Towards Optimizing Garlic Combine Harvester Design with Logistic Regression

Zhengbo Zhu 1, Wei Li 2,*, Fujun Wen 3, Liangzhe Chen 2 and Yan Xu 4,*

Abstract: In this paper, a garlic combine harvester machine was designed and some influential parameters of the machine were optimized. The working parts of the machine mainly consisted of a reel, a reciprocating cutter, a seedling conveyor, a profiling depth-stop device, a digging shovel and a lifting chain. Each part had unique structural parameters and motion parameters, as different parameters would deeply affect the performance of the machine. A logistical regression algorithm was utilized to analyze the working speed of the reel, the digging depth of the reciprocating cutter and the lifting speed of the lifting chain. This paper also discussed the influence of these three functions on the damage rate based on the collected data when harvesting garlic. Specifically, each function was tested 60 times for collecting data. The experimental results showed that the order of influence of the three functions on the damage rate was the digging depth, working speed and lifting speed. Moreover, the lowest damage rate was 0.18% when the digging depth was 100 mm, the working speed was 1.05 km h⁻¹ and the lifting speed was 0.69 m s⁻¹. A validation test was taken out based on the three functions of the analysis results, and the damage rate was 0.83%, which was close to the analysis results, and proved that the analysis results were accurate and meaningful. The research results are beneficial to the development and application of the garlic combine harvester.

Keywords: crops; data analysis; garlic; harvester; parameter optimization

1. Introduction

Garlic has high edible and commercial values, and it is planted in more than 160 countries [1–4]. Nowadays, high-yielding garlic heavily depends on a dense planting mode in China, which could significantly improve the yield and oligarchical status in the international market [5–7]. However, this kind of garlic production requires a lot of human labor. With the sharp reduction in rural manpower and the aging of farmers, the labor cost during harvest is increasing year by year. At present, it has reached up to USD4000 to USD5000/ha., accounting for more than 40% of the production costs. Research shows that reasonable close planting can effectively improve the unit yield of garlic [8–10]. However, a high-density planting pattern makes the harvest loss rate and damage rate high, which is the main reason for the low mechanization rate of the garlic harvest in China [11]. In Europe, countries such as Spain and France, garlic harvesters include completed types, advanced technology, a high reliability and good application effect. Yet, they are not suitable for the close planting mode used in China [12–21]. The mechanization level of garlic production in China is low, especially for the mechanization level of the harvesting link,
which is less than 3%. The existing harvesters are mainly mining and laying ones, and the application of combine harvesters is very difficult [22–30]. The garlic industry in China is an advantageous industry with strong international competitiveness. It plays a significant role in promoting Chinese economic growth and helps farmers become rich. It is necessary to overcome the problem of mechanized harvesting under a dense planting production mode. According to the requirements of a garlic mechanical harvesting operation, our research team optimized the technical route by carrying out key technological research and developing a 4DS-1200-type cutting and digging combined garlic harvester. In this paper, a garlic combine harvester machine was designed. The structure, working principle and key components of the harvester were introduced. We studied the operating parameters of the working speed of the reel, the digging depth of the reciprocating cutter and the lifting speed of the lifting chain, and identified these as the main influencing factors of our hypothesis. We then carried out the parameter optimization test.


2.1. System Structure

The structure schematic diagram of the 4DS-1200 cutting and digging combined garlic combine harvester is shown in Figure 1, which mainly includes a dial wheel, reciprocating cutter, garlic seedling conveyor, profiling depth-limiting device, digging shovel, lifting chain, box and other working parts.

![Figure 1. Structure diagram of garlic combine harvester of cut–dig type under 4DS-1200 model. Note: 1. lateral conveying device; 2. driving shed; 3. manipulation system; 4. lateral conveying device; 5. chain transmission mechanism; 6. profile depth limitation device; 7. position adjustment device; 8. dial wheel; 9. reciprocating cutter; 10. swing rod; 11. transverse conveying device of garlic seedling; 12. mining shovel; 13. lifting chain; 14. hydraulic cylinder; 15. driving wheel; 16. hydrostatic driving system; 17. transmission; 18. power system; 19. vehicle bridge; 20. stock bin.](image)

2.2. Working Principle and Main Technical Parameters

The working principle block diagram of the harvester is shown in Figure 2. By controlling the hydraulic cylinder, the harvest header can be lowered, the excavation depth is adjusted by the depth-limiting wheel and the position of the dial wheel is adjusted by the position adjustment device of the dial wheel. During the rotation of the dial wheel, the whole plant of garlic is lifted up and dialed to the reciprocating cutter. The cut garlic seedlings fall into the lateral transport device and are transported to the side of the machine. Then, the garlic is excavated and shoveled from the soil. Garlic is dug out and gradually moved through the lifting chain. The horizontal transport device and lateral transport device is used to complete the soil cleaning and flexible transport steps. After the garlic
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Dial wheel device is mainly composed of a wheel shaft, bearing, spoke plate, dial rod and an installation height adjustment mechanism. The overall structure is shown in Figure 3. During the harvesting operation, the stalk is rotated around the wheel shaft, and the whole garlic in front is transferred backward to complete the feeding operation.

![Figure 3. Structure diagram of dial wheel device. Note: 1. rod; 2. shaft; 3. plate; 4. bearing; 5. installation of height adjusting mechanism.](image)

The schematic diagram of the operation parameters of the dial wheel device is shown in Figure 4. Taking the projection of the center of the dial wheel on the ground as the origin, the forward direction of the harvester is in an X-axis-positive direction, and the upward direction through the center is in a Y-axis-positive direction. In order to reduce the impact

### Table 1. Major technical parameters of garlic combine harvester of cut–dig type under 4DS-1200 model.

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Wheeled self-propelled</td>
<td></td>
</tr>
<tr>
<td>Rated power</td>
<td>47.5</td>
<td>kW</td>
</tr>
<tr>
<td>Size</td>
<td>5600 × 1500 × 2800</td>
<td>mm</td>
</tr>
<tr>
<td>Weight</td>
<td>3060</td>
<td>kg</td>
</tr>
<tr>
<td>Working width</td>
<td>1200</td>
<td>mm</td>
</tr>
<tr>
<td>Digging depth</td>
<td>0 to 100</td>
<td>mm</td>
</tr>
<tr>
<td>Working speed I</td>
<td>0 to 1.05</td>
<td>km·h⁻¹</td>
</tr>
<tr>
<td>Working speed II</td>
<td>0 to 2.71</td>
<td>km·h⁻¹</td>
</tr>
</tbody>
</table>

### 3. Design and Analysis of Key Components

#### 3.1. Dial Wheel Device

The main technical parameters of the harvester are shown in Table 1.
of the dial rod on the garlic seedling, the horizontal velocity of the dial rod is zero when it falls vertically toward the garlic seedling.

Figure 4. Diagram of operating parameters of the dial reel.

Hence, we had:

\[ v_x = R \omega \sin \omega t_1 + v_\alpha = 0 \]  

(1)

where \( v_x \) is the dividing speed in the horizontal direction of the dial rod, \( m \cdot s^{-1} \). \( R \) is the radius of the dial wheel, \( m \). \( \omega \) is the angular velocity, \( rad \cdot s^{-1} \). \( v_\alpha \) is the working speed of the harvester, \( m \cdot s^{-1} \). \( t_1 \) is the time when the straw went into the grass, \( s \).

When the dial wheel works, the lowest position \( B \) point of the dial rod should be pressed above the center of gravity of the garlic seedling to avoid cutting apart the garlic seedling while being picked up. The center of gravity of the garlic seedling was determined to be below the middle of the cutting part of the garlic seedling, so the lowest point of the straw stalk was set to be at 1/2 of the cutting part of the garlic seedling.

Then, we had:

\[ R = O_2B = R \sin \omega t_1 + \frac{1}{2} (L - h) \]  

(2)

\[ \lambda = \frac{v_b}{v_\alpha} = \frac{\omega R}{v_\alpha} \]  

(3)

where \( L \) is the average height of the garlic seedling, \( mm \). \( h \) is the vertical distance between the moving knife of the reciprocating cutter and the ground, namely, the cutting height, \( mm \). \( \lambda \) is the speed ratio. \( v_b \) is the linear velocity in the circumferential direction of the dial rod, \( m \cdot s^{-1} \).

According to the debugging effect of the prototype field experiment, the measured \( \lambda \) value was selected as 2.1, the average height \( L \) of the garlic seedlings in the measured harvest period was 450 mm and the cutting height \( h \) was 50–100 mm. The values were substituted into Formulas (1)–(3), the range of \( R \) was 229.7–262.5 mm and the selected \( R \) value was 250 mm.

Additionally:

\[ H = L + R \sin \omega t_1 - h \]  

(4)
where \( H \) is the vertical distance between the wheel axis and the reciprocating cutter in mm. The range of \( H \) value was 564.3–614.3 mm, and the \( H \) value was 600 mm.

Additionally:

\[
n_1 = \frac{60v_a \lambda}{2\pi R}
\]

(5)

where \( n_1 \) is the rotation speed of the dial wheel, r·min\(^{-1}\). We set \( v_a = 0.29 \) to \( 0.53 \) m·s\(^{-1}\) and substituted it into Formula (5); thus, we had \( n_1 = 23.3 \) to \( 42.5 \) r·min\(^{-1}\).

3.2. Reciprocating Cutter

The schematic diagram of the reciprocating cutter working principle is shown in Figure 5, which is mainly composed of a spindle, swing ring, swing fork, swing fork shaft, swing arm and guide rod. The angle between the pin axis and the vertical line is called the swing ring angle \( \alpha \), and the swing range of the swing ring is \( 2\alpha \).

![Figure 5. Principle diagram of reciprocating cutter. Note: 1. spindle; 2. swing fork; 3. swing ring; 4. swing fork shaft; 5. swing arm; 6. guide rod; 7. cutter.](image)

The parameter relationships among the tool path \( s \), swing angle \( \alpha \) and swing arm length \( l \) were as follows:

\[
l = \frac{s}{2\sin \alpha}
\]

(6)

where \( l \) is the swing arm length, mm. \( s \) is the moving knife stroke, mm. \( \alpha \) is the swing angle, \(^{\circ}\).

The moving knife stroke was \( s = 76.2 \) mm, and the swing angle was \( \alpha = 15^{\circ} \). We substituted them into Formula (6) to obtain the swing arm length \( l \approx 147 \) mm. Considering factors such as deviations, the design value was 150 mm.
Additionally:

\[ v_p = \beta v_a = \frac{n_2 s}{30} \]  

where \( v_p \) is the average speed of the moving knife, m\( \cdot \)s\(^{-1}\). \( \beta \) is the cutter speed ratio and its value is usually set to 1.9. \( n_2 \) is the swing mechanism speed, r\( \cdot \)min\(^{-1}\).

With this, we obtained \( v_a = 0.29 \) to 0.53 m\( \cdot \)s\(^{-1}\). Then, \( v_p = 0.55 \) to 1.01 m\( \cdot \)s\(^{-1}\) and \( n_2 = 216.9 \) to 396.5 r\( \cdot \)min\(^{-1}\).

3.3. Elevating Chain

Considering the position of the center of gravity of the harvester and to achieve a better separation-and-lifting effect of the garlic and soil, the angle of the lifting chain was set to \( \Phi = 40^\circ \). In order to prevent the congestion and mechanical damage of the garlic caused by the rolling of the garlic and soil mixture in the process of soil cleaning and lifting, the traditional straight rod chain was configured into a ‘one straight three bend’ groove structure, as shown in Figure 6.

![Figure 6](image-url)

Figure 6. Structure diagram of groove-type rod under ‘one straight and three bent’ model. Note: 1. straight rod; 2. bending rod; 3. tooth rubber belt.

Additionally:

\[ n_e = \frac{60v_e}{2\pi R_1} \]  

where \( R_1 \) is the dividing circle radius of the driving wheel of the toothed rubber belt, m. \( n_e \) is the rotational speed of the toothed rubber belt drive wheel, r\( \cdot \)min\(^{-1}\). \( v_e \) is the lifting speed, m\( \cdot \)s\(^{-1}\).

By setting \( v_e = 0.69 \) to 0.93 m\( \cdot \)s\(^{-1}\) and \( R_1 = 97 \) mm, we obtained \( n_e = 68.0 \) to 91.6 r\( \cdot \)min\(^{-1}\).

4. Field Test

4.1. Test Materials

The experimental material was ‘Jinxiang Purple Garlic’ with uniform growth in the field. The row spacing was 18 cm and the plant spacing was 12 cm. The test site was flat with sandy soil as the soil type, a water content of 19.6 to 21.3%, soil hardness of 228 to 248 kPa at a 10 cm depth and soil bulk density of 1.38 to 1.42 g\( \cdot \)cm\(^{-3}\).
4.2. Instrument Device

We used a cutting and digging combined garlic combine harvester (4DS-1200, self-made), measuring tape (N2020, measuring range 50 m, Tianjin Xiongshi Tools Co., Ltd., Tianjin, China), stopwatch (CASIO HS-70 W, Casio Electronics (Shenzhen) Co., Ltd., Shenzhen, China), tachometer (Delixi, DLY-2301, Delixi Group Co., Ltd., Shanghai, China), soil moisture meter (TDR300, Spectrum Technologies, Inc., Washington DC, USA), soil firmness meter (SC900, Spectrum Technologies, Inc., Washington DC, USA), ring knife soil-fetching device (custom, Shaoxing Yina Instrument Manufacturing Co., Ltd., Shaoxing, China) and electric heating drum dryer (101-3 AB, Tianjin Test Instruments Co., Ltd., Tianjin, China).

4.3. Test Method

The field experiment site was located in the Xinzhuang experimental field of Kangqiao Village, Wangpi Town, Jinxiang County. The researchers carried out the prototype reliability test and parameter calibration in the experimental field in May 2019. The single-factor test was carried out on 16 and 17 May 2020, the orthogonal test was carried out on 19 May and the regression analysis results of the orthogonal test were verified on 21 May. The single test operation stroke for the single-factor test and the orthogonal test was approximately 20 m. The middle 15 m was divided into three districts, and the length of each district was approximately 5 m, respectively. The test index data of each district were collected separately. The statistical analysis software was mainly Excel and SPSS software (18.0.1, International Business Machines Corporation, Armonk, NY, USA). The field experiment is shown in Figure 7.

![Figure 7. Photo of field test.](image)

4.4. Test Indicators

The main test indexes of the garlic combine harvester included the loss rate, clear garlic rate, garlic damage rate and impurity rate. While the loss rate of the cut-and-cut garlic combine harvester was extremely low, the clear garlic rate was extremely high and the impurity rate was greatly affected by the soil environment and was not controllable. Therefore, the test index was the garlic damage rate, and the selected calculation formula was:

\[
P = \frac{M_d}{M} \times 100\%
\]

where \(P\) is the garlic damage rate, %. \(M_d\) is the number of garlic pieces damaged in the harvest plot. \(M\) is the total number of garlic pieces in the harvest area.
4.5. Test Design

4.5.1. Single-Factor Test Design

The single-factor test design is shown in Table 2.

Table 2. Factors and levels of single-factor test.

<table>
<thead>
<tr>
<th>Levels</th>
<th>Working Speed/ (km·h⁻¹)</th>
<th>Digging Depth/ (mm)</th>
<th>Lifting Speed/ (m·s⁻¹)</th>
<th>Cutting Height/ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.05</td>
<td>80</td>
<td>0.57</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>1.27</td>
<td>85</td>
<td>0.69</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>1.48</td>
<td>90</td>
<td>0.81</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>1.70</td>
<td>95</td>
<td>0.93</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>1.91</td>
<td>100</td>
<td>1.05</td>
<td>90</td>
</tr>
</tbody>
</table>

4.5.2. Orthogonal Experimental Design

On the basis of a single-factor experiment, the factor level of an orthogonal experiment was selected, and three levels of mining depth, operating speed and lifting speed were selected for the orthogonal experiment, choosing L⁹(3⁴) as the orthogonal table. The orthogonal experiment design is shown in Table 3.

Table 3. Factors and levels of orthogonal experiment.

<table>
<thead>
<tr>
<th>Levels</th>
<th>Working Speed/ (km·h⁻¹)</th>
<th>Digging Depth/ (mm)</th>
<th>Lifting Speed/ (m·s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.05</td>
<td>80</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>1.48</td>
<td>90</td>
<td>0.81</td>
</tr>
<tr>
<td>3</td>
<td>1.91</td>
<td>100</td>
<td>0.93</td>
</tr>
</tbody>
</table>

5. Results and Analysis

5.1. Single-Factor Test

5.1.1. Effect of Operating Speed on Garlic Damage Rate

When the digging depth was 90 mm, the lifting speed was 0.81 m·s⁻¹ and the cutting height was 70 mm, the garlic damage rate–operating speed curve is shown in Figure 8. The experimental data showed that the working speed and damage rate had a power–function relationship. The data also showed that a reduced working speed had a significant effect on the garlic damage rate (p < 0.05).

![Figure 8](image_url)

**Figure 8.** Effect of equivalent friction on damage rate on working speed. Note: digging depth was 90 mm, lifting speed was 0.81 m·s⁻¹ and cutting height was 70 mm.
5.1.2. Effect of Excavation Depth on Garlic Damage Rate

When the operating speed was 1.48 km·h$^{-1}$, the lifting speed was 0.81 m·s$^{-1}$ and the cutting height was 70 mm; the relationship curve between the garlic damage rate and the digging depth is shown in Figure 9. The experimental data showed that the digging depth and damage rate had a power–function relationship. The data also showed that an increase in the digging depth had a significant effect on the garlic damage rate ($p < 0.05$).

![Figure 9](image)

**Figure 9.** Effect of equivalent friction on damage rate on digging depth. Note: working speed was 1.48 km·h$^{-1}$, lifting speed was 0.81 m·s$^{-1}$ and cutting height was 70 mm.

5.1.3. Effect of Lifting Speed on Garlic Damage Rate

When the operating speed was 1.48 km·h$^{-1}$, the digging depth was 90 mm and the cutting seedling height was 70 mm; the curve of the garlic damage rate and lifting speed is shown in Figure 10. The experimental data showed that the lifting speed and damage rate had a power–function relationship. The data also showed that a reduced lifting speed had a significant effect on the garlic damage rate ($p < 0.05$).

![Figure 10](image)

**Figure 10.** Effect of equivalent friction on damage rate on lifting speed. Note: working speed was 1.48 km·h$^{-1}$, digging depth was 90 mm, and cutting height was 70 mm.
5.1.4. Effect of Cutting Height on Garlic Damage Rate

When the operation speed was 1.48 km·h⁻¹, the lifting speed was 0.81 m·s⁻¹, and the excavation depth was 90 mm; the relationship curve between garlic damage rate and cutting height is shown in Figure 11. The experimental data showed that the cutting height had no significant effect on the garlic damage rate (p > 0.05).

![Figure 11](image)

Figure 11. Effect of equivalent friction on damage rate on cutting height. Note: working speed was 1.48 km·h⁻¹, digging depth was 90 mm and lifting speed was 0.81 m·s⁻¹.

5.2. Multifactor Orthogonal Test

According to the results of a single-factor test and field harvest operation, three factors that had a significant impact on the test index were selected to carry out a three-level orthogonal test, which was carried out on three plots, and a range analysis was carried out for the orthogonal experiment results.

The influence of each factor on the index can be judged by testing the range of each level of a factor. The three plots of each experiment were used to calculate the garlic damage rate. The statistical results are shown in Table 4.

<table>
<thead>
<tr>
<th>No.</th>
<th>A Working Speed/(km·h⁻¹)</th>
<th>B Digging Depth/(mm)</th>
<th>C Lifting Speed/(m·s⁻¹)</th>
<th>Damage Rate/(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.05</td>
<td>80</td>
<td>0.69</td>
<td>2.16</td>
</tr>
<tr>
<td>2</td>
<td>1.05</td>
<td>90</td>
<td>0.81</td>
<td>2.16</td>
</tr>
<tr>
<td>3</td>
<td>1.05</td>
<td>100</td>
<td>0.93</td>
<td>2.08</td>
</tr>
<tr>
<td>4</td>
<td>1.48</td>
<td>80</td>
<td>0.81</td>
<td>8.16</td>
</tr>
<tr>
<td>5</td>
<td>1.48</td>
<td>90</td>
<td>0.93</td>
<td>3.83</td>
</tr>
<tr>
<td>6</td>
<td>1.48</td>
<td>100</td>
<td>0.69</td>
<td>1.30</td>
</tr>
<tr>
<td>7</td>
<td>1.91</td>
<td>80</td>
<td>0.93</td>
<td>8.62</td>
</tr>
<tr>
<td>8</td>
<td>1.91</td>
<td>90</td>
<td>0.69</td>
<td>2.11</td>
</tr>
<tr>
<td>9</td>
<td>1.91</td>
<td>100</td>
<td>0.81</td>
<td>1.30</td>
</tr>
<tr>
<td>$K_1$</td>
<td>8.04</td>
<td>17.69</td>
<td>9.49</td>
<td></td>
</tr>
<tr>
<td>$K_2$</td>
<td>12.85</td>
<td>11.03</td>
<td>11.01</td>
<td></td>
</tr>
<tr>
<td>$K_3$</td>
<td>14.10</td>
<td>6.27</td>
<td>14.49</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>6.06</td>
<td>11.42</td>
<td>5.00</td>
<td></td>
</tr>
</tbody>
</table>

\[ y = 3.5334x^{-0.047} \]
\[ R^2 = 0.0049 \]
According to the analysis of the $K$ value, the change of excavation depth on the level had the largest fluctuation on the garlic damage rate, followed by the working speed and the lifting speed, respectively.

According to the analysis of the $R$ value, the order of the influence degree of the three factors on the garlic damage rate was as follows: excavation depth, operation speed and lifting speed. In other words, the excavation depth had the greatest influence on the garlic damage rate, and the lifting speed had the smallest influence on the garlic damage rate.

The variance analysis of the orthogonal test is shown in Table 5. The variance analysis results show that each factor was observed to have a significant influence on the garlic damage rate. The operation speed and the excavation depth had extremely significant effects on the garlic damage rate ($p < 0.01$), and the lifting speed had significant effects on the garlic damage rate ($p < 0.05$).

Table 5. Variance analysis of orthogonal test.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>d f</th>
<th>Mean Square</th>
<th>Damage Rate(%)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working speed/(km·h$^{-1}$)</td>
<td>20.442</td>
<td>2</td>
<td>10.221</td>
<td>6.204</td>
<td>**</td>
</tr>
<tr>
<td>Digging depth/(mm)</td>
<td>65.810</td>
<td>2</td>
<td>32.905</td>
<td>19.972</td>
<td>**</td>
</tr>
<tr>
<td>Lifting speed/(m·s$^{-1}$)</td>
<td>13.174</td>
<td>2</td>
<td>6.587</td>
<td>3.998</td>
<td>*</td>
</tr>
<tr>
<td>Error</td>
<td>32.951</td>
<td>20</td>
<td>1.648</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>540.710</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: ** shows significant correlation at 0.01 levels, and * shows significant correlation at 0.05 levels.

The regression analysis of the orthogonal test results showed that:

$$P = 11.912 + 2.348A - 0.190B + 6.954C \quad (10)$$

In the formula, $P$ is the garlic damage rate, %. $A$ is the operating speed, km·h$^{-1}$, the value range is $A = 1.05, 1.48, 1.91$. $B$ is the excavation depth, mm, and the range is $B = 80, 90, 100$. $C$ is the lifting speed, m·s$^{-1}$, and the value range is $C = 0.69, 0.81, 0.93$.

According to Formula (10), when the excavation depth was 100 mm, the lifting speed was 0.69 m·s$^{-3}$ and the operating speed was 1.05 km·h$^{-1}$; the garlic damage rate reached the minimum, which was 0.18%. However, that stage of parameters does not appear in the orthogonal test table; therefore, additional sets of experiments are required.

The linear regression analysis of the orthogonal test results is shown in Table 6. Supplementing a group of experiments, we found that the level of each factor was $A_1B_3C_1$, while the measured garlic damage rate was 0.83%. The difference between the results of the linear regression analysis and orthogonal test was small, so the lowest garlic damage rate was the combination of the orthogonal test results.

Table 6. Analysis on regression coefficient.

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>95.0% Confidence Interval for Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beta</td>
<td>Std. Error</td>
<td></td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>Constant</td>
<td>11.912</td>
<td>3.492</td>
<td></td>
<td>3.412</td>
<td>4.689</td>
</tr>
<tr>
<td>Working speed/(km·h$^{-1}$)</td>
<td>2.348</td>
<td>0.689</td>
<td>0.372</td>
<td>3.409</td>
<td>0.923</td>
</tr>
<tr>
<td>Digging depth/(mm)</td>
<td>-0.190</td>
<td>0.030</td>
<td>-0.702</td>
<td>-6.428</td>
<td>-0.252</td>
</tr>
<tr>
<td>Lifting speed/(m·s$^{-1}$)</td>
<td>6.954</td>
<td>2.467</td>
<td>0.308</td>
<td>2.818</td>
<td>1.850</td>
</tr>
</tbody>
</table>
6. Conclusions and Discussion

6.1. Data Analysis

(1) In this study, a theoretical analysis showed that when the operating speed was 0.55 to 1.01 m·s\(^{-1}\), the speed range of the reel was 23.3 to 42.5 r·min\(^{-1}\), the rotating speed range of the reciprocating cutter was 216.9 to 396.5 r·min\(^{-1}\) and the speed range of the lifting chain was 68.0 to 91.6 r·min\(^{-1}\). During the actual operation, the excavation depth was generally 80 to 100 mm.

(2) The linear regression analysis of the orthogonal test results showed that when the operation speed was 1.05 km·h\(^{-1}\), the excavation depth was 100 mm and the lifting speed was 0.93 m·s\(^{-1}\), the garlic damage rate was the smallest, which was 0.18%, and the measured garlic damage rate was 0.83%.

(3) In the single-factor test, the working speed, digging depth, lifting speed and cutting height were set as factors, and each factor had five levels. The results of the single-factor test showed that a reduction in the working speed, digging depth and lifting speed had a significant effect on the garlic damage rate, but a reduction in the cutting height had no significant effect on the garlic damage rate. In this section, we used Excel for the data analysis software.

(4) In the orthogonal experiment, factors and levels were selected based on a single-factor test, and we chose L9(3\(^{4}\)) as the orthogonal table. According to the analysis of the R value, the order of the influence degree of the three factors on the garlic damage rate was as follows: excavation depth, operation speed and lifting speed. In other words, the excavation depth had the greatest influence on the garlic damage rate, and the lifting speed had the smallest influence on the garlic damage rate. In this section, we used the SPSS data analysis software.

6.2. Discussion

(1) Garlic is a bulb crop with a shallow planting depth, and its maturity, diameter, weight, moisture content and other parameters vary greatly, which was the main reason for the test error. We further focused on the research of soil cleaning technology to effectively reduce the harvest impurity content rate.

(2) Compared with scientific reports of the “Design and test of double-row walking garlic combine harvester” [31], the authors studied a garlic combine harvest tool. Their optimal combination of parameters was achieved as follows: a working speed of 0.51 m·s\(^{-1}\), digging depth of 97.2 mm and clamping distance of 7.6 mm, corresponding to the damage and loss rates of 0.63% and 1.25%, respectively. In this paper, we reduced the working speed to 1.05 km·h\(^{-1}\) (0.29 m·s\(^{-1}\)) and achieved a lower damage rate of 0.18% from our model, which is more meaningful for the research and optimization of the garlic combine harvester.

(3) Compared with scientific reports of the “Design and Experiment of Modularized Garlic Combiner Harvester” [32], the authors studied a modularized garlic combine harvester. The machine mainly consisted of a stem lifter, an arrow-shaped ripper, belt holding conveyor, stem aligning and cutting device and collector. The damage rate was 1.8%. In this study, our model achieved a lower damage rate of 0.18%, which is of great significance for the research and optimization of the garlic combine harvester.

6.3. Conclusions

(1) This study carried out research on the 4DS-1200 garlic combine harvester under the garlic dense planting production mode in China, mainly including the design of functional components such as a reel, reciprocating cutter, garlic seedling conveyor, profiling depth-limiting device, digging shovel, lifting chain and box (which could complete the whole plant feeding), seedling cutting, garlic seedling conveying, garlic digging, soil cleaning and lifting at one time and operating steps such as loading and unloading.
(2) The results of the single-factor test showed that the operation speed, excavation depth and lifting speed had a significant effect on the damage rate ($p < 0.05$), and the cutting height had no significant effect on the damage rate ($p > 0.05$). The results of the orthogonal test showed that the excavation depth and operation speed had an extremely significant influence on the index ($p < 0.01$), and the lifting speed had a significant influence on the index as well ($p < 0.05$).

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**References**


