# DESIGN AND TESTING OF PICKUP TOOTH CONVEYOR BELT TYPE BUCKWHEAT PICKUP DEVICE
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# 扒齿输送带式荞麦捡拾装置的设计与试验研究

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## ABSTRACT
*To address the high rate of grain loss in the two-stage harvest of buckwheat, a pickup tooth conveyor belt type buckwheat pickup device was developed to mitigate the grain loss in the buckwheat pickup process. The critical components of the pickup mechanism and conveyor mechanism were designed, and the essential parameters were determined. The operational efficiency of pickup tooth conveyor belt type buckwheat pickup device was verified through field orthogonal test. The field test results indicate that the loss rate is most significantly affected by the speed of the pickup tooth, followed by the tilt angle of the pickup tooth. the forward speed of the combine exerts minimal influence. After the multi-objective parameters of the regression equation model were optimized, the optimal parameters of the factors were obtained: the speed of the pickup tooth was 0.8 m/s, the forward speed of the combine was 1.1 m/s, and the tilt angle of the pickup tooth was 0°, Under this condition, the loss rate of buckwheat grain reached 6.92%.*

## 摘要
*针对荞麦两段式收获过程中籽粒损失率较高的问题，设计了一种扒齿输送带式荞麦捡拾装置，以减少荞麦捡拾过程中的籽粒损失。对关键零部件扒齿捡拾机构和输送机构进行了设计，并确定了关键参数。通过田间正交试验验证扒齿输送带式荞麦捡拾装置的工作效果。田间试验结果表明，扒齿线速度对损失率影响最大，扒齿的倾角次之，机器前进速度的影响最小。对建立的二次回归模型进行多目标承参数优化后，得到各因素最佳参数组合：当捡拾速度为 0.8 m/s， 扒齿倾角为 0°，机器前进速度为 1.1 m/s，在上述条件下，荞麦籽粒的损失率达到最小值为 6.92%。*

## INTRODUCTION
Buckwheat is extensively considered a multi-purpose grain crop due to its exceptional nutritional composition, high medicinal value, and notable health benefits *(Wang et al., 2023)*. As living standards have improved, there has been increased awareness of nutrition and health, resulting in increased demand for buckwheat in both domestic and international markets *(Qi et al., 2022)*. With the growth of buckwheat plants, the stems undergo bifurcation, flowers and branches intertwining each other. Buckwheat also exhibits a high stem-to-grain ratio, uneven grain maturity, and susceptibility of mature grains to detachment. Additionally, its stem has a high moisture content during harvest *(Wang et al., 2020; Wang et al., 2022)*. Consequently, mechanized harvesting of buckwheat is challenging. Mechanized harvesting of buckwheat can be categorized into one-time combined harvesting and two-stage harvesting *(Wang et al., 2018)*. The two-stage harvesting method allows grains to fully dried and ripen under sunlight and the moisture content of the stems was reduced Consequently, it is considered the optimal mechanized harvesting method for buckwheat *(Zhang et al., 2019)*. A two-stage pickup combine was utilized for pickup, threshing, and cleaning operations. The pickup device serves as a crucial component in the two-stage harvest, significantly affecting the overall quality of buckwheat harvesting *(Wang et al., 2023)*.

Existing research has identified that the main types of two-stage harvesters consist of belt type, telescopic pickup type, and elastic drum type. *Shi et al. (2011)*, from the Nanjing Agricultural Mechanization Research Institute, demonstrated that the application of a toothed belt pickup device for two-stage harvesting of oilseed rape achieved a minimum loss rate of 3.92%.

*Li et al. (2016)*, from Hunan Agricultural University, demonstrated that an elastic-tooth drum pickup device achieved a theoretical minimum loss rate of 3.16% for two-stage pickup and harvesting of oilseed rape. Because of the unique characteristics of buckwheat harvesting, conventional pickup devices often impact buckwheat swath, resulting in grain loss during collection. Current research on pickup devices (e.g., grains, herbage, oilseed rape, and film residue recovery) can serve as a reference for this study *(Ivan and Vlăduţ, 2015; Ivan et al., 2015; Chen et al., 2020; Tian et al., 2020)*.

To address the above problems, a pickup tooth conveyor belt-type buckwheat pickup device was developed to shorten the pickup path and minimize impact on the buckwheat. Key components were designed, and field tests were conducted to verify the performance of the device. The optimal combination of working parameters was determined through orthogonal testing.

## MATERIALS AND METHODS

### *Structural design and operational principle of the machine*

The pickup tooth conveyor belt-type buckwheat pickup device primarily consists of a pickup mechanism, conveyor mechanism, pickup table, feed plate, and chain rake conveyor. The structure of the device is illustrated in Figure 1.

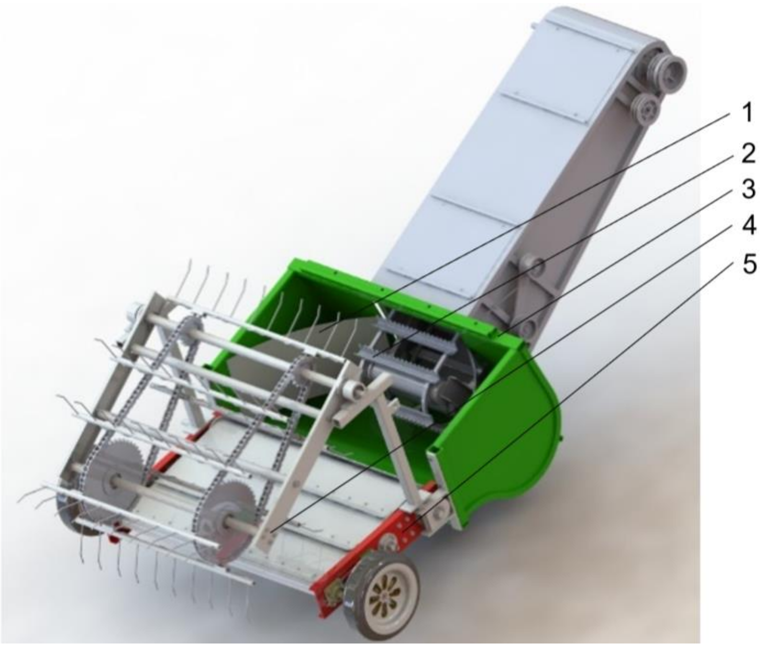



**Fig. 1 - The structure diagram of the pickup tooth conveyor belt type buckwheat pickup device**
*1 – feed plate; 2 – chain rake conveyor; 3 – pickup table;*
*4 – pickup mechanism; 5 – conveyor mechanism*

When the pickup tooth conveyor belt-type buckwheat pickup device is in operation, it is mounted in front of the combine and powered by the self-propelled mechanism. The pickup mechanism collects the buckwheat and transports it to the pickup table via a flexible scraper. The feed plate directs the collected buckwheat to the chain rake conveyor, which subsequently conveys it to the threshing and cleaning device.

### *Key component design and parameter determination*

#### The design of pickup mechanism

The working principle of the pickup mechanism involves linear motion following the combine harvester's forward movement, while simultaneously rotational motion. As shown in Figure 2, its structure mainly includes driven shaft, driven sprocket, chain, mounting plate, driving shaft, driving sprocket, pickup tooth, rack, etc.

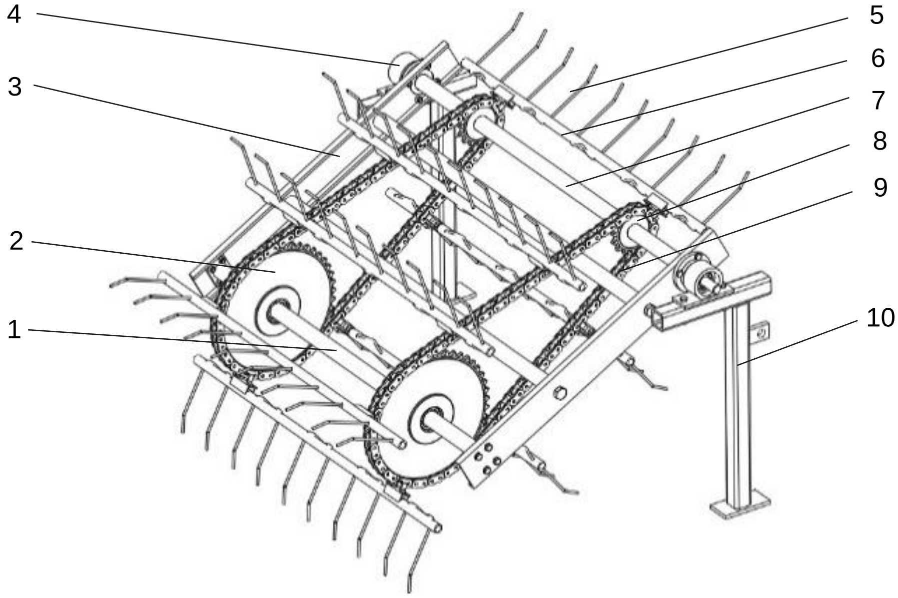



**Fig. 2 - The structure diagram of the pickup mechanism**
*1 – driven shaft; 2 – driven sprocket; 3 – mounting plate; 4 – bearing with fix seat; 5 – pickup tooth; 6 – hollow shaft;7 – driving shaft; 8 – driving sprocket; 9 –chain; 10 – rack.*

(1) Width of the pickup mechanism

In practical operation, the width of the conveyor mechanism should be determined based on the width of the buckwheat swath after cutting. The working width of the pickup device must be greater than the maximum width of the buckwheat swath, which typically ranges from 500 to 1400 mm. Therefore, considering both the design requirements of agricultural machinery and practical working conditions, the width of the pickup mechanism is set to *W* = 1600 mm *(China Academy of Agricultural Mechanization Sciences, 2007)*.

(2) Normal working conditions of the pickup mechanism

To effectively scrape the buckwheat swath onto the conveyor mechanism, the pickup tooth should avoid striking the buckwheat stems and grains at high speeds, as this can cause the grains to fall off. Therefore, the speed at the tip of the pickup tooth should be carefully determined. At a certain speed of the combine, if the speed of the pickup tooth is excessively small, buckwheat plants are difficult to pick up. At excessively high pickup tooth speeds, the buckwheat stalks and grains are struck with too much force, causing the grains to fall off. Therefore, controlling the speed of the pickup tooth is crucial for the effective handling of buckwheat plants. The motion path of pickup tooth is a combination of the forward motion of the pickup combine and the rotary motion of pickup tooth. To achieve effective pickup, the absolute speed of the pickup tooth (pickup tooth relative to the ground) when contacting the buckwheat swath should be opposite to the forward speed of the combine. This requires that the ratio of the speed of the pickup tooth (pickup tooth relative to the combine) to the forward speed of the combine be greater than 1. (λ > 1), that is

$$\omega R > V_m \tag{1}$$

where:

$\omega$ is the driven sprocket angular speed [rad/s]; $R$ is the turning radius of the pickup tooth [mm]; $V_m$ is the forward speed of the combine [m/s].

(3) The design of the pickup tooth

In this study, the pickup tooth was designed, and practical experience suggested that a specific bending angle of the pickup tooth can help increase the pickup rate.

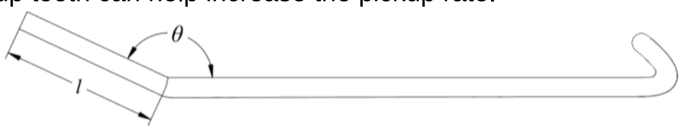



**Fig. 3 – The design of the pickup tooth**

Through the force analysis of the buckwheat plants picked up by the pickup mechanism, the suitable bending angle $\theta$ can be calculated, and the buckwheat plants were simplified into a particle. The force situation is presented in Figure 4, when the buckwheat plants were scraped to the conveyor mechanism by the pickup device.

To ensure the pickup tooth successfully picking up buckwheat, the friction between the buckwheat plants and the pickup tooth must exceed the gravity and centrifugal force acting on the plants at the pickup point. This ensures that the conditions required for scraping up the buckwheat plants are met.

$$F_f \geq G\cos\beta + F_r\cos\alpha \tag{2}$$

$$F_f = \mu F_N \tag{3}$$

$$F_r = m\omega R^2 \tag{4}$$

where:

$F_f$ is the friction force on buckwheat plants when they are lifted [N]; $G$ represents gravity of buckwheat plants [N]; $\beta$ is the angle between the bending section of pickup tooth and the direction of gravity [°]; $F_r$ is the centrifugal force received by buckwheat plants when they are picked up [N]; $\alpha$ is the angle between the bending section of the pickup tooth and the centrifugal direction [°]; $\mu$ is the friction coefficient between buckwheat plant and pickup tooth; $F_N$ is the thrust exerted by the pickup pair when the buckwheat plant is scraped towards the conveyor mechanism [N].

According to the geometric relation, there are:

$$\alpha = 180° - \theta \tag{5}$$

where: $\theta$ is the bending angle of pickup tooth

According to the principle of action and reaction

$$F_N = G\sin\beta + F_r\sin\alpha \tag{6}$$

Can be obtained from the Formula (2), (3), (4), (5), (6)

$$\mu g\sin\beta + \mu\omega R^2\sin\alpha > g\cos\beta + \omega R^2\cos\alpha \tag{7}$$

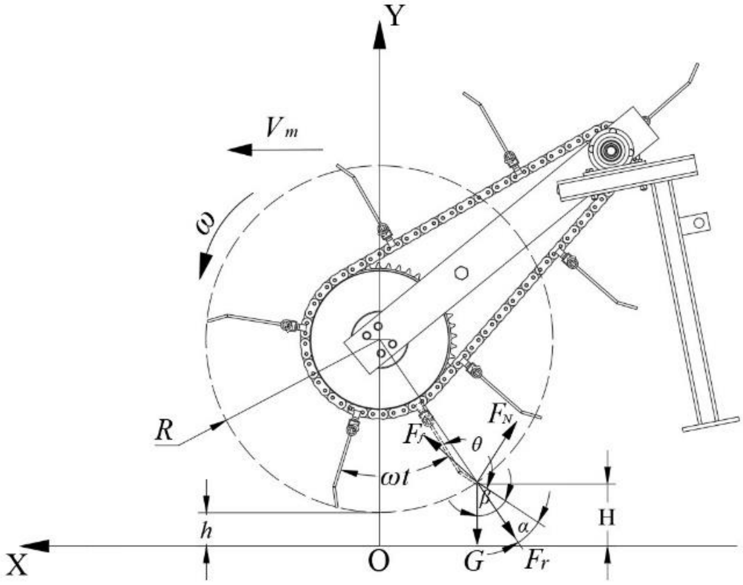



**Fig. 4 – The stress situation of the pickup mechanism**

The buckwheat plants were cut down by a swather and then aired for 7 days. Five areas were randomly selected to examine the thickness $H$ of buckwheat at the natural laying state. The measurement times of the respective group were 3 time, and the average value was taken. Its laying thickness ranged from 44 to 61 mm. The smallest lay-up thickness was selected, which was 44 mm.

$$\beta - \alpha = \arccos[R/(R + H - h)] = 22.26° \tag{8}$$

$$\beta = 22.26° + \alpha = 202.26° - \theta \tag{9}$$

where:

$H$ is the thickness of buckwheat grass laying [mm]; $h$ is the minimum distance between pickup tooth and ground [mm].

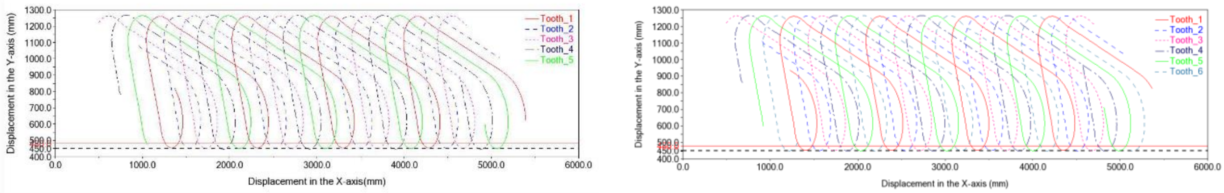
The coefficient of friction ($\mu$) between buckwheat and the pickup tooth was 0.43. Substituting Eq. (9) into Eq. (7), the calculated bending angle of the pickup tooth is 129.01°, which is rounded to 130°. The length of the bent section of the pickup tooth ($l$) should exceed the thickness of the buckwheat layer, i.e., greater than 44 mm. Considering the stacking of some buckwheat swaths, the length of the bent section was set to 60 mm.

(4) Pickup tooth row spacing

The pickup tooth rotates relative to the combine as the joint harvester advances to collect the buckwheat, causing the tip of the pickup tooth to move in a staggered trajectory and creating a missing area. To improve pickup efficiency, the size of the missing area should remain within a reasonable range. The size of the missing area is primarily influenced by the forward speed of the combine, the speed of the pickup tooth, and the number of pickup tooth rows. The optimal spacing between pickup tooth rows is determined by analyzing the motion path of the pickup tooth tip.

Due to the complexity of pickup tooth trajectories, which are difficult to measure, this study uses ADAMS software to simulate the trajectories of pickup tooth tips across different rows. The model, created in SOLIDWORKS, was imported into ADAMS, where material properties, motion pairs, drives, chain systems, and tape systems were added.

The forward speed of the combine was set to $V_m$=1.0 m/s, the rotary speed of the pickup tooth was set to $\omega$ = 4 rad/s, the simulation time was set to 5 s, and the number of simulation steps was set to 500. The motion tracks of pickup tooth tips for different rows are shown in Figure 6. The pickup tooth tips traverse the entire thickness of the buckwheat plant layer, allowing buckwheat plants to be moved to the conveyor mechanism, which confirms that the pickup tooth can pick up the buckwheat swath. As shown in Figure 5(a), with fewer than five rows of pickup tooth, not all buckwheat plants can be picked up; however, with six rows or more, all plants are effectively picked up. Therefore, the pickup tooth count should be more than six. The number of pickup tooth rows was determined based on the thickness of the buckwheat swath. In practical production, variations in the thickness of laid buckwheat plants were observed. Field experiments indicated that too many rows of pickup tooth can increase the contact with buckwheat stalks and grains, resulting in potential grain loss. Thus, the optimal design specifies seven rows of pickup tooth ($n$ = 7)




(a) The motion trajectories of 5 rows of tooth (b) The motion trajectories of 6 rows of tooth

**Fig. 5 – The trajectories of pickup tooth**

**Parameter design and selection of conveyor mechanism**

The conveyor mechanism works in tandem with the pickup mechanism to lift the buckwheat swath and convey it smoothly to the pickup table. Its structure is illustrated in Figure 6. Specifically, it mainly comprises a driving roller, driven roller, auxiliary roller, conveyor belt, flexible scraper, side plate, wheel, etc.

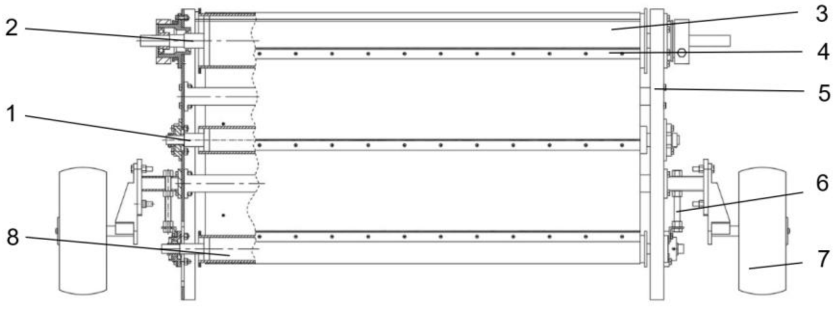



**Fig. 6 – The structure diagram of conveyor mechanism**

*1 – auxiliary roller; 2 – driving roller; 3 – conveyor belt; 4 – flexible scraper; 5 – side plate; 6 – adjust screw; 7 – wheel; 8 – driven roller.*

As depicted in Figure 6, the flexible scraper is attached to the conveyor belt through a bolted connection, and the conveyor belt is positioned around the driving roller, driven roller, and auxiliary roller. The driving and driven rollers are mounted on a side plate equipped with a sliding groove. The relative position of the driving and driven rollers is regulated by adjusting the screw for conveyor tensioning *(Yu et al., 2017)*.

(1) Width of the conveyor mechanism

The role of the conveyor mechanism is to work in conjunction with the pickup mechanism to complete the pickup and transport of buckwheat plants. Consequently, the width of the conveyor mechanism should match that of the pickup mechanism, set at $w$ = 1600 mm.

(2) Distance of flexible scraper

When the distance between the flexible scrapers is too large, it can cause an increase in the leakage and grain loss rates of the buckwheat swath. To reduce leakage, the line speed of the flexible scraper can be increased; however, increasing the speed also raises the impact force, which in turn increases the grain loss rate. Therefore, the distance *l* of the flexible scraper cannot be too large. If the distance *l* of the flexible scraper is too small, the number of scrapers will increase, leading to more frequent contact with the buckwheat swath and thus an increase in grain loss rate. Therefore, *l* should not be too small. According to agricultural machinery design standards, the tooth spacing for a typical spring-tooth conveyor mechanism ranges from 63 mm to 100 mm. The initial design proposes a flexible scraper interval of $l$ = 100 mm.

***Field experiment***

The forward speed of the combine, the speed of the pickup tooth, and the tilt angle of the pickup tooth (the angle between the pickup tooth and the chain's normal direction) were selected as evaluation indices to explore optimal combinations of working parameters and to conduct field tests *(Li et al., 2024)*.

The field experiment was conducted on July 11, 2022, at the test field of Northwest Agriculture and Forestry University of Science and Technology, North Campus, located in Yangling District, Xianyang City, Shaanxi Province. The buckwheat variety planted was "Guqiao No.1," and the test plot covered an area of 4 acres. The test included measurements of buckwheat grain maturity and stalk and grain moisture content. The grain maturity rate was 73.4%, the stalk moisture content was 78.36%, and the grain moisture content was 27.58%. After nine days of drying post-harvest, the stalk moisture content was 57.63%, and the buckwheat grain moisture content was 15.81% *(Zhang et al., 2022)*. Subsequently, a combine equipped with a pickup tooth conveyor belt-type buckwheat pickup device was used to harvest the buckwheat, and the buckwheat grain loss rate was measured.

**Fig. 7 – The site of the field trial**

The field experiment was divided into multiple groups, with each group harvesting a buckwheat swath whose length being 20 m. The natural loss of fallen grains in the field was collected prior to the experiment. The natural fallen mass of buckwheat was recorded as $m_1$. A colored strip of cloth was placed by the machine to collect debris, and the quality of the grains it captured was screened and recorded as $m_2$. The mass of buckwheat grains on the ground after harvest by the pickup combine was recorded as $m_3$, and the total grain loss mass was recorded as $m$. The grain loss mass $m$ is calculated as follows:

$$m = m_3 - m_1 \tag{10}$$

The quality of the grains within the grain bin after the test was recorded as $m_4$, and the grain loss rate $Y$ is expressed as:

$$Y = \frac{m}{m_2+m_3+m_4} \tag{11}$$

**RESULTS**

Design-Expert software was used to conduct a secondary rotary combination design test on the test data, clarifying the optimal coordination of operational parameters for the pickup tooth conveyor belt-type buckwheat pickup device.

The test factors and levels are shown in Table 1, with each level selected to meet field operation requirements. The average value of the statistical results, obtained by repeating the test three times for each test group, is presented in Table 2.

**Table 1**

**Table of factors and levels**

| Level | Factors | | |
|---|---|---|---|
| | The forward speed of the combine, $X_1$ | The speed of the pickup tooth, $X_2$ | The tilt angle of the pickup tooth, $X_3$ |
| | [m/s] | [m/s] | [°] |
| 1 | 0.6 | 1.0 | -10 |
| 2 | 0.8 | 1.2 | 0 |
| 3 | 1.0 | 1.4 | 10 |

**Table 2**

**Experimental program and results**

| Number | Factors | | | Indicators | Number | Factors | | | Indicators |
|---|---|---|---|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | $Y$ | | $X_1$ | $X_2$ | $X_3$ | $Y$ |
| 1 | 0.8 | 1.2 | 0 | 7.36 | 10 | 1.0 | 1.0 | 0 | 10.23 |
| 2 | 0.8 | 1.2 | 0 | 6.89 | 11 | 0.8 | 1.2 | 0 | 8.04 |
| 3 | 1.0 | 1.2 | 10 | 8.37 | 12 | 0.6 | 1.2 | -10 | 10.25 |
| 4 | 0.6 | 1.2 | 10 | 8.52 | 13 | 0.8 | 1.4 | 10 | 14.87 |
| 5 | 0.8 | 1.2 | 0 | 7.15 | 14 | 1.0 | 1.0 | -10 | 9.06 |
| 6 | 0.8 | 1.0 | 10 | 8.80 | 15 | 0.6 | 1.2 | 0 | 16.63 |
| 7 | 1.0 | 1.4 | 0 | 13.62 | 16 | 0.8 | 1.0 | -10 | 8.93 |
| 8 | 0.6 | 1.0 | 0 | 8.16 | 17 | 0.8 | 1.2 | 0 | 7.81 |
| 9 | 0.8 | 1.4 | -10 | 15.41 | | | | | |

### *Regression model construction and testing*

The experimental results were analyzed using Design-Expert software, and a quadratic regression equation model of grain loss rate $Y$ was developed with $X_1$, $X_2$, and $X_3$ as independent variables. The significance of the regression equation model was verified through analysis of variance (ANOVA) and regression coefficient tests. The results are presented in Table 3.

**Table 3**

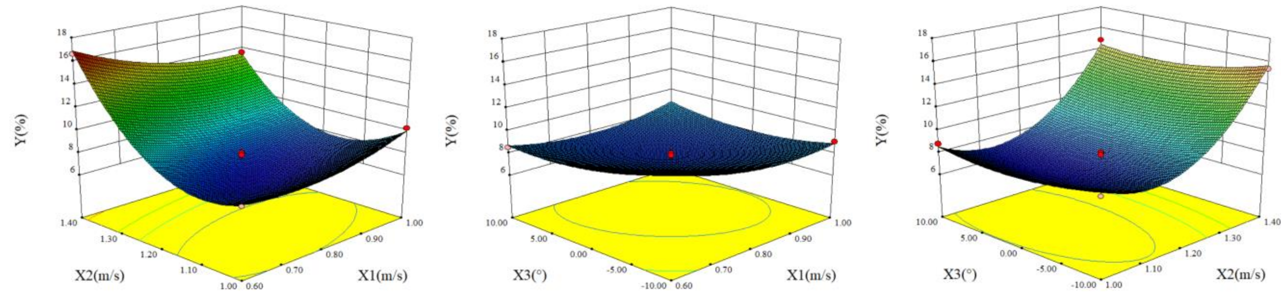
**Regression equation variance analysis of pickup loss rate response surface**

| Indicators | $Y$ | | | | |
|---|---|---|---|---|---|
| Source | Sum of Squares | Degrees of Freedom | Mean Square | F value | P-value |
| Regression | 154.55 | 9 | 17.17 | 56.19 | <0.0001 |
| $X_1$ | 1.34 | 1 | 1.34 | 4.40 | 0.0741 |
| $X_2$ | 74.48 | 1 | 74.48 | 243.72 | <0.0001 |
| $X_3$ | 2.09 | 1 | 2.09 | 6.84 | 0.0346 |
| $X_1X_2$ | 6.45 | 1 | 6.45 | 21.11 | 0.0025 |
| $X_1X_3$ | 1.04 | 1 | 1.04 | 3.40 | 0.1075 |
| $X_2X_3$ | 0.042 | 1 | 0.042 | 0.14 | 0.7217 |
| $X_1^2$ | 4.24 | 1 | 4.24 | 13.88 | 0.0074 |
| $X_2^2$ | 57.84 | 1 | 57.84 | 189.26 | <0.0001 |
| $X_3^2$ | 3.02 | 1 | 3.02 | 9.87 | 0.0164 |
| Residual error | 2.14 | 7 | 2.14 | | |
| Lack of fit | 1.25 | 3 | 1.25 | 1.87 | 0.2749 |
| Error | 0.89 | 4 | 0.89 | | |
| Sum | 156.69 | 16 | 156.69 | | |

According to Table 3, the regression equation for the loss rate $Y$, expressed in coded values, was obtained by excluding the insignificant terms from the regression equation.

$$Y = 7.45 + 3.05X_2 - 0.51X_3 - 1.27X_1X_2 + 3.71{X_2}^2 + 0.85{X_3}^2 \tag{12}$$

The interaction between the other two factors and their effect on *Y* was analyzed by fitting the response surface, with any factor in Eq. 12 set to the zero level, as shown in Figure 8.




(a) (b) (c)

**Fig. 8 – Response surfaces effect of factor interaction on test indicators**

As shown in the response surface of Figure 8(a), when $X_3$ was set to 0°, $X_1$ and $X_2$ significantly affected *Y*. *Y* first decreased and then increased as $X_1$ and $X_2$ increased. When $X_2$ increased from 1.0 m/s to 1.4 m/s, the effect of $X_1$ on *Y* initially decreased and then increased; when $X_1$ increased from 0.6 m/s to 1.0 m/s, the effect of $X_1$ on *Y* tended to decrease. As shown in the response surface of Figure 8(b), *Y* first decreased and then increased with increasing $X_1$ and $X_3$; however, the effects of $X_1$ and $X_3$ on *Y* were not significant, consistent with the results of the regression equation variance analysis. As shown in the response surface of Figure 8(c), *Y* decreased and then increased with increasing $X_2$ and $X_3$; however, the effects of $X_2$ and $X_3$ on *Y* were also not significant, consistent with the regression equation variance analysis results.

***Parameter optimization and experiment of Pickup tooth conveyor type buckwheat pickup device***

The influence of the three test factors on grain loss rate was ranked as follows: the speed of the pickup tooth ($X_2$), the tilt angle of the pickup tooth ($X_3$), and the forward speed of the combine ($X_1$). To further determine the optimal parameter combination for the pickup tooth conveyor belt-type buckwheat pickup device, a regression equation model was used for multi-objective parameter optimization. Using the test influence factor range as boundary conditions and the minimum grain loss rate as the optimization objective, a mathematical model was established *(Zhang et al., 2024)*:

$$\begin{cases} min\, Y\,(X_1, X_2, X_3) \\ s.t. \begin{cases} 0.6m/s \le X_1 \le 1.0m/s \\ 1.0m/s \le X_2 \le 1.4m/s \\ -10° \le X_3 \le 10° \end{cases} \end{cases}$$

The Design-Expert software regression equation model was used to find the optimal parameters for the test impact factors: $X_1$ at 0.82 m/s, $X_2$ at 1.09 m/s, and $X_3$ at 1.43°. Under the optimal combination of parameters, the grain loss rate *Y* was 6.92%.

Based on the results of the multi-objective optimization and the practical operating requirements of the pickup tooth conveyor belt-type buckwheat pickup device, the test parameters were set as follows: the forward speed of the combine of 0.8 m/s, the speed of the pickup tooth of 1.1 m/s, and the tilt angle of the pickup tooth of 0°. Under these test conditions, three experiments were conducted, yielding a loss rate of 6.92%.

## CONCLUSIONS

To address the problem of excessively high grain loss during the buckwheat pickup process in two-stage mechanized harvesting, a pickup tooth conveyor belt-type buckwheat pickup device was designed to reduce grain loss. The design of key components, including the pickup mechanism and conveyor mechanism, was conducted, and critical design parameters were determined. The operational parameters influencing grain loss rate were identified, and field tests were conducted.

Through the orthogonal, the quadratic regression equation model was established. The model analysis showed the speed of the pickup tooth had the most significant effect on the grain loss rate, followed by the tilt angle of the pickup tooth and the forward speed of the combine. The response surface method was used to analyze the orthogonal test results, and the regression equation model was solved by multi-objective optimization. The reasonable test parameters of pickup tooth conveyor belt type buckwheat pickup device were determined: the forward speed of the combine was 0.8 m/s, the speed of the pickup tooth was 1.1 m/s, and the tilt angle of the pickup tooth was 0°. Under these conditions, the grain loss rate was 6.92%.

**ACKNOWLEDGEMENT**

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