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Optimization of Operation Parameters of the Garlic Plant Divider and Lifter Mechanisms

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Abstract: The technology of the divider and lifter mechanisms of a garlic harvester using the depth limit, straw divide, and straw lift modes was studied in Lanling County, Shandong Province, China, according to the characteristics of high hardness, good uprightness and narrow row spacing of garlic planting. A test prototype of the divider and lifter mechanisms of the garlic harvester was designed and manufactured. Single-factor experiments and orthogonal regression experiments were carried out using the experimental factors of working speed, the angle of the divider, the height of the tip of the divider's tooth from the ground, the ratio of the lifter's speed to working speed and the length of the lifter's tooth. The index was the success rate of feed. The results showed that the working speed, the angle of the divider and the length of the lifter's tooth had a significant influence on the success rate of feed ($p < 0.05$), but the experimental factors of the height of the tip of the divider's tooth from the ground and the ratio of the lifter's speed to working speed did not have a significant influence on the success rate of feed ($p > 0.05$). The effects of the angle of the divider, the working speed, and the length of the divider's tooth on the success rate of feed decreased in significance. When the working speed was 0.72 km·h^{-1}, the length of the lifter's tooth was 343.5 mm and the angle of the divider was 20°, the success rate of feed was the highest (98.18%). The research results are conducive to promoting high-quality and efficient combined harvesting of garlic in Lanling County, Shandong Province, China.

Keywords: harvesting machinery; garlic harvester; straw divider; straw lifter; orthogonal regression test

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1. Introduction

China ranks first in the world in terms of garlic production and export volume [1–4]. At present, its garlic industry is in an important stage of transformation from traditional to modern [5,6]. Combined harvesting is important in the modern production of garlic [7–9].

The level of garlic production mechanization is high in Western European countries and Japan [10,11], and research on harvesting technology and equipment is advanced. For example, the Spanish company J.J. BROCH developed the ARCO-4 garlic combine harvester. In addition, the ERME Company in France, the Asa-lift Company in Denmark, the Dewulf Company in Belgium and the Yanmar Company in Japan have also developed garlic combine harvesters [12–15]. Combined harvesting mainly includes the steps of rowing, garlic digging, soil clearing, transportation, straw cutting and collection [16–19]. Combined harvesting is of great significance to reduce production losses, save labor resources and improve product competitiveness [20,21]. The steps of garlic digging, soil clearing, transportation, straw cutting and collection have achieved high levels of mechanization in Western European states and Japan, but the rowing step is still assisted by a simple divider's tooth, a method which requires high responsiveness and technical skill in the operator, and is more suitable for the wide row spacing (>40 cm) planting mode. However, the garlic planted in China has the characteristics of high straw, large planting density, and narrow row spacing (<20 cm) [22,23]. The divider's tooth will lead to a low feeding success rate in China because of the difference in planting mode, and the existing garlic combine harvesters cannot work normally. These are the most important reasons for the low level of garlic combined harvesting in China. Lack of research on the technology and mechanisms of combined harvesting has seriously restricted the improvement of the mechanization level of garlic harvesting in China, which limits the improvement of production efficiency and hinders the development of garlic industry modernization. Lanling County in Shandong Province is the main garlic planting area in China. With the increase in labor costs, garlic combined harvesting is imperative. Straw dividing and lifting are the most critical technologies for improving the success rate of feed for a garlic combined harvester. In this paper, the technology of the depth limit, straw divide and straw lift modes for the rowing step in garlic combined harvesting was studied, and a test prototype was designed for garlic harvesting in Lanling County based on the characteristics of high hardness, good uprightness and narrow row spacing for garlic planting. The test prototype can coordinate the feeding operation steps such as terrain imitation, dividing and lifting. The effects of the working speed, the angle of the divider, the height of the tip of the divider's tooth from the ground, the ratio of the lifter's speed to the working speed and the length of the lifter's tooth on success rate of feed were also studied.

2. Materials and Methods

2.1. Main Structure and Principle

2.1.1. Main Structure

A mechanical structure and parameter diagram of the test prototype of the divider and lifter mechanisms is shown in Figure 1. The test prototype mainly includes the frame, the depth-limiting wheel, the divider and the lifter. The lifter mainly includes the bearing, shaft, tooth and other mechanisms. The test prototype moves forward under the action of external force, the depth-limiting wheel and the divider tooth are in the middle of the garlic line and the lifter is facing the garlic line, and it rotates clockwise under the action of the transmission shaft and the gearbox to realize the holding feed.

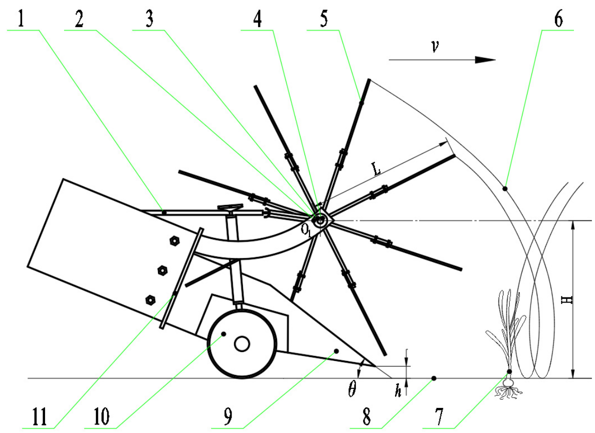

Figure 1. Structure of test prototype of divider and lifter mechanisms. 1. Transmission shaft; 2. gear box; 3. bearing; 4. shaft; 5. lifter's tooth; 6. trajectory curve; 7. garlic; 8. ground; 9. divider's tooth; 10. depth-limiting wheel; 11. frame.

2.1.2. Principle of Divider and Lifter Mechanisms

The trajectory of the endpoint of the lifter's tooth is a cycloid, and its equation can be obtained as:

$$\begin{cases} x = vt + L\cos\omega t \\ y = L\sin\omega t \end{cases} \quad (1)$$

where L is the length of the lifter's tooth, m; v is the working speed of the machine, m·s^{-1}; and ω is the angular velocity, rad·s^{-1}.

Then, the speed ratio of the lifter's speed to the working speed (λ) can be obtained as:

$$\lambda = \frac{\omega L}{v} \quad (2)$$

2.2. Test Conditions and Method

The test was conducted in May 2021 in Lanqiao Village, Lanqiao Town, Lanling County. The garlic was sown by hand. 'Cangshan Wrinkle Garlic' was selected as the test material with row spacing of 180 mm and plant spacing of 70 mm. The height of the garlic plants was between 310 mm and 390 mm. The soil was sandy soil, and soil hardness at a depth of 100 mm was measured by a soil hardness meter (Product Model: SC900, Spectrum Corporation of America) as 222–247 kPa. Soil moisture content was measured by a soil moisture meter (Product Model: TDR300, Spectrum Corporation of America) as 19.9–23.3%.

We conducted single-factor tests, orthogonal tests and regression analysis validation tests sequentially using a self-made test prototype of the divider and lifter mechanisms. The operating distance was 50 m for each single-factor test and orthogonal test. Three 10-m blocks were selected as three districts. The field test of the test prototype of the divider and lifter mechanisms is shown in Figure 2.

Figure 2. Field test of test prototype of divider and lifter mechanisms.

2.3. Test Indicators

The success rate of feed (y) was the test index for the test prototype of the divider and lifter mechanisms, and the specific calculation method can be obtained as:

$$y = \frac{M_d}{M} \times 100\% \quad (3)$$

where M_d and M are the amount of gripped garlic and the total amount of garlic in the test district, respectively.

2.4. Test Design

2.4.1. Single-Factor Test

The single-factor test design is shown in Table 1.

Table 1. Factors and levels for single-factor test.

Levels	Working Speed ($km \cdot h^{-1}$)	Angle of the Divider (°)	Height of the Tip of the Divider's Tooth from the Ground (mm)	Ratio of the Lifter's Speed to the Working Speed	Length of the Lifter's Tooth (mm)
1	0.72	20	50	1.50	300
2	0.9	30	75	1.75	325
3	1.08	40	100	2.00	350
4	1.26	50	125	2.25	375
5	1.44	60	150	2.50	400

2.4.2. Orthogonal Regression Test

According to the significance level of each factor obtained from the single-factor test, the working speed, the angle of the divider and the length of the lifter's tooth were selected as orthogonal test factors to carry out a three-factor, three-level orthogonal regression test. The orthogonal regression test design is shown in Table 2 and is based on Box–Behnken central composite design theory.

Table 2. Factors and levels for orthogonal regression test.

Levels	Working Speed *X*1 ($km \cdot h^{-1}$)	Angle of the Divider *X*2 (°)	Length of the Lifter's Tooth *X*3 (mm)
−1	0.72	20	300
0	1.08	40	350
1	1.44	60	400

3. Results

3.1. Single-Factor Tests

Data processing and statistical analysis of the experimental results were performed using Excel and SPSS software.

3.1.1. Effect of Working Speed on Success Rate of Feed

When the working speed was examined as a single factor, a divider angle of 40°, a height of the tip of the divider's tooth from the ground of 100 mm, a ratio of the lifter's speed to the working speed of 2.0 and a length of the lifter's tooth of 350 mm were selected. Figure 3 shows the variation curve of the success rate of feed with the working speed. The test results showed that the working speed was in a quadratic function relationship with the success rate of feed, and the effect of the working speed on the success rate of feed was significant (p-value < 0.05). The faster the working speed, the greater the vibration, which reduced the success rate of feed.

3.1.2. Effect of Angle of the Divider on Success Rate of Feed

When the angle of the divider was examined as a single factor, a working speed of 1.08 $km \cdot h^{-1}$, a height of the tip of the divider's tooth from the ground of 100 mm, a ratio of the lifter's speed to the working speed of 2.0 and a length of the lifter's tooth of 350 mm were selected. Figure 4 shows the variation curve of the success rate of feed with the angle of the divider. The test results showed that the angle of the divider was in a quadratic function relationship with the success rate of feed, and the effect of the angle of the divider on the success rate of feed was significant (p-value < 0.05). As the angle of the divider increased, the straw became less upright when feeding, which reduced the success rate of feed.

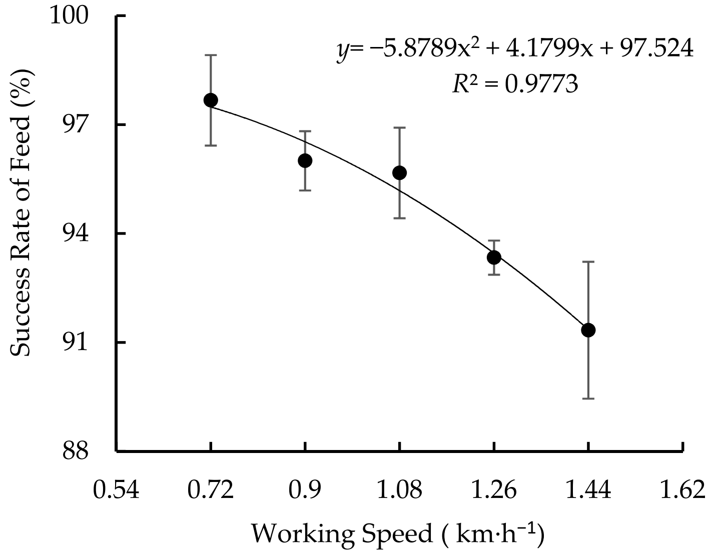

Figure 3. Effect of working speed on success rate of feed. Note: the angle of divider was 40°, the height of the tip of the divider's tooth from the ground was 100 mm, the ratio of the lifter's speed to working speed was 2.0 and the length of the lifter's tooth was 350 mm.

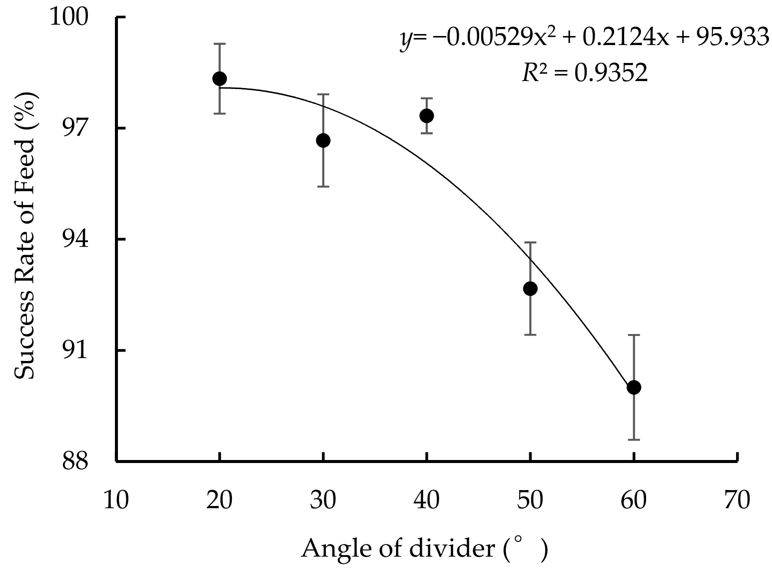

Figure 4. Effect of the angle of the divider on success rate of feed. Note: working speed was 1.08 km·h^{-1}, the height of the tip of the divider's tooth from the ground was 100 mm, the ratio of the lifter's speed to working speed was 2.0 and the length of the lifter's tooth was 350 mm.

3.1.3. Effect of Height of the Tip of the Divider's Tooth from the Ground on Success Rate of Feed

When the height of the tip of the divider's tooth from the ground was examined as a single factor, a working speed of 1.08 km·h^{-1}, an angle of the divider of 40°, a ratio of the lifter's speed to the working speed of 2.0 and a length of the lifter's tooth of 350 mm were selected. Figure 5 shows the variation curve of the success rate of feed with the height of the tip of the divider's tooth from the ground. The test results showed that the effect of the height of the tip of the divider's tooth from the ground on the success rate of feed was not significant (p-value > 0.05). As the straw of the garlic was upright in the period of harvesting and the divider's tooth was arranged between rows, the height of the tip of the divider's tooth from the ground did not affect the success rate of feed.

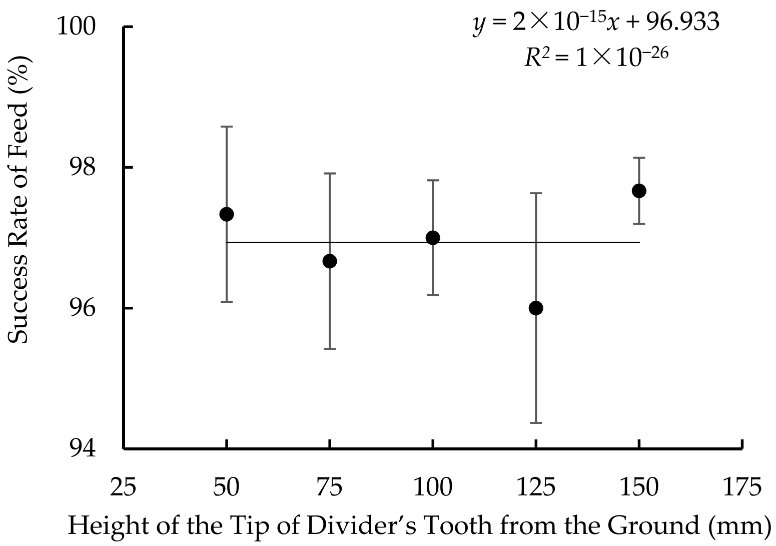

Figure 5. Effect of the height of the tip of the divider's tooth from the ground on success rate of feed. Note: working speed was 1.08 km·h^{-1}, the angle of the divider was 40°, the ratio of the lifter's speed to working speed was 2.0 and the length of the lifter's tooth was 350 mm.

3.1.4. Effect of Ratio of the Lifter's Speed to the Working Speed on Success Rate of Feed

When the ratio of the lifter's speed to the working speed was examined as a single factor, a working speed of 1.08 km·h^{-1}, a divider angle of 40°, a height of the tip of the divider's tooth from the ground of 100 mm and a length of the lifter's tooth of 350 mm were selected. Figure 6 shows the variation curve of the success rate of feed with the ratio of the lifter's speed to the working speed. The test results showed that the effect of the ratio of the lifter's speed to the working speed on the success rate of feed was not significant (p-value > 0.05). When the ratio of the lifter's speed to the working speed exceeded 1, the lifter's tooth sent all straw to the feeding mechanism and therefore the ratio of the lifter's speed to the working speed did not affect the success rate of feed.

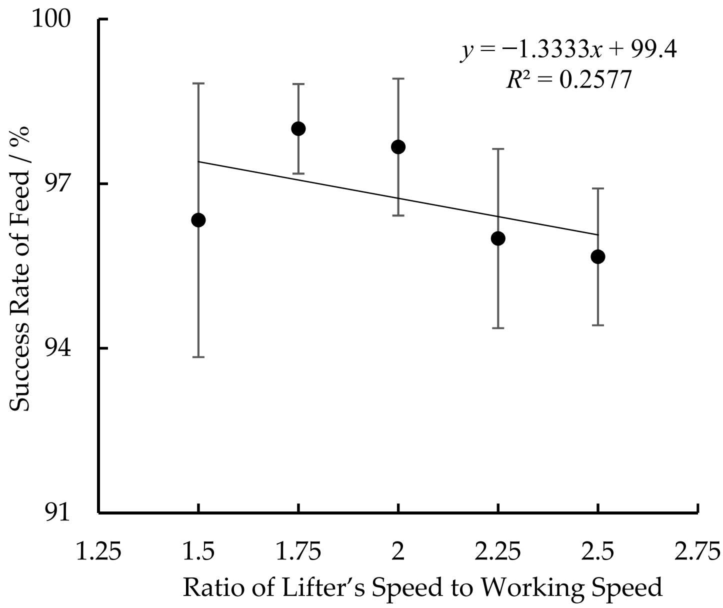

Figure 6. Effect of the ratio of the lifter's speed to the working speed on success rate of feed. Note: working speed was 1.08 km·h^{-1}, the angle of the divider was 40°, the height of the tip of the divider's tooth from the ground was 100 mm and the length of the lifter's tooth was 350 mm.

3.1.5. Effect of Length of the Lifter's Tooth on Success Rate of Feed

When the length of the lifter's tooth was examined as a single factor, a working speed of 1.08 km·h^{-1}, a divider angle of 40°, a height of the tip of the divider's tooth from the ground of 100 mm and a ratio of the lifter's speed to working speed of 2.0 were selected. Figure 7 shows the variation curve of the success rate of feed with the length of the lifter's tooth. The test results showed that the length of the lifter's tooth was in a linear function relationship with the success rate of feed and the effect of the length of the lifter's tooth on the success rate of feed was significant (p-value < 0.05). The longer the length of the lifter's tooth, the better the straw uprightness, which improved the success rate of feed.

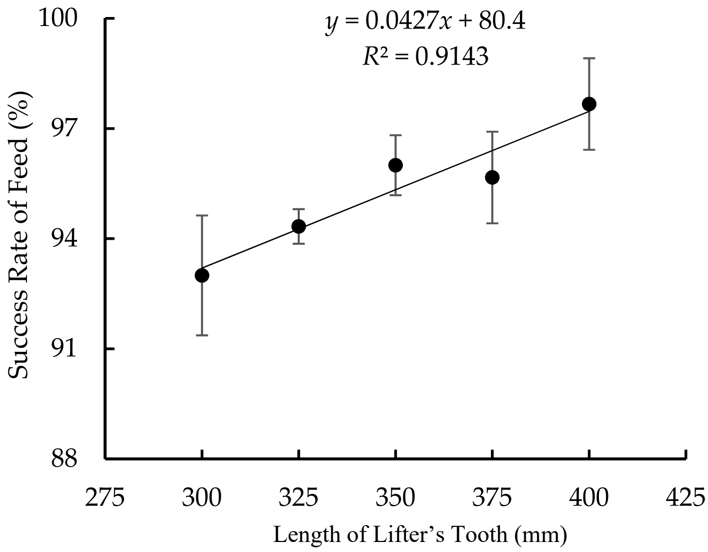

Figure 7. Effect of the length of the lifter's tooth on success rate of feed. Note: working speed was 1.08 km·h^{-1}, the angle of the divider was 40°, the height of the tip of the divider's tooth from the ground was 100 mm and the ratio of the lifter's speed to working speed was 2.0.

3.2. Multifactor Orthogonal Regression Test

The statistical results of the orthogonal regression test are shown in Table 3.

Table 3. Statistical results for orthogonal regression test.

No.	**Working Speed** ***X*1 (km·h^{-1})**	**Angle of the Divider** ***X*2 (°)**	**Length of the Lifter's Tooth** ***X*3 (mm)**	**Success Rate of Feed** ***y* (%)**
1	−1	−1	0	0.97
2	1	−1	0	0.95
3	−1	1	0	0.94
4	1	1	0	0.91
5	−1	0	−1	0.94
6	1	0	−1	0.89
7	−1	0	1	0.93
8	1	0	1	0.88
9	0	−1	−1	0.93
10	0	1	−1	0.84
11	0	−1	1	0.94
12	0	1	1	0.92
13	0	0	0	0.94
14	0	0	0	0.95
15	0	0	0	0.94
16	0	0	0	0.94
17	0	0	0	0.93

The ANOVA of the orthogonal regression test results is shown in Table 4. Results showed that $X3$, $X1X2$, $X1X3$, $X2X3$, $X1X1$ and $X2X2$ had no significant effect on y value, but $X1$, $X2$ and $X3X3$ had a significant effect on y value. The effects of the angle of the divider, the working speed and the length of the divider's tooth on the success rate of feed decreased in significance.

Table 4. The ANOVA of orthogonal regression test results.

Source	Sum of Squares	df	Mean Square	*F*-Value	*p*-Value
Model	0.013187	9	0.00	4.609606	0.0282 (*)
$X1$	0.002813	1	0.00	8.848315	0.0207 (*)
$X2$	0.00405	1	0.00	12.74157	0.0091 (**)
$X3$	0.000613	1	0.00	1.926966	0.2077
$X1$ $X2$	2.5×10^{-5}	1	0.00	0.078652	0.7872
$X1$ $X3$	1.21×10^{-17}	1	0.00	3.82×10^{-14}	1.0000
$X2$ $X3$	0.001225	1	0.00	3.853933	0.0904
$X1$^2	2.63×10^{-5}	1	0.00	0.082791	0.7819
$X2$^2	1.04×10^{-17}	1	0.00	3.27×10^{-14}	1.0000
$X3$^2	0.004447	1	0.00	13.99172	0.0073 (**)
Residual	0.002225	7	0.00		
Lack of Fit	0.002025	3	0.00	13.5	0.0147 (*)
Pure Error	0.0002	4	0.00		
Cor Total	0.015412	16			

Note: ** indicates very significant; * indicates significant.

According to multiple regression fitting analysis, the regression equation of success rate of feed y showed that:

$$y = 0.94 - 0.019X_1 - 0.023X_2 + 0.009X_3 - 0.003X_1X_2 + 0.018X_2X_3 + 0.003X_1^2 - 0.033X_3^2 \quad (4)$$

The integrated optimization function in Design-Expert software was used for optimization, and the optimal parameter combination for the success rate of feed y was obtained: the working speed was 0.72 km·h^{-1}, the angle of the divider was 20°, and the length of the divider's tooth was 343.5 mm, the value of y predicted by the model was 98.18%. Under the same level of factors, the test was carried out three times. The average success rate of feed was 97.67%. The difference between the test results and the model results was not obvious, which proved that the feeding success rate regression model was reliable.

4. Discussion

In this study, we found that straw uprightness was a key factor in feeding success. The higher the straw uprightness, the higher the feeding success rate. The three factors of the angle of the divider, the height of the tip of the divider's tooth from the ground and the length of the lifter's tooth all had an impact on the uprightness. Among them, an increase in the factor level of the angle of the divider produced a greater component force in forward direction when the prototype collided with the straw, and led to a decrease in the uprightness, thus reducing the success rate of feed. An increase in the factor level of the length of the lifter's tooth was conductive to righting the straw and led to an increase in the uprightness, thus increasing the success rate of feed. An increase in the factor level of the height of the tip of the divider's tooth from the ground had little effect on the uprightness, so a change in the success rate was not obvious. This showed the good adaptability of the machine to the height of the tip of the divider's tooth from the ground. In addition, due to the uneven ground in the field, an increase in the working speed caused the machine to vibrate, which reduced the success rate of feed. As for the factor of the ratio of the lifter's speed to the working speed, the prototype was designed with eight groups of lifter's teeth, and when the ratio exceeded 1 the lifter's teeth sent all straw to the feeding mechanism, so the ratio of the lifter's speed to the working speed did not affect the success rate of feed.

We also found that due to the narrow row spacing (18 cm), the effect of the angle of the divider angle on the straw uprightness was more obvious than that of the working speed on the machine vibration. On the other hand, the effect of the working speed on the machine vibration was more obvious than the length of the divider's tooth, which was mainly due to the unevenness of the field ground.

Based on the characteristics of garlic in the Lanling area, this paper has carried out research on the technology of dividing and lifting. An index of dividing and lifting was established, and four key factors affecting the index were studied. The results will also provide technical support for mechanized garlic harvesting under the mode of density planting and narrow row spacing, which will be conducive to improving the mechanization level of garlic harvesting in China and promoting the transformation and upgrading of the garlic industry.

5. Conclusions

The results showed that the working speed, the angle of the divider and the length of the lifter's tooth had significant influence on the success rate of feed ($p < 0.05$), but the experimental factors of the height of the tip of the divider's tooth from the ground and the ratio of the lifter's speed to the working speed did not have a significant influence on the success rate of feed ($p > 0.05$).

In this paper, a regression model of the success rate of feed of the prototype was established. When the working speed was 0.72 km·h^{-1}, the length of the lifter's tooth was 343.5 mm and the angle of the divider was 20°, the success rate of feed was the highest, which was 98.18%, and the measured value was 97.67%. The difference between the test results and the model results was not obvious, so the regression model was reliable.

There are many garlic varieties in China and many planting modes. Research on the technology of dividing and lifting is not complete, and further research needs to be conducted on more main planting areas to improve the results.

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