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Design and Parameter Optimization of Conveying and Baling Devices for Ramie Cutting and Baling Machine

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Abstract: Conveying and baling are two important links in the mechanized harvesting of ramie, in the face of ramie cutting and baling harvesting technology research gaps, low stalk conveying rate, high breaking rate and other problems. In this paper, according to the technical requirements of ramie harvesting, we designed a conveying and baling device, the hand-held ramie cutter. First, the key mechanism of the conveying and baling device of the equipment was designed. Then, we analyzed the location of stem clogging and the reasons for the breaking problem during the conveying and baling process. The field harvesting experiments were carried out according to the principles of Box–Behnken experimental design. Taking the machine travelling speed, conveying speed and ramie raking frequency as the test factors and using the Design-Expert V8.0.6.1 to process the data, we established a regression model for each experimental factor on the conveying rate and breaking rate. The order of influence of several factors on the breaking rate is: $X_2 > X_1 > X_3$; and the effects of the three factors on the conveying rate were $X_3 > X_2 > X_1$. Through response surface analysis (RSA), the effects of the factors on the indicators were explained, as was the impact of the factors on the indicators. Finally, the parameter optimization was carried out with the delivery rate as the core index. The best combination of motion parameters was obtained as follows: the travelling speed was 0.37 m/s, the chain conveying speed was 1.1 m/s, and the raking frequency was 144 times/min. With the combination of parameters under the field test verification, the results show that compared with the original work quality, the stalk delivery rate increased from 85.2% to 93% (an increase of 7.8%), the stalk breaking rate fell from 31.1% to 20.4% (a decrease of 10.7%). The performance of ramie harvesting and baling was greatly improved, and we achieved relatively satisfactory results.

Keywords: ramie cutting and baling machine; conveying and baling device; response surface method; parameter optimization

1. Introduction

Ramie is a perennial herbaceous plant with a long history of cultivation in China. Its fiber textile products are known as “Chinese sackcloth”, and at present, more than 90% of the world’s ramie production is in China [1,2]. The structure of ramie is shown in Figure 1; the fibers of the ramie phloem are long, thin and flexible, and the fabric has the advantages of abrasion resistance, breathability, antibacterial and mildew resistance [3]. Ramie has a high medicinal value and can be antibacterial, anti-inflammatory, anti-cancer, antioxidant and so on [4,5]. Ramie can be used as a high quality plant protein feed material, and its fresh stems are rich in crude protein, lysine and other nutrients [6,7]. Ramie is a promising green plant for heavy-metal-contaminated soil remediation, with the ability to absorb and enrich Cd, As, Cu and other heavy metal elements in the soil [8–10].
Ramie is harvested three times a year, mainly in the summer and fall when the environment is harsh and hot, and the harvesting is labor intensive and inefficient [11]. Due to the limitations of the ramie harvesting mechanization technology, the ramie industry continues to be in the doldrums, and the planting area and production are decreasing year by year. The ramie industry has declined sharply, and Europe and the United States had stopped the research into ramie harvesting equipment [12]. The domestic research has focused on ramie harvesting machines for feeding purposes, but there is little research into fiber ramie harvesters. The design of the ramie harvester for fiber is mainly based on other tall crop harvesters, such as reed harvesters, rape harvesters and corn harvesters [13–15]. Liu Jiajie [16] designed a 4QM-4.0 hemp green fodder combine harvester and carried out a pilot study on the reciprocating cutting table to reduce the problem of clogging and entanglement, and the cutting quality was good. Yang Yanwei [17] designed a combine harvester for ramie fiber and fodder harvesting. Two sets of combined harvesting systems for fiber and fodder were designed separately that could complete the harvesting of ramie fiber and fodder and return the hemp bones and chips to the field, so that the production efficiency was improved. The Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs conducted a study on ramie combine harvesters. They designed a 4LMZ-160 crawler-type ramie combine harvester, that is capable of performing functions such as the cutting, conveying and spreading of ramie stems. However, due to the lack of a theoretical research basis, the quality of the operation still needs to be improved [18].

Combined with the physical characteristics of ramie stalks and the technical requirements of harvesting, this paper designs a hand-held ramie cutting and baling machine with a tracked chassis that is flexible, simple to operate and easy to maintain [19]. It can complete the ramie cutting, conveying and baling functions in one go. The article analyzed the reasons for the problems of low stalk conveying rate and high breaking rate in the conveying and baling process of the equipment. Combined with the field test, three main factors affecting the two indexes were screened out: travelling speed, chain conveying speed and the raking frequency of baling device. According to the principle of Box–Behnken experimental design, the response surface optimization field test was carried out, and the influence of each factor on the evaluation index was explored through surface analysis. Through the multi-objective parameter optimization of the regression equation, the best technical parameters were obtained. The aim of this article is to optimize the technical parameters of the equipment through structural design, field trials and parameter optimization to enhance work performance.
2. Structural Design and Working Principle

2.1. Overall Structure of Equipment

The hand-held ramie cutting and baling machine is mainly composed of a crawler chassis, a reciprocating double-action cutter, a stalk support device, a double-row chain conveying device, an automatic baling device, etc. [20]. The overall structure is shown in Figure 2.

![Three-dimensional model of the whole machine](image)


The main workflow of the harvester is as follows: the height of the chassis is adjusted to make the cutter fit the ramie roots to ensure the stubble height meets the requirements. As the machine travels, the ramie passes through the star wheel and is cut by the reciprocating cutter. The stalks are then transported to one side by double rows of chains and then baled, and finally, the bales are thrown to the field.

2.2. Design of Key Components

The conveyor and baler are the key parts of ramie harvesting operation, and their performance will directly affect the quality of ramie harvesting [21]. The conveyor unit clamps and conveys the cut stalks to the designated position, while the bale tying device is used to move the stalks to the bale tying area to finish baling. The ramie bale cutter is designed for the high-pole, high-fiber ramie species. The physical properties of the stalks are special, as the fibers are tough and tensile, while the woody parts are hard and easy to break. Therefore, the following requirements should be met during operation. There is friction between the stalks and the baffle, and the conveyor chain should have a certain clamping capacity, to ensure that the stalks are always upright when conveying, to reduce the fall and to improve the conveying rate. A reasonable raking mechanism should be designed, optimizing the connection in the conveying–baling process, and reducing the problem of collision during conveying. It should be ensured that the process of conveying is smooth and the chance of blocking is reduced.

2.2.1. Determination of Machine Travelling Speed $V_m$

The size of $V_m$ directly affects the productivity. At the same time, it should be considered that it should match with the planting density, cutting width, chain clamping capacity, conveying capacity and other elements. If $V_m$ is too small, the productivity is too low for the operation. If $V_m$ is too big, even though it can improve productivity to a certain extent, it puts higher requirements on the subsequent conveying and baling processes and is more prone to clogging and entanglement problems; the working stability is greatly reduced. As this model is a small hand-held machine, coupled with the terrain limitations of small field operations and combined with the design experience, the range of travelling speed is selected as $0.3 \text{ m/s} - 0.6 \text{ m/s}$.
2.2.2. Design of Clamping and Conveying Device

The function of the chain is to clamp and convey the stalk laterally to the left side of the baling device. At present, crop clamping and conveying devices mainly include three forms: the chain type, double-belt type and three-belt type [22–24]. The main principle of the belt clamping conveyor is to forcefully clamp the stalk by friction, which is mainly used for fragile and easily damaged varieties of crops [25]. However, ramie is not suitable for the belt conveyor because of its inverted and tilted growth and harsh growing environment. Therefore, a chain conveyor is used in this design. The “dentate” structure (hereinafter referred to as teeth) is designed to enhance the clamping and conveying ability, and the basic structure of the chain is shown in Figure 3.

![Schematic diagram of the chain structure.](image)

The height of the chain has an important influence on the harvesting operation. Through the study of ramie growth conditions, ramie is harvested three times a year, and the average height of the mature stalks of the three crops gradually decreases. In order to improve the adaptability of the machine, the average height of the second hemp was used as a reference. Combining the agronomic requirements of ramie harvesting, reviewing data and researching relevant machinery and equipment, the height of the clamping chains was determined: the height of the top row of chains should be approximately 2/3 of the stalk height; therefore, the second row of chains was designed at 1.2 m, setting the height of the bottom row of chains at 30 cm from the ground [26]. The overall structure of the conveying unit is shown in Figure 4.

![Schematic diagram of the conveying device.](image)

The structure of the clamping and conveying device is shown in Figure 5. The stalk clamping area is a closed space consisting of pressure springs, chains and teeth. When the machine is travelling at speed \( V_m \), the stalk is cut by the cutter and then passes through...
the rotating star wheel into the clamping area. The stalks are transported by the chain at speed \( V_1 \), and the pitch of the “teeth” is \( b \). The stalks are transported laterally by the chain at speed \( V_1 \) to the baling area [27].

Analyzing the working principle of stalk conveying, if we want to ensure that the stalks pass smoothly during the conveying process and do not accumulate and cause blockage, the necessary condition is that the number of cut stalks is always smaller than the number of stalks conveyed, so the conveying speed of the chain should match the speed of the whole machine, as shown in Equation (1).

\[
\frac{V_1}{V_m} > \frac{k_2 B b}{k_1 s}
\]  

(1)

In the formula, \( V_1 \) is the chain conveying speed, m/s; \( k_2 \) is the hemp field planting density, Plants/mm\(^2\); \( B \) is the machine cutting width, mm; \( b \) is the chain finger spacing, mm; \( s \) is the conveying space, mm\(^2\); \( k_1 \) is the stalk density in the closed space, tree/mm\(^2\) [28].

The conveying speed of the chain directly affects the conveying rate, which needs to refer to both the travel speed of the whole machine and the movement speed of the raking mechanism. If \( V_1 \) is too small, it leads to stems falling over and clogging the machine; if \( V_1 \) is too large, it damages the stalks and increases the breaking rate. Therefore, in conjunction with design experience, it was determined: \( V_1 = (1.2\text{~}2.5) V_m \) [29]. However, this design is based on a small tracked chassis, and the structure and terrain restrict the travelling speed from being too high. In order to ensure the conveying stability, the chain transmission speed still needs to maintain a certain level; therefore, combined with the design experience, we choose \( V_1 = (1.8\text{~}2.2) V_m \).

2.2.3. Design of the Raking Mechanism

(1) Structural design

After the machine is started, the chain begins continuous transverse conveying. The raking mechanism performs the “raking” action at a fixed frequency, aiming at plucking the conveyed stalks into the baling device, improving the overall smoothness of the conveying process and preventing the stalks from clogging. Its basic working principle is a crank–rocker mechanism, where the power provided by the carrier passes through the transmission box, driving the crank to make a uniform rotation, and the fork can be simplified as a connecting rod [30].

The main function of the raking mechanism is to push the stalks conveyed by the chain into the baling area by means of a continuous rotary movement. Therefore, this mechanism cannot hinder the conveying of the subsequent stalks when it is working. The overall design of the raking mechanism is shown in Figure 6. The rocker and crank are fixed on the frame (transmission box). Mechanism 2 is a crank; one end is connected to the transmission box, and one end of rocker 3 is connected to the transmission box. Mechanism...
1 is a fork; three rows of forks are designed to cover the main part of the stalk to ensure stable and reliable clamping. The crank is designed as an eccentric wheel mechanism, which is connected with fork 1 through two rotating vice to make the work more reliable and smooth. The raking frequency should be matched with the conveying speed through the speed analysis and test to determine the basic range: 135–185 times/min.

![Figure 6](image-url)

**Figure 6.** Structure diagram of the ramie rake mechanism. 1. The fork; 2. The crank; 3. The rocker.

(2) Kinematic analysis

The raking mechanism can be simplified to a four-link mechanism. The continuous rotation of the eccentric wheel drives the hemp raking mechanism to perform continuous rotary motion. The movement diagram of the mechanism is shown in Figure 7; the transmission box AD is fixed on the frame; the crank AB is the eccentric wheel; the connecting rod BC is the toggle connecting rod; CD is the rocker.

![Figure 7](image-url)

**Figure 7.** Kinematic diagram of the hemp rake mechanism.

The displacement principle of the mechanism EBC is

\[ \vec{AB} + \vec{BC} = \vec{AD} + \vec{DC} \]  

(2)

The equation for the displacement of point E on the mechanism EBC is

\[
\begin{cases}
    x_E = x_B + L_{EB}\cos\alpha_4 \\
    y_E = y_B + L_{EB}\sin\alpha_4
\end{cases}
\]  

(3)

In the formula, \( L_{EB} \) is the length of the rod EB. The displacement of point E is the displacement change of the fork vertex, and its trajectory is shown as the purple curve in Figure 8.
3. Theoretical Analysis of the Conveying–Baling Process

3.1. Principle of Clamping and Conveying

The force analysis of the stalk clamping and conveying process is shown in Figure 9. During the conveying phase, the stalk is subjected to the pressure of the “teeth” $F_1$, the pressure of the springs $F_2$ and the pressure of the chain $F_3$, where $F_2$ and $F_3$ will not be present at the same time. The frictional force of the chain $f_1$, the frictional force of the pressure springs $f_2$, the frictional force of the tines $f_3$ and the frictional force of the base plate on the stalk $f_4$, $f_1$ and $f_2$ will not be present at the same time. During the raking process, the stalk is subjected to the pressure of the forks $F_4$, the frictional force $f_4$ and the frictional force $f_3$ of the base plate.

The teeth are designed with an oblique inclination angle $\alpha$, where the pressure $F_1$ between the stalk and the teeth is $\alpha$ from the horizontal direction, so that the stalk can be carried smoothly out of the teeth and into the baling area at the end of the conveyor. $\alpha$ is usually taken as 60°–70°, in view of the harvester being a small piece of equipment; the chain conveying speed is relatively low; therefore, it is determined that $\alpha$ is 70°. The contact surface of the teeth is also rounded to reduce the stress on the stalks.

3.2. Analysis of the Causes for Breakage and Clogging in the Conveying–Baling Process

The physical properties of ramie stalks are special: the woody part is hard and brittle, the bast part is slender and flexible, and the surface of the stalk has a high coefficient of friction. The conveying and baling processes are two important steps in ramie harvesting; the two steps and their interface directly affect the efficiency of stalk conveying and baling quality. Through the preliminary field trials, the problems of stem breakage and clogging mainly appeared in these two processes:

(1) Conveying stage

The stalk clamping and conveying process and force state are shown in Figure 10, with five points of contact between the stalk and the machine. The combined forces on the stalk

Figure 8. Motion track of E point.

Figure 9. Force analysis of the stalk conveying process.
cross-sections at each contact point are $F_a$, $F_b$, $F_c$, $F_d$ and $f_e$. The height of each cross-section from the ground is $L_0$, $L_1$, $L_2$, $L_3$ and $L_4$, respectively.

Figure 10. Schematic diagram of the conveying process and force analysis. 1. Crown of Ramie; 2. Root of Ramie; 3. Short-growing Ramie.

Due to the presence of friction between the baffles and the stalks, obstruction by short plants 3, the stalks are prone to be bent, crooked, inclined and further accumulate during the conveying process, hindering the subsequent stalks from being conveyed. The force analysis of the conveying process yields Equation (4), and the contact force between the stalk and the base plate at the beginning is the friction force:

$$f_1 = \mu mg;$$

In the formula, $\mu$ is the friction coefficient between the stalk and bottom baffle; $m$ is the weight of the stalk; $g$ is the acceleration of gravity.

When the stalks are transported for a distance and then bent and deformed, the contact force between the base plate and the stalks can be expressed as Equation (5):

$$F_a = F_z + \mu mg + \mu F_n \cos \alpha;$$

In the formula, $F_z$ is the resistance of short stalks and fallen stalks; $F_n$ is the pressure of the bending deformation of the stalks on the bottom baffle; $\alpha$ is the angle between the bending deformation of the stalks on the pressure of the bottom baffle and the vertical direction.

Therefore, in the conveying process, if the stalks are inclined and deformed, the bottom friction force increases cumulatively, the degree of tilt continues to increase and further impedes the conveying of the subsequent stalks, resulting in the accumulation of blockage and stalk breakage.

(2) Connection of the conveying and baling processes

The stalk conveying–baling process and its force state are shown in Figure 11. The clamping chain moves horizontally with the speed $V_t$, and the instantaneous speed of the stalk contacting mechanism is $V_T$ at a fixed frequency of rotary motion, which is at an angle of $\beta$ in the horizontal direction. There are three contact parts between the raking mechanism and the stalks, and the heights from the ground are $L_5$, $L_6$ and $L_7$, respectively.

The breaking of the stalk during the articulation process is mainly due to the large deformation that occurs in an instant. The stalk enters the raking mechanism with a horizontal velocity $V_h$, and the magnitude and direction of the velocity changes instantaneously. The large deformation of the flexible body stalk is explained with the help of the floating coordinate method in flexible multibody dynamics.
The complex interaction between multiple rigid bodies (such as racks and chains) and flexible body stalks in the conveying process can be abstracted and simplified as a multi-body system. The floating coordinate system $A$ is established on the system inertial coordinate system $O$. The floating coordinate system is established on the flexible body stalk. The rigid body displacement of the flexible body is the motion of the floating coordinate system. The deformation of the flexible body is the displacement of the flexible body at any point in the flexible body relative to the floating coordinate system. The motion of any point on the flexible body is the synthetic motion of the floating coordinate system $A$ and the deformation of the flexible body. Therefore, the position and velocity of any point $P$ can be expressed as Figure 12.

For any point $P$ of the flexible body, its position vector is

$$r = r_0 + A(S_p + U_P)$$

(6)

In the formula, $r$ is the vector of the point in the inertial coordinate system; $r_0$ is the vector of the floating coordinate system in the inertial coordinate system; $A$ is the direction cosine matrix; $S_p$ is the vector of the point $P$ in the floating coordinate system when the flexible body is deformed; and $U_P$ is the relative deformation vector.

At the moment when the stalks enter the baling area, the thrust of the raking mechanism causes a sudden change in the motion of the stalks, while the crown of the plant (point $P$) maintains its original motion due to inertia. Therefore, there is a distance between point $P$ and the main body of the stalk, and the bending deformation of the stalk is too large, which eventually leads to breakage.
4. Field Experiments and Optimization of Equipment Parameters

4.1. Materials and Methods

(1) Test conditions

On 23 November 2022, a field experiment was conducted at the ramie test field of Baima Test Base, Nanjing Agricultural Mechanisation Research Institute, Nanjing, Ministry of Agriculture and Rural Affairs, in Lishui District, Nanjing City, Jiangsu Province, China. The ramie in the test area was the third crop with good growth, the average height was 1.5 m, the row spacing was 30 cm, and the terrain in the test area was flat. In addition to the ramie harvester, the equipment used in this experiment also included a tachymeter, tape measure, stopwatch, electronic balance and other auxiliary tools.

Plant growth parameters such as spacing of ramie rows, natural height, natural height, collapse rate, and moisture content were measured and recorded. The results are shown in Table 1.

Table 1. Records of ramie growth status.

<table>
<thead>
<tr>
<th>Measurement Items</th>
<th>Measurement Point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing between rows/mm</td>
<td></td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Natural height of plant/mm</td>
<td></td>
<td>1520</td>
<td>1540</td>
<td>1480</td>
<td>1550</td>
<td>1522.5</td>
</tr>
<tr>
<td>Collapse rate/%</td>
<td></td>
<td>2.5</td>
<td>4</td>
<td>4.1</td>
<td>5.8</td>
<td>4.1</td>
</tr>
<tr>
<td>Average moisture content/%</td>
<td></td>
<td>77.2</td>
<td>78.9</td>
<td>80.1</td>
<td>79</td>
<td>78.8</td>
</tr>
</tbody>
</table>

(2) Test Methods

A scientific and reasonable test design can achieve the expected test purpose with a shorter time and less manpower and material resources. The evaluation index is an important basis for evaluating the operation quality of the baler, and the test factor refers to the parameter that can influence the evaluation index of the whole machine, and the expected index can be achieved by controlling the level of the factor artificially.

① Test factors

This test involves the analysis of multiple factors, so the response surface test design is chosen, which has the advantages of fewer tests, higher efficiency and saving time.

Through the analysis in the previous chapter, reviewing the literature and referring to similar harvesting equipment, the range of values of the three key working parameters, namely, travelling speed, conveying speed and raking frequency, was preliminarily determined.

② Evaluation indicators

Since there is a gap in the current standards related to the operation quality of ramie harvesters, the evaluation of their operation quality is calculated with reference to the standards related to other crops [21,31].

The stalk conveying rate and breaking rate were used as the evaluation indexes for the operation quality of the ramie baler. Stalk delivery rate: the ratio of the number of missing stalks \( n_1 \) to the number of harvested stalks \( N \) during ramie harvesting, calculated according to Equation (7).

\[
S = \frac{n_1}{N} \quad (7)
\]

where \( S \)—conveying rate, %; \( n_1 \)—the number of stalks missed in the conveying process; \( N \)—the total number of stalks.

In the stalk conveying–baling process, the breaking rate is a measure of conveying–baling process fluency of the main indicators. Breaking rate: in each hemp bale, the number of broken stalks accounted for in proportion to the total number of stalks, according to the Formula (8) calculation.

\[
L = \frac{n_2}{N_1} \quad (8)
\]
where $L$—stalk breaking rate, %; $n_2$—the number of broken stalks in the bale; $N_1$—the number of stalks in a single bundle.

4.2. Results and Discussion

4.2.1. Experimental Programs and Results

According to the principle of Box–Behnken experimental design, the travelling speed $X_1$, the chain conveying speed $X_2$ and the raking frequency $X_3$ were set as the experimental factors, and the stalk conveying rate $Y_1$ and the breaking rate $Y_2$ were designated as the evaluation indexes of the experimental program, and a total of 15 groups of tests were carried out. In the field test, the single test measurement stroke was set to 7–10 m, able to complete two bales in the first two meters for the preparation area. The field harvesting test for ramie is shown in Figure 13. The table of factors and coding levels are shown in Table 2 [32,33].

![Field experiment process and results.](image)

**Figure 13.** Field experiment process and results.

**Table 2.** Box–Behnken design coded factors and the observed responses.

<table>
<thead>
<tr>
<th>No.</th>
<th>$X_1/(\text{m}\cdot\text{s}^{-1})$</th>
<th>$X_2/(\text{m}\cdot\text{s}^{-1})$</th>
<th>$X_3/(\text{times}\cdot\text{min}^{-1})$</th>
<th>$Y_1\ (\text{trees}\cdot\text{s}^{-1})$</th>
<th>$Y_2%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>−1</td>
<td>87.9</td>
<td>21.2</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>−1</td>
<td>91.6</td>
<td>21.5</td>
</tr>
<tr>
<td>3</td>
<td>−1</td>
<td>1</td>
<td>0</td>
<td>89.9</td>
<td>19.8</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>−1</td>
<td>0</td>
<td>81.8</td>
<td>27.5</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>90.2</td>
<td>19.6</td>
</tr>
<tr>
<td>6</td>
<td>−1</td>
<td>0</td>
<td>1</td>
<td>88.3</td>
<td>28.1</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>−1</td>
<td>1</td>
<td>85.4</td>
<td>31.1</td>
</tr>
<tr>
<td>8</td>
<td>−1</td>
<td>0</td>
<td>−1</td>
<td>88.7</td>
<td>20.4</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>89.5</td>
<td>20.9</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>91.4</td>
<td>19.5</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>92</td>
<td>27.1</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>89.6</td>
<td>19.8</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>−1</td>
<td>−1</td>
<td>86</td>
<td>23.3</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>87.9</td>
<td>30.6</td>
</tr>
<tr>
<td>15</td>
<td>−1</td>
<td>−1</td>
<td>0</td>
<td>84</td>
<td>23.9</td>
</tr>
</tbody>
</table>

$X_1$: travelling speed; $X_2$: conveying speed; $X_3$: ramie raking frequency; $Y_1$: conveying rate; $Y_2$: breaking rate.

4.2.2. Regression Modeling and Significance Testing

Using Design-Expert.V8.0.6.1 software, the results were analyzed based on the experimental results. A mathematical regression model was established for the effect of travelling speed, chain conveying speed and raking frequency on stem breaking rate:

\[
Y_1 = 89.77 - 0.1125X_1 + 3.37X_2 + 0.1375X_3 + 0.9250X_1X_2 + 0.35X_1X_3 - 0.575X_2X_3 - 2.06X_1^2 - 1.20933X_2^2 - 0.7417X_3^2 \tag{9}
\]

\[
Y_2 = 20.1 - 0.0825X_1 - 2.24X_2 + 3.81X_3 - 0.975X_1X_2 + 0.425X_1X_3 + 0.55X_2X_3 - 0.95 + 1.63X_2^2 + 4.02X_3^2 \tag{10}
\]
A significance test and ANOVA were performed, and the results of the exclusion of insignificant terms are shown in Tables 3 and 4, as follows.

**Table 3. Analysis of variance results for the conveying rate.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>117.89</td>
<td>9</td>
<td>13.10</td>
<td>28.24</td>
<td>0.0009</td>
</tr>
<tr>
<td>$X_2$</td>
<td>91.12</td>
<td>1</td>
<td>91.12</td>
<td>196.46</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>$X_1X_2$</td>
<td>3.42</td>
<td>1</td>
<td>3.42</td>
<td>7.38</td>
<td>0.042</td>
</tr>
<tr>
<td>$X_1^2$</td>
<td>15.64</td>
<td>1</td>
<td>15.64</td>
<td>33.73</td>
<td>0.0021</td>
</tr>
<tr>
<td>$X_2^2$</td>
<td>3.22</td>
<td>1</td>
<td>3.22</td>
<td>6.93</td>
<td>0.0463</td>
</tr>
<tr>
<td>Residual</td>
<td>2.32</td>
<td>5</td>
<td>0.4638</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of fit</td>
<td>2.03</td>
<td>3</td>
<td>0.6775</td>
<td>4.73</td>
<td>0.1796</td>
</tr>
<tr>
<td>Pure error</td>
<td>0.2867</td>
<td>2</td>
<td>0.1433</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>120.21</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4. Analysis of variance results for the breaking rate.**

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>26.10</td>
<td>17.05</td>
<td>0.003</td>
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<tr>
<td>$X_2$</td>
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<td>1</td>
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<td>26.17</td>
<td>0.0037</td>
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<tr>
<td>$X_3$</td>
<td>116.28</td>
<td>1</td>
<td>116.28</td>
<td>75.98</td>
<td>0.0003</td>
</tr>
<tr>
<td>$X_1^2$</td>
<td>59.82</td>
<td>1</td>
<td>59.82</td>
<td>39.08</td>
<td>0.0015</td>
</tr>
<tr>
<td>Residual</td>
<td>7.65</td>
<td>5</td>
<td>1.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of fit</td>
<td>6.67</td>
<td>3</td>
<td>2.22</td>
<td>4.54</td>
<td>0.189</td>
</tr>
<tr>
<td>Pure error</td>
<td>0.98</td>
<td>2</td>
<td>0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>242.52</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from the table, the $p$-values of the conveying rate $Y_1$ and the breaking rate $Y_2$ are less than 0.01, and the values of the misfit term are 0.2414 and 0.189, respectively, which are greater than 0.05. This indicates that the final regression models obtained are well fitted. The coefficients of determination (R2) of the models were 0.9856 and 0.9684, indicating that the two regression models were able to reflect 98% and 96.8% of the variation in the response values, respectively, and that the error generated by this test was very small, and the results of the response surface analysis were highly credible. Therefore, this model can be used to predict and analyze the changes in the performance of the ramie harvester.

It can be seen from the analysis that the degree of influence of these three factors on the stalk conveying rate is $X_2 > X_1 > X_3$; and the effect of the three factors on the breaking rate is $X_3 > X_2 > X_1$.

### 4.2.3. Impact of Interactions on Evaluation Indicators

In order to analyze the effect of the interaction between the three factors of travelling speed, conveying speed and raking frequency on the evaluation indexes, one of the factors was fixed at the intermediate level, and the effects of the other two factors were analyzed.

1. **Influence law of interaction on stalk conveying rate**

The response surface of three factors on the conveying rate of hemp stalks is shown in Figure 14. The first picture shows the interaction between machine travelling speed and chain conveying speed on the conveying rate. When the raking frequency $X_3$ is 160 times/minute, the interaction of the two factors is significant. As the travelling speed increases, the delivery rate increases and then decreases. This is because an increase in travelling speed leads to an increase in the number of stalks in the enclosed space of the chain per unit time. When the number of stalks in the enclosed space reaches a certain level due to increasing travelling speed, it is not favorable for stalk entry. The interaction between the stalks and the friction between the roots of the stalks and the frame increase substantially, affecting the overall smoothness. As the conveying speed increases, the
conveying rate gradually increases, which is because the falling of the stalks mainly occurs in the chain conveying link. The increase in chain conveying speed can reduce the situation of falling stalks and improve the conveying stability. When the conveying speed is too high, it becomes difficult for hemp stalks to enter the conveying zone, which affects the stalk conveying rate.

Figure 14. Laws on the effect of interaction factors on conveying rate.

The second picture shows the interaction between travelling speed and raking frequency on the conveying rate when the chain conveying speed $X_2$ was 0.9 m/s. The interaction of the two factors was not significant. At the same raking frequency, the conveyance rate increases and then decreases with the increase in travelling speed. This is because when the travelling speed increases, the number of stalks increases to a reasonable value for the chain conveying interval, and the conveying efficiency is improved. When the travelling speed reaches a certain level, the feeding volume is gradually too large to affect the overall conveying smoothness, reducing the conveying rate.

The third picture represents the interaction between conveying speed and raking frequency on the stalk conveying rate when the travelling speed $X_1$ was 0.45 m/s, and the interaction of the two factors was not significant.
The influence of interactive Factors on Stem breaking rate

The response surfaces of the effects of the three factors on stalk breaking rate are shown in Figure 15. The first picture shows the response surface of the interaction between travelling speed and conveying speed on fracture rate. The interaction between the two factors was not significant when the raking frequency $X_3 = 160$ times/min. The rate of stem breakage increases gradually when the travelling speed increases. This is because the travelling speed directly affects the number of stalks fed. The increase in the amount of feed increases the interaction and interference between the stalks. A tilting of the front stalks can exacerbate the problem of falling and breaking in the subsequent stalks. As the conveying speed increases, the stem breaking rate decreases. That is because when the conveying speed is too slow, the stalks tend to fall over, preventing the subsequent stalks from being conveyed and causing stalk aggregation and breakage. An increase in conveying speed reduces the rate of collapse.

![3D Surface](image1)
Interaction of $X_1$–$X_2$ factors

![3D Surface](image2)
Interaction of $X_1$–$X_3$ factors

![3D Surface](image3)
Interaction of $X_2$–$X_3$ factors

Figure 15. Laws on the effect of interaction factors on the breaking rate.

The second picture shows the interaction between machine travelling speed and raking frequency on stalk delivery rate. The interaction of the two factors was not significant.
the chain conveying speed $X_2 = 0.9$ m/s. At the same travelling speed, when the raking frequency reached a certain value, the stem breaking rate increased rapidly. This is because the stalks were transported to the baling area with a certain initial speed, and the mismatch between the raking frequency and the initial speed caused the collision of the stalks.

Moreover, due to the inertia of the stalks in the instantaneous acceleration process, the crown of the plant has a smaller instantaneous displacement compared with the main stem, resulting in excessive bending and deformation of the stalks and a substantial increase in the breaking rate. The third picture shows the interaction between chain conveying speed and raking frequency on the stem breaking rate, and the interaction of the two factors was not significant when the travelling speed $X_1 = 0.45$ m/s.

4.3. Parameter Optimization

Combining the above analyses with the current operation of ramie harvesters, the conveying rate is directly related to the winding and clogging problems of the machine. In order to optimize the operating quality of the baler, it is necessary to increase the conveying efficiency and, at the same time, reduce the stalk breaking rate. Therefore, it is expected to increase the conveyance rate of the ramie baler most significantly. Using the equations of $Y_1$ and $Y_2$, the importance of the conveyance rate is set to be the highest (“+++++”), and the stem breaking rate is set to be slightly lower (“++++”). The boundary conditions are formulated as follows.

$$
\begin{align*}
\text{max} Y_1 & (+++++) \\
\text{max} Y_2 & (+++++) \\
0.3 & \leq X_1 \leq 0.6 \\
0.7 & \leq X_2 \leq 1.1 \\
135 & \leq X_3 \leq 185
\end{align*}
$$

Using Design-Expert to optimally solve the formula, the optimal combination of motion parameters is obtained as follows: the travelling speed is $0.37$ m/s, the chain conveying speed is $1.1$ m/s, the raking frequency is 144 times/min; at this time, the stalk conveying rate is 91.88%, and the stalk breaking rate is 19.62%.

The field validation test was conducted on 30 November 2022 at the Ramie test field of Baima Base, Nanjing Agricultural Mechanisation Research Institute, Ministry of Agriculture and Rural Affairs, Lishui District, Nanjing, Jiangsu Province, China. According to the optimization results, the travelling speed, chain conveying speed and raking frequency were set to $0.37$ m/s, $1.1$ m/s and 144 times/min, respectively, and the validation was carried out under this parameter, and the final result was a conveying rate of 93%. The stalk breaking rate was 20.4%. Compared with the original working quality of the baler, the stalk conveying rate was increased from 85.2% to 93% (an increase of 7.8%), and the stalk breaking rate was reduced from 31.1% to 20.4% (a decrease of 10.7%). The field validation test proved that the results of parameter optimization had a high degree of confidence, and the above prediction model was accurate and reliable.

5. Conclusions

Key components such as the clamping and conveying device and the hemp raking mechanism were designed. The basic structure and technical parameters were confirmed: the range of travelling speed $V_m$ is $0.3$ m/s~$0.6$ m/s, the range of chain conveying speed $V_1 = (1.8~2.2)V_m$, and the frequency of straddling is $135$~$185$ times/min. The causes of straw breakage and blockage in the conveying–baling process were systematically analyzed. In the conveying process, the friction of the baffle plate and the short stalks played the role of obstruction. In the conveying–baling process, the mismatch in the speed of movement led to the sudden deformation of the stalks. Field tests were conducted using a ramie baler. According to the principle of Box–Behnken experimental design, the results were analyzed by response surface analysis. The results showed that the three factors of travelling speed $X_1$, chain conveying speed $X_2$ and raking frequency $X_3$ had the following effects on the breaking rate of the stalks: $X_2 > X_1 > X_3$; and the effects of the three factors on the conveying
rate were $X_3 > X_2 > X_1$. The interaction between travelling speed and chain conveying speed had a significant effect on the conveying rate. Through the regression model, multi-objective optimization analysis was used to optimize each parameter. The optimization obtained the travelling speed of 0.37 m/s, the chain conveying speed of 1.1 m/s and the raking frequency of 144 times/min. Validation was carried out under this technical parameter. Compared with the original working quality of the equipment, the stalk conveying rate was increased from 85.2% to 93% (an increase of 7.8%), and the stalk breaking rate was reduced from 31.1% to 20.4% (a decrease of 10.7%). In this study, the structural design and field test optimization analysis of the conveyor and baling device for the ramie cutting and baling machine are carried out. It plays an important role in optimizing the overall working performance and improving the working efficiency. It can provide a reference for the research into related harvesting and baling equipment.

Author Contributions: Conceptualization, S.S.; data curation, H.L. and S.S.; formal analysis, K.T.; funding acquisition, B.Z.; investigation, S.S. and H.L.; methodology, S.S. and J.H.; project administration, J.H.; resources, C.S.; software, C.S.; supervision, J.H. and B.Z.; validation, C.S.; visualization, K.T.; writing—original draft, S.S.; writing—review and editing, B.Z. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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