</td>
<td>3.59</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.73</td>
<td>2.86</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>−1</td>
<td>−1</td>
<td>4.64</td>
<td>5.05</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>−1</td>
<td>0</td>
<td>4.99</td>
<td>5.16</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.92</td>
<td>3.17</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>−1</td>
<td>1</td>
<td>3.92</td>
<td>4.46</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>4.42</td>
<td>4.82</td>
</tr>
<tr>
<td>8</td>
<td>−1</td>
<td>0</td>
<td>−1</td>
<td>2.26</td>
<td>2.69</td>
</tr>
<tr>
<td>9</td>
<td>−1</td>
<td>0</td>
<td>1</td>
<td>2.04</td>
<td>1.84</td>
</tr>
<tr>
<td>10</td>
<td>−1</td>
<td>1</td>
<td>0</td>
<td>2.12</td>
<td>2.01</td>
</tr>
<tr>
<td>11</td>
<td>−1</td>
<td>−1</td>
<td>0</td>
<td>2.98</td>
<td>2.78</td>
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<td>12</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>3.87</td>
<td>4.12</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.61</td>
<td>2.56</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3.61</td>
<td>3.47</td>
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<tr>
<td>15</td>
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<td>0</td>
<td>0</td>
<td>2.43</td>
<td>2.63</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.61</td>
<td>2.49</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>0</td>
<td>−1</td>
<td>4.35</td>
<td>4.96</td>
</tr>
</tbody>
</table>

X1, X2, and X3 are the level values of forward speed, tilt angle of grain lifter, and rotating speed of grain lifter, respectively.

4.4.2. Analysis of Variance

In order to further optimize the test results, the quadratic regression analysis of variance and significance tests were carried out by Design-Expert 8.0.6.1 software, as shown in Table 4. After multiple regression fitting, the regression equations of ear loss and missing loss among each factor and assessment index were obtained:

\[
Y_1 = 34.006 + 1.790 X_1 - 0.454 X_2 - 0.213 X_3 + 8.06 \times 10^{-3} X_1 X_2 - 3.61 \times 10^{-3} X_1 X_3 + 2.44 \times 10^{-4} X_2 X_3 + 0.115 X_1^2 + 4.12 \times 10^{-3} X_2^2 + 4.78 \times 10^{-4} X_3^2 \tag{21}
\]

\[
Y_2 = 41.985 + 0.644 X_1 - 0.439 X_2 - 0.281 X_3 + 1.2 \times 10^{-2} X_1 X_2 + 1.39 \times 10^{-4} X_1 X_3 + 2.61 \times 10^{-4} X_2 X_3 + 0.292 X_1^2 + 3.76 \times 10^{-3} X_2^2 + 6.17 \times 10^{-4} X_3^2 \tag{22}
\]

Table 4. Variance analysis of quadratic response surface regression model.
Table 4. Cont.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Loss Rate of Ear</th>
<th>Loss Rate of Missing Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sum of Squares</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>$X_1^2$</td>
<td>0.00716</td>
<td>1</td>
</tr>
<tr>
<td>$X_2^2$</td>
<td>3.61</td>
<td>1</td>
</tr>
<tr>
<td>$X_3^2$</td>
<td>0.77</td>
<td>1</td>
</tr>
<tr>
<td>Residual</td>
<td>0.18</td>
<td>7</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>0.047</td>
<td>3</td>
</tr>
<tr>
<td>Pure error</td>
<td>0.13</td>
<td>4</td>
</tr>
<tr>
<td>Correct total</td>
<td>14.5</td>
<td>16</td>
</tr>
</tbody>
</table>

$p < 0.01$ (highly significant, **); $p < 0.05$ (significant, *).

According to Table 4, the significance test value of the regression model of ear loss $p = 0.0003$ ($p < 0.01$) indicates that the regression model of ear loss is extremely significant, the influence of primary $X_1$, $X_2$, $X_3$ and secondary terms $X_1^2$, $X_3^2$ on the model was significant ($p < 0.05$). However, the quadratic terms $X_1^2$ and interaction terms $X_1X_2$, $X_1X_3$, $X_2X_3$ and have no significant influence on the model. Remove from the regression model. The significance test value of the leakage loss regression model $p = 0.0003$ ($p < 0.01$) indicates that the leakage loss regression model is extremely significant, the influence of primary $X_1$, $X_2$, $X_3$ and secondary terms $X_1^2$, $X_3^2$ on the model was significant ($p < 0.05$). However, the quadratic terms $X_1^2$ interaction term $X_1X_2$, $X_1X_3$, $X_2X_3$ and have no significant influence on the model. Remove from the regression model. After simplifying the model and eliminating non-significant items, the final regression equation of ear loss and edge leakage is obtained as follows:

\[
Y_1 = 34.006 + 1.790X_1 - 0.454X_2 - 0.213X_3 + 4.12 \times 10^{-3}X_2^2 + 4.78 \times 10^{-4}X_3^2 \tag{23}
\]

\[
Y_2 = 41.985 + 0.644X_1 - 0.439X_2 - 0.281X_3 + 3.76 \times 10^{-3}X_2^2 + 6.17 \times 10^{-4}X_3^2 \tag{24}
\]

According to the results of variance analysis, the selected test factors $X_1$, $X_2$, and $X_3$ are the main factors that affect the loss rate of grain lifter, among them, the main and secondary effects on the loss rate of heading and missing loss rate are the forward speed, the tilt angle of grain lifter and the rotation speed of grain lifter.

4.4.3. Response Surface Analysis

In order to further study the interaction relationship between each test factor and the test index, the response surface method was used to analyze the impact of the interaction on the loss rate of ear shedding and the loss rate of missed harvest, that is, one factor was fixed at the level of 0, and the influence law of the other two factors on the test index was investigated.

As shown in Figure 5a, when the rotation speed of the grain lifter is 330 r/min, the loss rate of ear shedding increases with the increase in the forward speed. This is because, with the increase in the forward speed of the harvester, the difficulty of separating the inner and outer plants by the harvester increases, resulting in the increase in ear shedding loss. With the increase in the tilt angle of the grain lifter, the supporting effect of the front on the lodging plant was enhanced, and the position of the posterior row became higher, which reduced the loss of ear. However, with the increase in the tilting angle, the sliding resistance of the stalk along the surface of the tiller increased, which reduced the supporting effect of the tiller on the fallen plants and led to the increase in the loss rate of ears.

As shown in Figure 5b, when the tilt angle of the grain lifter is present, the rate of ear loss decreases first and then increases with the increase in the rotation speed of the grain lifter. This is because with the increase in the rotation speed of the grain lifter, the front part of the grain lifter strengthened the effect of helping and dividing the grass of the fallen
plants, and the backward conveying speed of the stalks and the backward conveying speed of the stalks at the dead corner of the barrier net increased, reducing the loss of ears. With the increase in the rotation speed of the grain lifter, the lifting speed of the lodging plant was too fast, resulting in the increase in the broken rod of the plant and the increase in the number of plants outside the ear discharge opening, resulting in the poor ear discharge, resulting in the increase in ear loss rate. The loss rate of ear shedding increased with the increase in forward speed, and the reasons were similar to the analysis in Figure 5a.

As shown in Figure 5c, when the forward speed was 1.0 m/s, the spike loss rate first decreased and then increased with the increase in the rotation speed of the crop helper, for reasons similar to those analyzed in Figure 5b. With the increase in the tilt angle of the crop support, the loss rate of ear removal first decreased and then increased, and the reasons were similar to the analysis in Figure 5a.

![Figure 5](imageurl)

**Figure 5.** Influence of interaction on ear loss rate. (a) $Y_1 = f(x_1, x_2, 330)$. (b) $Y_1 = f(x_1, 28, x_3)$. (c) $Y_1 = f(1.0, x_2, x_3)$.

As shown in Figure 6a, when the rotation speed of the grain lifter is 330 r/min, the leakage loss rate increases with the increase in the forward speed. The reason is that with the increase in the forward speed of the harvester, the ability of the grain lifter to lift the fallen and crooked plants cannot meet the actual needs of production, resulting in a continuous increase in the leakage loss rate. With the increase in the tilt angle of the grain lifter, the effect of the front of the grain lifter on the propping plant was enhanced, and the stability of the back to the plant was improved, which reduced the loss of the crop loss. With the increase in the tilt angle, the sliding resistance of plants along the surface of the grain lifter increased, which reduced the supporting effect on the fallen plants and led to the increase in the loss rate of leakage.

As shown in Figure 6b, when the tilt angle of the grain lifter is present, the loss rate of leakage decreases first and then increases slightly with the increase in the rotation speed of the grain lifter. This is because with the increase in the rotation speed of the grain lifter, the lifting speed of the grain lifter on the crooked and fallen plants is gradually accelerated, and the loss of leakage is reduced; however, with the increase in the rotation speed of the grain lifter, the front of the grain lifter lifted the plant too fast, resulting in the bending and breaking of the plant, resulting in the increase in the loss rate of leakage; the loss rate of leakage increases with the increase in forward speed, for reasons similar to those analyzed in Figure 6a.

As shown in Figure 6c, when the forward speed is 1.0 m/s, the leakage loss rate first decreases and then increases with the increase in the rotation speed of the grass holder for reasons similar to those analyzed in Figure 6b; the loss rate of leakage decreases first and then increases with the increase in the tilt angle of the grain lifter, and the reasons are similar to the analysis in Figure 6a.
In order to solve the problem of sorghum skewing and lodging during harvest, which led to the serious loss of cutting table and leakage during harvest, the mechanical and physical characteristics of sorghum plants were studied. Different growth states of sorghum had an important impact on the later harvest, and the lodging sorghum should be cut after straightening. In addition, it can provide theoretical support for the determination of structural parameters and working parameters of the grain lifter and provide a decision-making basis for the subsequent development of the cutting table.

The optimization results obtained by Design-Expert software are as follows: The forward speed is 0.81 m/s, the tilt angle of the grain lifter is 28.26°, and the rotation speed of the grain lifter is 330 r/min. When the forward speed is 0.8 m/s, the tilt angle of the grain lifter is 28°, and the rotation speed of the grain lifter is 330 r/min, the loss rate of ear shedding and loss rate of missing reach the minimum, and their values are 1.92 and 2.03, respectively.

In order to verify the above optimization results, another test was conducted in Zhu Tai Town test field, Linzi District, Zibo City, Shandong Province, in October 2022, and the verification test was carried out under the conditions of optimized parameter combination (forward speed of 0.8 m/s, tilt angle of grain lifter of 28°, and rotation speed of grain lifter of 330 r/min), three test areas were randomly selected, and their average values were taken after repeated tests. The results showed that the loss rate of ear shedding was 2.19, and the error with the theoretical value was less than 3%. The round optimization results were credible.

5. Conclusions

4.5. Parameter Optimization and Verification

Due to the high lodging rate of sorghum plants during harvest, combined with the actual operation process, leakage and ear loss will lead to harvest loss, but leakage has a greater impact on harvest loss, so in order to simplify the problem, the two losses are fuzzy treatment to form a cutting table harvest loss, that is, the weight of ear loss rate and missing loss rate is set to be 0.4 and 0.6, respectively, and the optimization template in Design-Expert software is used to optimize and solve the problem. The objectives and constraints are as follows:

\[
\begin{align*}
\min \zeta &= 0.4Y_1 + 0.6Y_2 \\
\text{s.t.} & \quad 0.8 \text{ m/s} \leq x_1 \leq 1.2 \text{ m/s} \\
& \quad 20^\circ \leq x_2 \leq 36^\circ \\
& \quad 300 \text{ r/min} \leq x_3 \leq 360 \text{ r/min}
\end{align*}
\]

Figure 6. Influence of interaction on loss rate of leakage. (a) \(Y_2 = f(x_1, x_2, 330)\). (b) \(Y_2 = f(x_1, 28, x_3)\). (c) \(Y_2 = f(1.0, x_2, x_3)\).

The optimization results obtained by Design-Expert software are as follows: The forward speed is 0.81 m/s, the tilt angle of the grain lifter is 28.26°, and the rotation speed of the grain lifter is 330 r/min. When the forward speed is 0.8 m/s, the tilt angle of the grain lifter is 28°, and the rotation speed of the grain lifter is 330 r/min, the loss rate of ear shedding and loss rate of missing reach the minimum, and their values are 1.92 and 2.03, respectively.

In order to verify the above optimization results, another test was conducted in Zhu Tai Town test field, Linzi District, Zibo City, Shandong Province, in October 2022, and the verification test was carried out under the conditions of optimized parameter combination (forward speed of 0.8 m/s, tilt angle of grain lifter of 28°, and rotation speed of grain lifter of 330 r/min), three test areas were randomly selected, and their average values were taken after repeated tests. The results showed that the loss rate of ear shedding was 2.19, and the error with the theoretical value was less than 3%. The round optimization results were credible.
2. The segmented reverse spiral grain lifer was developed to provide a solution for reducing the mechanized harvest loss of lodging sorghum. Based on the working principle and technical requirements of the grain lifter, the method of determining the main parameters of the grain lifter was established, which provides theoretical support for the development and design of this type of grain lifter.

3. A field comparison experiment was carried out to verify the effectiveness of the structure and parameter design theory of this type of grain lifter on reducing ear loss and crop loss; the Box–Behnken response surface method was used to analyze the effects of harvester forward speed, tilting angle, and rotation speed on the loss of heading and the loss of leakage, and the order of the factors affecting the loss rate of heading and the loss rate of leakage was determined as forward speed, tilting angle, and rotation speed. Field verification experiments were carried out. The results showed that when the forward speed of the harvester was 0.8 m/s, the tilt angle of the harvester was 28°, and the rotation speed of the harvester was 330 r/min, the minimum loss rate of the cutting table was 2.01, and the loss rate of leakage was 2.19%.

Author Contributions: Conceptualization, Q.W.; Methodology, L.N. (Lin Niu); Software, D.L.; Formal analysis, J.M. (Jie Ma); Resources, C.Z.; Data curation, J.M. (Jiarui Ming); Writing—original draft, Q.H.; Writing—review & editing, D.G.; Funding acquisition, L.N. (Lei Ni). All authors have read and agreed to the published version of the manuscript.

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