Article

Parameter Optimization and Testing of a Self-Propelled Combine Cabbage Harvester

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Abstract: On account of a lack of suitable and specialized harvesting equipment for cabbage species and planting modes in China, in this study, a type of 4GCSD-1200 type cabbage harvester was designed to further optimize the working performance of the cabbage harvester. First, the structure and working principles of the harvester were introduced, and the cabbage harvesting process was analyzed. Based on the test method and theoretical analysis, a single-factor test was carried out on the main working parameters of the sample machine, the advancing speed, rotating speed of the pulling roller, rotating speed of the conveyor belt, and the cutter-head were taken as independent variables, and the qualifying rate of cabbage harvesting was taken as the response value. According to the Box–Behnken test design principles, a four-factor three-level response surface analysis was adopted to establish a mathematical model between all test factors and the qualifying rate of cabbage harvesting, then all test factors and their interaction effects were analyzed. The test results showed that the optimal working parameters of the harvester were: the advancing speed was 1.1 km/h, the rotating speed of the pulling roller was 90 r/min, the rotating speed of the conveyor belt was 205 r/min, and the rotating speed of the cutter-head was 395 r/min. The verification test results showed that the qualifying rate of cabbage harvesting was 96.3%, showing a good harvesting effect, with uniformly cut notches and a low damage rate. The test indicates that by optimizing the working parameters, the damage during the mechanized harvesting of cabbage can be reduced and the qualifying rate of harvesting can be improved; the working effect could, therefore, satisfy the requirements of market harvesting.

Keywords: cabbage; harvester; parameter optimization; field test keyword

1. Introduction

Cabbage is one of the most important cultivated vegetables in China. It is planted all around China and covers a huge cultivation area [1]. Thanks to the long-term, intensive, and large-scale planting modes in European and American countries with advanced agricultural systems, extensive research has been conducted on the working performance of cabbage harvesters in the 20th century [2,3]. The CKM-1 [4] and NKH-1 [5] single-row cabbage harvester, designed in the Soviet Union, adopts a chain-type clamping and conveying method; however, this showed low harvesting efficiency and a very high damage rate. The cabbage harvester designed by Hansen [6] in the USA adopts the conveying method of the double spiral in contrarotation. The double spiral-conveying device has a simple structure and stable conveying performance; however, the screw thread in the front of the device damages the cabbage during operation. Compared with the spiral conveyance structure, the clamping and conveying mechanism can realize the flexible conveying of cabbages while changing the material of the conveyor belt and the tensioning mechanism, thus reducing the damage rate. Lenker et al. [7] and Wadsworth et al. [8] designed cabbage

harvesters, both using a pair of rubber conveyor belts in counter-rotation to clamp and convey the cabbages. Bleinroth et al. [9] designed a type of coping delivery device, based on a conveyor belt, which can keep the cabbage plants in an erect and compressed state while being conveyed and can improve the accuracy of root cutting. The mature machine models in foreign countries are large-scale operation devices, working in big fields and with a complicated structure, which is suitable for the flat planting of cabbages with large row spacing; thus, they cannot meet the agronomic requirements of cabbage planting. At present, cabbages are mainly harvested manually in China. The universities and research institutions of China have made a series of studies on cabbage harvesting technology and equipment; Wang et al. [10] and Li et al. [11] further optimized and improved the 4YB-1 type harvester, but only did this as a concept design on the whole machine, without making a sample machine; thus the design scheme needed to be further verified. Zhou et al. [12] designed a cabbage conveyor that realized cabbage conveying through a double-helix structure and optimized the working parameters of the components in the laboratory, further reducing the damage to the cabbages in the conveying process. Du et al. [13] designed a caterpillar-style self-propelled cabbage harvester, which was applied in the Jiangsu and Zhejiang provinces in China; however, there is no subsequent research on the high damage rate in the process of mechanized harvesting. Fang et al. [14] designed a kind of coping-type cabbage harvester, which conveys cabbages using a coping and double-helix structure. Li et al. [15] adopted a ball-clamp structure with a wavy conveyor belt to wrap the cabbages, to further reduce damage. However, this structure could only harvest cabbages of uniform size; in the case of larger or smaller cabbages, there are problems with clogging or cabbages going missing. The research results mentioned above are still in the testing or development stage and are not mature enough to develop commercialized harvesters; thus, they are far from actual practice.
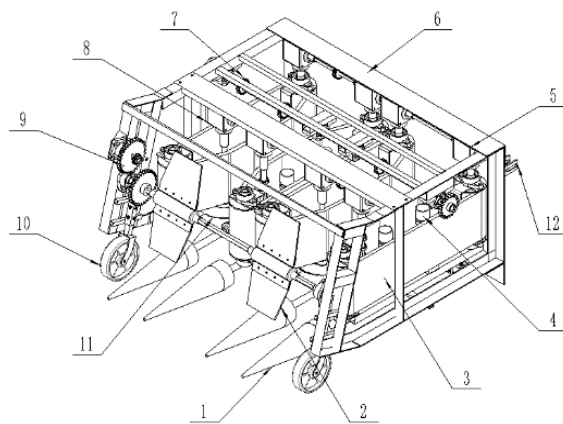
To solve this problem, based on the agronomic requirements of cabbage planting and marketization requirements, the author's research group designed a cabbage harvester with a vertical clamping conveyor, which can realize the combined operations of cabbage pulling, conveying, root-cutting, leaf-stripping, and collecting. To further optimize the working performance of the cabbage harvester, based on the physical properties and mechanical property tests for harvesting cabbages [16], taking the related working parameters of the machine as the independent variables, the qualifying rate of cabbage harvesting under a combination of different factors and levels was obtained by tests. A multi-factor response surface analysis was used to determine the influence of each factor and their interaction effect on the parameters related to working performance, then the combination of optimal control variables was obtained to achieve an efficient working effect, with low loss for the cabbage combine harvester.

2. Machine Structure and Working Principles

2.1. Structure of the Machine

The 4GCSD-1200-type cabbage harvester is mainly composed of a crawler walking chassis, a harvesting header, a leaf-stripping mechanism, and a material container. The cabbage harvester designed in this research adopted the dual-power crawler walking chassis developed by the author's research group at the Nanjing Institute of Agricultural Mechanization in the Ministry of Agriculture and Rural Affairs. The chassis is fully hydraulically driven to provide power to the cabbage header. The gap between the crawler belts is adjusted by an oil cylinder and the adjustment range is 800–1200 mm, to let the harvester travel over a ridged surface or furrows. The height of the header can be adjusted by a trifilar suspension to meet the harvesting requirements. The structure of the leaf-stripping mechanism is similar to that of the current machine model and will not be described in this study. The conveying header of the cabbage harvester is mainly composed of the pulling device, the clamping and conveying device, the double-disk root-cutting device, and the chain-gear transmission system. The cabbage-conveying header is on the crawler walking chassis and the two are hinged through a trifilar suspension structure. They

are vertically arranged, based on the central plane. The structure of the conveying header of the cabbage harvester and the structure of the whole machine are shown in Figure 1a,b.

(**a**)   (**b**)

Figure 1. Cabbage harvester: (**a**) The structure of the conveying header of the cabbage harvester. (**b**) The structure of the whole machine. (1) Pulling mechanism. (2) Reel. (3) Flexible clamping and conveyor belt. (4) Belt tensioner. (5) Transmission gearbox of the conveying mechanism. (6) Body frame. (7) Chief drive shaft. (8) Transmission gearbox of the root-cutting mechanism. (9) Transmission gearbox of the reel mechanism. (10) Ground wheel. (11) Double-disk root-cutting mechanism. (12) Fixed plate in trifilar suspension hinge.

2.2. Principles of Harvesting

During the operation of the sample machine, the motor of the walking chassis drives the directly connected hydraulic pump to work, and the hydraulic pump drives the cabbage header to work with all components by controlling the hydraulic motor of related working components by the electrically controlled valve group, to realize the pulling, clamping and conveying, root-cutting, leaf-stripping, and the collecting of cabbages. The pulling roller first stays above the soil surface and under the outer leaves of the cabbage, then it lifts to push the cabbage upward until its root leaves the ground. The reel is above the feeding mouth, and its rotation drives the reel flap to set the cabbage upright and sends it into the clamping and conveying mechanism. When the clamping and conveying mechanism clamps the cabbage and conveys it backward, the double-disk root-cutting mechanism cuts the root of the cabbage and sends it into the leaf-stripping mechanism via the horizontal conveyor belt. After the wrapping leaves are removed, the cabbage enters the material container.

3. Analysis of the Working Process and the Selection of Key Parameters

3.1. Analysis of the Cabbage Harvesting Process

There are three stages in mechanized cabbage harvesting using the cabbage harvester: pulling, conveying, and root cutting. To realize the efficient and low-loss harvesting of cabbages, it is necessary to clarify the relationship between the rotating speed of the pulling roller, the rotating speed of the conveyor belt, the rotating speed of the cutter-head, and the advancing speed. We set the time for harvesting a unit row spacing of cabbages as t, the time required for pulling up a cabbage by the pulling roller is set as t_1; the time required from the conveying mechanism to the root-cutting mechanism is set as t_2; the time required for the one-time root-cutting of a cabbage is t_3. The possible relations between them are as follows:

$t < t_1$: the walking speed of the machine v is too fast; before the first cabbage is pulled up and sent into the conveying mechanism, the second cabbage has entered the pulling mechanism. There are three situations in this case; if $t < t_2$, that is, the rotating speed of the conveyor belt is too low, the number of cabbages entering the conveying mechanism is too

large per unit time, the cabbages will then be clogged at the feeding mouth of the conveying mechanism, and will be extruded, rubbed and collided, thus reducing the qualifying rate of mechanized harvesting. If $t > t_3 > t_2$, that is, if the rotating speed of the conveyor belt is high and the rotating speed of the cutter-head is low, before the cabbage root is cut completely, the cabbage is conveyed backward; thus, the qualifying rate of mechanized harvesting of cabbages is reduced. In this case, the lower limit value of the rotating speed of the cutter-head can be determined. If $t > t_2 > t_3$, that is, if the conveying device conveys cabbages one after another, the rotating speed of the conveyor belt is low and the rotating speed of the cutter-head is high; in this case, the cabbages can be conveyed and the root can be cut efficiently, and the lower limit value of the rotating speed of the conveyor belt can also be determined.

$t \geq t_1$: the advancing speed of the machine v is too slow, since the working distance is constant (the length of the pulling roller is constant), the acting time on the cabbage by the pulling roller per unit of time is increased, and the cabbages are rubbed and damaged; thus, the qualifying rate of harvesting is reduced. At the same time, if t is too long, the working efficiency of the machine is reduced; thus, the advancing speed should be set to a reasonable rate [17,18].

3.2. Analysis of the Cabbage Pulling Process

The pulling device is mainly composed of reels and pulling rollers, which are the most important components for cabbage conveying, root-cutting, and collecting. As shown in Figure 2, the pulling roller comprises a circular cone at an inclination angle that is determined by the angle between the conveying mechanism and the ground level, to ensure that the root is perpendicular to the cutting plane when the cabbage enters the conveying device.
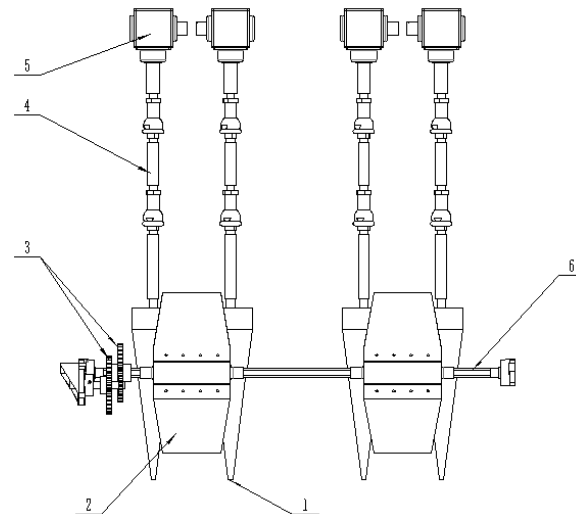

Figure 2. Cabbage pulling device: (1) Pulling roller. (2) Reel. (3) Transmission gear of the reel. (4) Universal drive shaft. (5) Straight-toothed gearbox. (6) Drive shaft of the reel.

Through preliminary tests and observations, the pulling rollers act directly on the cabbage; thus, the rotating pulling rollers are the main reason for the rubbing and damaging of cabbages. In order to analyze the motion law of the cabbage by the pulling rollers, the cabbage and the pulling rollers form a rigid body system for force analysis. To simplify the model, the positions of the mass point and the center of mass are not considered, as shown in Figure 3. It can be obtained by the theorem of the center of mass motion, as follows:
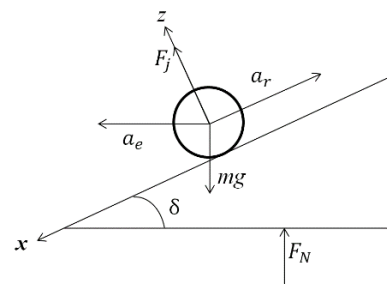
$$\sum m v_z = \sum F_z^{(e)}$$

Figure 3. Force analysis of cabbage pulling.

That is,

$$m_j a_j - m(a_e - a_r \cos ffi) = f_N \cos ffi = {}^-F_j \cos ffi \tag{1}$$

$$F_M - (m_j + m)g - F_j \sin ffi = m a_r \sin ffi \tag{2}$$

Based on the motion law of the mass center of rigid body motion, the equilibrium equations of forces in the directions of X and Z are as follows:

$$m(a_j \cos ffi - a_r) = mg \sin ffi \tag{3}$$

$$mg \cos ffi = F_j \tag{4}$$

The following equations can be derived:

$$a_J = \frac{g({}^- \cos^2 ffi + \sin ffi \cos ffi)}{K_M - 1 + \cos^2 ffi} \tag{5}$$

$$F_M = m(a_j \cos ffi - g \sin ffi) + mg \cos ffi + (m_j + m)g \tag{6}$$

To drive the cabbages upward rather than letting them fall down, the device should satisfy the condition of $a_r > 0$. The following equation can be obtained from Equation (2), where:

$$\frac{mg({}^- \cos^2 ffi + \sin ffi \cos ffi)}{m_j - m + m \cos^2 ffi} > g \frac{\sin ffi}{\cos ffi} \tag{7}$$

That is,

$$^- > \frac{\tan ffi (K_M - 1 + \cos^2 ffi)}{\cos^2 ffi} - \tan ffi \tag{8}$$

where μ is the friction coefficient between the cabbage and the pulling roller; F_M is the constraint reaction of the whole rigid body; a_r is the relative acceleration of the cabbage, in m/s^2; a_e is the walking acceleration of the harvester, in m/s^2; δ is the angle between the cone on the pulling roller and the horizontal line (°); F_j is the supporting force from the pulling roller to the cabbage, N; a_j is the absolute acceleration of the cabbage harvester, in m/s^2; m_j is the weight of the single cone on the pulling roller, in kg; f_N is the friction between the cabbage and the pulling roller, N; K_M is the ratio between the weight of the pulling roller and the weight of the cabbage.

In harvesting, to ensure that the cabbage moves upward rather than downward, Equation (8) should be satisfied. Therefore, the material properties should be considered in designing the pulling mechanism, although it is not necessary to consider this factor when optimizing the parameters of the mechanism. The gap between pulling rollers is determined by the pressure from the rollers to the cabbage; moreover, the pressure is in positive correlation to the friction between the pulling roller and the cabbage. It can be obtained from Equation (5) that, the relative motion between the pulling roller and the cabbage has a great impact on the delivery of the cabbage, thus, the rotating speed of the pulling roller is essential to the qualifying rate of cabbage harvesting. According to [19],

when the taper angle of the pulling roller δ was 14–20°, the success rate of cabbage-pulling and delivery was at its highest. The ratio between the cone radius and the length of the cone axis is determined by the tangent value of the angle ff, and the gap between pulling rollers is 50–80 mm, to let through the cabbage rhizomes; thus, the diameter of the end of the pulling roller was designed to be 100 mm, and the length of the conical pulling roller was designed to be 200 mm; at this point, the angle between the pulling roller and the horizontal line was 14°, which could meet the design requirements.

3.3. Analysis of the Cabbage Clamping and Conveying Process

Cabbages are conveyed by means of flexible clamping on a horizontal conveyor belt [20]; that is, the flexible sponge belt clamps and delivers the cabbages backward, as shown in Figure 4.
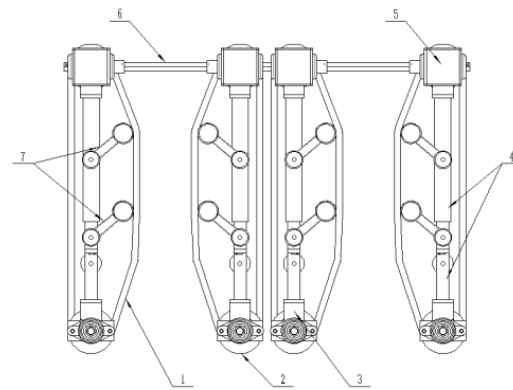

Figure 4. Flexible clamping and conveying mechanism: (1) Flexible clamping and conveyor belt. (2) Driven wheel. (3) Fixed plate of the driven wheel. (4) Mounting rack of the clamping and conveying mechanism. (5) T2 gearbox. (6) Main drive shaft of the conveyor belt. (7) Tension mechanism.

The motion analysis of the cabbage conveying process in Figure 5 shows that, in the continuous feeding of cabbages, the condition required for no clogging of cabbages is:
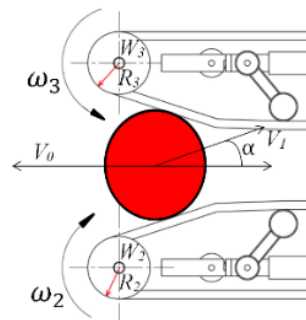

Figure 5. Motion analysis of cabbage conveying.

$$v_1 sin\, ff \ \geq \ v_0 \tag{9}$$

where v_1 is the linear velocity of the conveyor belt, in m/s; α is the ascending angle of the delivery mechanism (°); v_0 is the operation velocity of the harvester, in m/s.

Based on the force analysis of the cabbage deformation situation at the base level in a delivery interval, a deformation analysis was made on the force condition of the cabbage after entering the conveying device [20]. Figures 6 and 7 show that the forces on points A and C, F_A and F_C, are:

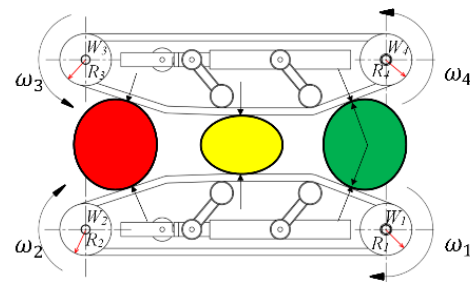$$F_A = F_C = \frac{F_2 L_1}{L} \tag{10}$$

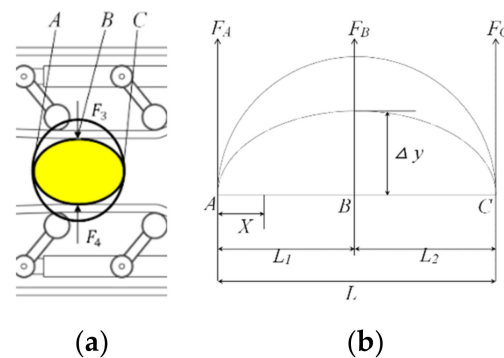**Figure 6.** Schematic diagram of the conveying process.

(**a**)   (**b**)

Figure 7. Schematic diagram of deformation in cabbage clamping and conveying. (**a**) Schematic diagram of transport local deformation analysis. (**b**) Analysis of local deformation.

The counterforce at point B can be obtained, based on the equilibrium equation, as follows:

$$F_B = \frac{F_2 L_2}{L} \tag{11}$$

The deflection curve equation can be obtained by the integration of extruding cabbages:

$$y = \frac{F_2 L_2 x}{6LEJ} = x^2 - L_2^2 + L^2 \tag{12}$$

Since $x = L_1 = L_2$, the deformation deflection of the section of cabbage at the base level after it is clamped, Δy, is:

$$\Delta y \frac{F_2 L_2 L_1 L}{6EJ} \tag{13}$$

where E is the elasticity modulus; J is rotary inertia; L is the length of AC, in mm; L_1 is the length of AB, in mm; L_2 is the length of BC, in mm.

It can be established, based on Equation (9), that the rotating speed of the conveyor belt is related to the advancing speed of the harvester. If the rotating speed of the conveyor belt is too low, the conveying efficiency would be reduced, affecting smooth transit and causing clogging of cabbages with incompletely cut roots, thus reducing the qualifying rate of cabbage harvesting. Through preliminary tests and observations, the types of damage on cabbages are mainly friction, extrusion, and collision. The reason is that the deformation quantity of cabbages is too large as a result of the effect of the rigid parts in the conveying process. If the deformation deflection of the cabbage, Δy, is too large, the cabbage will be easily damaged and smashed, thus reducing the qualifying rate of cabbage harvesting. In Equation (13), the deformation deflection of cabbage is determined by the elasticity modulus. To reduce as much damage to the cabbages as possible, the flexible sponge belt was used to wrap up the cabbage to reduce the relative friction on the cabbage. The tension mechanism designed in this study converts some deformation of the cabbage to the clamping and delivery mechanism. In the process of clamping, the flexible belt itself had deformations to some extent and the deformation deflection of the cabbage was reduced

accordingly, preventing the cabbage from deformation and sliding, to some extent. In addition, in terms of root-cutting, the cabbage plant will not slide away due to the force on the cabbage, used to avoid invalid root cutting.

3.4. Root-Cutting Process Analysis

The root-cutting mechanism is a double disk of blades [21], as shown in Figure 8. The root-cutting mechanism is composed of a cutting disk and a disk saw. The cutting disk can cut the cabbage roots smoothly and efficiently. The disk saw has the function of clamping, while the two cutter-heads are partially overlapping with each other for 1–2 mm, to ensure the completeness of the roots after cutting.
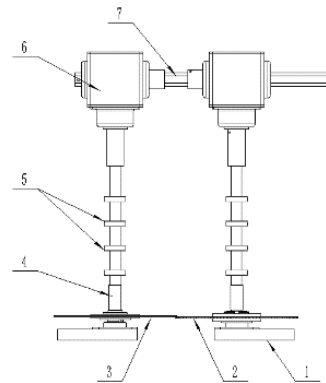

Figure 8. Double-disk root-cutting mechanism. (1) Cutter fixed bearing seat. (2) Circular. (3) Circular saw. (4) Cutter drive shaft. (5) Limit bearing. (6) Variable direction gear box. (7) Cutting root mechanism drive shaft.

The equations of the root-cutting force, Q_x, and the clamping force, P_y, can be obtained from the force analysis in Figure 9, as follows:

$$Q_x = N_x + T_x \tag{14}$$

$$P_y = T_y - N_y \tag{15}$$

Figure 9. Schematic diagram of cabbage root cutting.
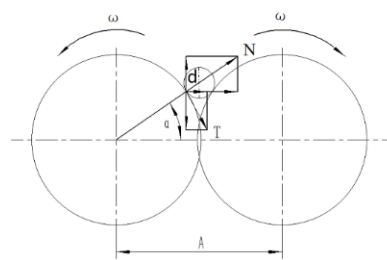
To clamp the cabbage root by the cutter-heads, the following equation should be satisfied:

$$P_y > 0 \tag{16}$$

That is, $T_y > N_y$ and $T = Nf$, and have:

$$Nfcosff > Nsinff \tag{17}$$

When $f > tan\alpha$ or $\varphi > \alpha$, the cutting disk showed good clamping performance [22,23]. At this time:

$$ff = \arccos\frac{A/2}{(D+d)/2} = \arccos\frac{A}{D+d} \tag{18}$$

where N is the normal counterforce from the cutter-head to the cabbage root, the projection of which in the x-axis and y-axis was N_x, N_y.

T is the friction from the cutter-head to the cabbage root, the projection of which, in *the* x-axis and y-axis, was T_x and T_y.

f is the friction coefficient between the cutting disk and cabbage root; in general, $f = 0.7$ [22].

α is the angle between the cutter-head's normal reaction against the cabbage root, N, and the x-axis ($°$).

A is the center distance between two disks, in mm.

D is the diameter of the cutting disks, in mm.

d is the diameter of the section of the root-cutting part, in mm (in general, 25–35 mm).

In the Jiangsu and Zhejiang provinces in China, the average diameter of cabbage root $d = 30$ mm, with a row spacing of 450 mm. Since the cabbage harvester that is designed in this study adopts double-row harvesting, to avoid interference between mechanical structures, the diameter of the cutting disk $D = 200$ mm, with an overlapping part of 2 mm, and the center distance $A = 198$ mm. Based on the parameters above, calculate Equation (18), and get $\alpha = 30.6°$, $\tan\alpha = 0.6$. At this time, when $f > \tan\alpha$, this means that the root-cutting mechanism has good clamping performance. The rotating speed of the cutter-head also has a great impact on the quality of root-cutting. The lower the rotating speed of the cutter-head, the lower the cutting power, which may result in incomplete root cutting, or even failures, further reducing the qualifying rate of cabbage harvesting.

4. Test and Result Analysis

4.1. Test Location, Materials, and Equipment

From 3–7 June 2020, the first field operation performance test of the cabbage harvester was carried out at the Hengtang Vegetable Cooperative, Changshu City, Jiangsu Province, China. The variety of cabbage cultivated in this test base is Qingyu; this cabbage has high and round heads, a single head weights 0.8–1.5 kg, and the hypocotyledonary axis is long. The market demand for this variety is large, and the head diameter in the mature period is about 180–200 mm. The cabbage planting mode in this area is open-field ridge planting, generally in single-ridge double-row or single-ridge four-row planting. The cabbage seedlings were first cultivated before being transplanted. Generally speaking, 54,000–63,000 seedlings per hectare are planted. Before planting, ditching, hilling, and ridge-forming were completed. The average width of the ridge is about 2000 mm, the width of the ditch bottom is 2200 mm, the depth of and width of the ditch are 150–200 mm and 200–300 mm, respectively, the row spacing is 450 mm, and the plant spacing is between 300 and 330 mm. There is a 600-mm machine working path between every two rows of cabbage, as shown in Figure 10. The test equipment and instruments include the cabbage harvester, tachometer, meter ruler, electronic scale, electronic second chronograph, counter, and tool kit.

Figure 10. Agronomic requirements for cabbage planting.

4.2. Test Method and Evaluation Indexes

On the basis of the motion process analysis of cabbage harvesting, the dynamic matching of advancing speed, the rotating speed of the pulling roller, the rotating speed of the conveyor belt, and the rotating speed of the cutter-head have a direct impact on the quality of cabbage harvesting. Thus, taking the qualifying rate of cabbage harvesting as the

evaluation index, a multi-factor test was carried out on the influencing factors above, since there are no related standards or regulations on mechanized cabbage harvesting. Field tests are based on the GB/Z 26582-2011 production technical practice for cabbage harvesting [24] and JB/T 6276-2007 on the testing methods of beets and the harvesting machinery [25], the field working performance test of mechanized cabbage-harvesting was carried out. The standard for cabbage harvesting is: harvest when the cabbage leaf ball is tight, keep two outer leaves (rosette leaves) when harvesting to ensure that the leaf head is clean without damage or cracks, and leave a smooth surface of the roots after cutting. In this case, the standard for cabbage harvesting is reached. That is, the qualifying rate of cabbage harvesting is considered to match the evaluation index of the working performance of the cabbage harvester.

In the testing process, we selected a test field with good consistency. Each group of tests weas repeated five times, and the results of each factor are the average values of multiple tests. Each test was carried out on a two-row cabbage field for harvesting (about 50 m in length). There are 290–330 cabbages in all. Since the cabbages in the field were transplanted manually, with a plant distance of 300–330 mm, the number of cabbages in each ridge was different, and the test results may have some reasonable errors. After each group of tests, we calculated the total number of test cabbages, successfully harvested cabbages (successful root cutting with no damage), and unqualifying harvested cabbages, and recorded the test results. In this test, the qualifying rate of cabbage harvesting, *y,* was taken as the evaluation index for the performance of mechanized cabbage harvesting.

$$Y = (1 - \frac{q_1}{Q}) \times 100\% \qquad (19)$$

where *y* is the qualifying rate of cabbage harvesting, %; q_1 is the number of unqualified harvested cabbages; *Q* is the total number of cabbages in the test.

4.3. Single-Factor Test of Cabbage Harvesting Performance
4.3.1. Single-Factor Test Design

Based on theoretical analysis, a single-factor test of the performance of cabbage harvesting was carried out by taking the advancing speed, the rotating speed of the pulling roller, the rotating speed of the conveyor belt, and the rotating speed of the cutter-head as test factors, and the qualifying rate of cabbage harvesting, *y*, was taken as the evaluation index. Through a preliminary cabbage-harvesting header test, the initial level of each factor was set (taking "0" as the reference value) thus: the advancing speed was 1 km/h, the rotating speed of the pulling roller was 100 r/min, the rotating speed of the conveyor belt was 200 r/min, and the rotating speed of the cutter-head was 300 r/min.

4.3.2. Test Results and Analysis
Influence of Advancing Speed on the Qualifying rate of Cabbage Harvesting

The speed of the pulling roller was set at 100 r/min, the speed of the conveyor belt was 200 r/min, and the speed of the cutter-head was 300 r/min; then, the influence of the advancing speed on cabbage harvesting was analyzed. It can be seen from Figure 11 that the faster the advancing speed, the more cabbages are conveyed per unit time. If the rotation speed of the pulling roller, conveyor belt, and cutter-head are relatively low, the cabbages easily become clogged, and the roots would not be completely cut off. At the same time, due to the practice of double-row harvesting and soft land in Jiangsu province, when the advancing speed is too fast, the adhesion of the left and right tracks of the power chassis is different, which causes more shaking of the header; it is, therefore, difficult to align the two rows of cabbage, thus causing a failure in cabbage harvesting. Therefore, with the increase in the advancing speed, the qualifying rate of cabbage harvesting is reduced.
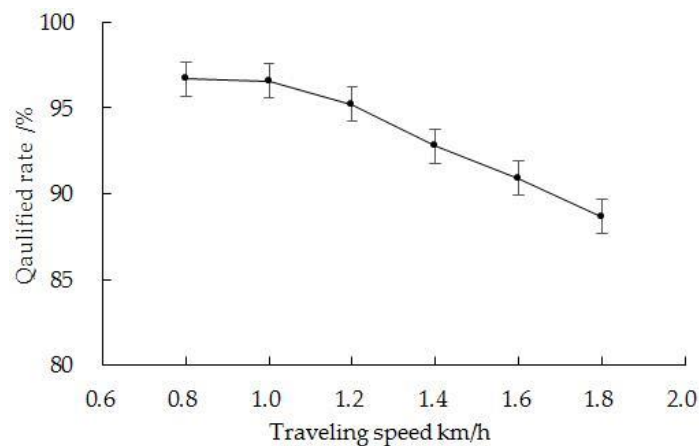
Figure 11. Influence of advancing speed on the qualifying rate of cabbage harvesting.

Influence of the Rotating Speed of the Pulling Roller on the Qualifying Rate of Cabbage Harvesting

Cabbage-pulling is the first step in the successful harvesting of cabbages. The advancing speed was set at 100 r/min, the speed of the conveyor belt was 200 r/min, and the speed of the cutter-head was 300 r/min; at this point, the influence of the rotating speed of the pulling roller on cabbage harvesting was analyzed. It can be seen from Figure 12 that the qualifying rate of cabbage harvesting first went up and then reduced with the increase in the rotating speed of the pulling roller. When the rotating speed of the pulling roller was 80–120 r/min, a high qualification rate could be obtained. When the pulling roller was not rotating, the harvester went forward to force the cabbages to extrude over each other, and this resulted in out-of-order feeding when the pulling roller failed in lifting the cabbage to provide an upward pulling force. At the same time, due to the interaction among cabbages, some cabbages would be crowded out of the feeding inlet, or their roots would not keep vertically downward, thus causing invalid root-cutting, reducing the qualifying rate of cabbage harvesting. With continuous increases in the rotating speed of the pulling roller, the cabbage is subject to friction from the high-speed rotation of the pulling roller, causing serious damage to the surface of cabbages, thus reducing the qualifying rate of cabbage harvesting.

Figure 12. Influence of rotating speed of pulling roller on the qualifying rate of cabbage harvesting.

Influence of the Rotating Speed of the Conveyor Belt on the Qualifying Rate of Cabbage Harvesting

Cabbage clamping and conveying is the key link in the mechanized harvesting of cabbage. It should not only satisfy the need for efficient and low-loss conveying, but also avoided the slipping of cabbages in the clamping and conveying process and ensure effective root cutting. The advancing speed was set at 1 km/h, the rotating speed of the

pulling roller was set at 100 r/min, and the speed of the conveyor belt was 200 r/min; then, the influence of the rotating speed of the conveyor belt on cabbage harvesting was analyzed. It can be seen from Figure 13 that the qualifying rate of cabbage harvesting first went up and then reduced with an increase in the rotating speed of the pulling roller. When the rotating speed of the pulling roller was 80–120 r/min, a high qualifying rate could be obtained. The reason is that, when the rotating speed of the conveyor belt is low, the number of cabbages conveyed per unit of time is relatively small; the cutter head of the root-cutting mechanism works with the current parameters and can achieve valid cutting. With the increase in the rotating speed of the conveyor belt, the acting time of the cutter-head on cabbage roots becomes shorter; the cabbage roots would not be completely cut off and would then be brought backward by the conveyor belt. At the same time, the cabbage roots that were not completely cut off would be kept away from the stump by the cutter-head and roll over, causing the subsequent cabbage clogging and reducing the qualifying rate of cabbage harvesting. Therefore, in subsequent tests, it is necessary to consider the influencing relationship of the rotating speed of the conveyor belt and the rotating speed of the cutter-head.
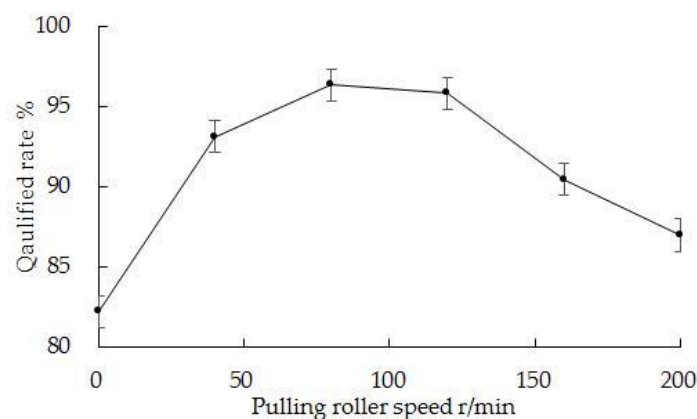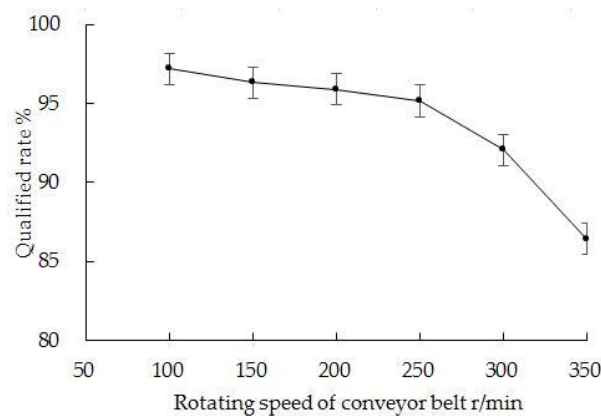

Figure 13. Influence of the rotating speed of the conveyor belt on the qualifying rate of cabbage harvesting.

Influence of the Rotating Speed of the Cutter-head on the Qualifying Rate of Cabbage Harvesting

The performance of root cutting determines the cabbage harvesting quality, having a direct influence on the qualifying rate of cabbage harvesting. The advancing speed was set at 1 km/h, the rotating speed of the pulling roller was set at 100 r/min, and the speed of the conveyor belt was 200 r/min; then, the influence of the rotating speed of the cutter-head on cabbage harvesting was analyzed. It can be seen from Figure 14 that, with the increase in the rotating speed of the cutter-head, the qualifying rate of cabbage harvesting increased linearly and then kept stable. When the rotating speed of the cutter-head was lower than 100 r/min, most of the cabbage roots were not cut off, showing that the root-cutting mechanism could not finish root cutting. When the rotating speed of the cutter-head was higher than 500 r/min, with rapid rotation of the cutter-head, the vibrations in the root-cutting mechanism increased, adding unstable factors to the root cutting; on the other hand, the root-cutting effect was not significantly improved. Thus, the continuous increase in the rotating speed of the cutter-head would increase the power consumption of the whole machine. At a rotating speed of 300–400 r/min for the cutter-head, a highly qualifying rate of cabbage harvesting could be obtained.
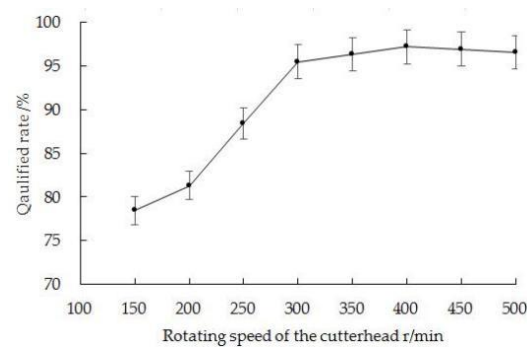
Figure 14. The influence of speed of the cutter-head on cabbage harvesting.

4.4. Parameter Optimization Test of Cabbage Harvesting Performance

4.4.1. Design of the Multi-Factor Test

In order to obtain the optimal parameter combination of the cabbage harvesting at the highest qualifying rate of harvesting, based on the results of the single-factor test, multivariate response surface analysis was adopted to perform quadratic polynomial regression analysis with the software, by taking the advancing speed, x_1, the rotating speed of the pulling roller, x_2, the rotating speed of the conveyor belt, x_3, and the rotating speed of the cutter-head, x_4, as test factors. Then, response surface analysis was used to explore the correlation of all test factors and their interaction effects. In the test, the qualifying rate of cabbage harvesting, y (%), was measured as the response value. The factor-level coding table is shown in Table 1.

Table 1. Factor-level coding table.

Levels	Test Factors			
	Advancing Speed x_1 (km · h^{-1})	Rotating Speed of the Pulling Roller x_2 (r · min^{-1})	Rotating Speed of the Conveyor Belt x_3(r · min^{-1})	Rotating Speed of the Cutter-Head (r · min^{-1})
+1	1.4	120	240	400
0	1.2	100	200	350
−1	1.0	80	160	300

4.4.2. Test Results

Based on the Box–Behnken design (BBD) test design principles [26], there were 29 test points, including 24 analysis factors and 5 zero-error estimations; the test arrangement and its results are shown in Table 2.

Table 2. Test scheme and its results.

Test No.	x_1	x_2	x_3	x_4	y/%
1	0	0	0	0	97.5
2	0	−1	0	−1	93.1
3	0	1	1	0	92.4
4	−1	0	−1	0	93.7
5	1	1	0	0	92.9
6	−1	−1	0	0	97.2
7	−1	0	0	−1	93.8
8	0	0	0	0	97.1
9	0	0	0	0	96.8
10	0	0	1	−1	90.1
11	0	1	0	−1	93.3
12	1	−1	0	0	92.8

Table 2. *Cont.*

Test No.	x_1	x_2	x_3	x_4	y/%
13	1	0	0	1	93.3
14	0	0	−1	−1	94.2
15	−1	0	1	0	92.1
16	0	−1	1	0	92.6
17	1	0	1	0	91.1
18	1	0	−1	0	91.3
19	0	1	0	1	94.6
20	0	−1	0	1	95.9
21	0	0	1	1	97.3
22	0	0	−1	1	95.7
23	0	0	0	0	94.9
24	−1	0	0	1	95.2
25	0	0	0	0	96.8
26	0	1	−1	0	94.9
27	0	−1	−1	0	95.5
28	−1	1	0	0	94.3
29	1	0	0	−1	92.7

4.4.3. Regression Modeling and Significance Analysis
Establishment of the Regression Model and Significance Test

The software package Design-Expert V8.0.6 was applied to analyze the test data and the regression coefficients in the response surface model of the qualifying rate of cabbage harvesting and the variance analysis of significance were obtained, as shown in Table 3.

$$
\begin{aligned}
y = 94.62 &- 1.02x_1 - 0.39x_2 - 0.81x_3 + 1.23x_4 + 0.75x_1x_2 + 0.35x_1x_3 \\
&- 0.20x_1x_4 + 0.10x_2x_3 - 0.38x_2x_4 + 1.43x_3x_4 - 2.01x_1^2 \\
&- 0.87x_2^2 - 1.95x_3^2 - 0.91x_4^2 - 0.38x_2x_4 + 1.43x_3x_4 - 2.01x_1^2 - 0.87x_2^2 - 1.95x_3^2 - 0.91x_4^2
\end{aligned}
\tag{20}
$$

Table 3. Variance analysis of the regression coefficients.

Sources of Variance	Regression Coefficients	Variance Sum	Degree of Freedom	Mean Square Error	F	P
Model	94.62	95.53	14	6.82	5.03	0.0023 **
x_1	−1.02	12.40	1	12.40	9.14	0.0091 **
x_2	−0.39	1.84	1	1.84	1.36	0.2637
x_3	−0.81	7.84	1	7.84	5.78	0.0307 *
x_4	1.23	18.25	1	18.25	13.45	0.0025 **
x_1x_2	0.75	2.25	1	2.25	1.66	0.2188
x_1x_3	0.35	0.49	1	0.49	0.36	0.5575
x_1x_4	−0.20	0.16	1	0.16	0.12	0.7364
x_2x_3	0.10	0.04	1	0.04	0.03	0.8662
x_2x_4	−0.38	0.56	1	0.56	0.41	0.5301
x_3x_4	1.43	8.12	1	8.12	5.98	0.0282 *
x_1^2	−2.01	26.21	1	26.21	19.31	0.0006 **
x_2^2	−0.87	4.94	1	4.94	3.64	0.0772
x_3^2	−1.95	24.60	1	24.60	18.13	0.0008 **
x_4^2	−0.91	5.37	1	5.37	3.96	0.0666
Residual error		19.00	14	1.36		
Lack-of-fit		14.97	10	1.50	1.49	0.3741
Error		4.03	4	1.01		
Sum		114.53	28			

Note: ** means very significant ($p < 0.01$); * means significant ($0.01 < p < 0.05$).

Table 3 shows that the test model on the qualifying rate of cabbage harvesting was significant ($p < 0.01$) but the lack-of-fit was insignificant ($p < 0.01$), showing that the obtained regression model had high fitting precision. The first-order terms, x_1 and x_4, and quadratic terms, x_1^2 and x_3^2, were highly significant; the first-order term x_3, the interaction term x_3x_4 was significant, and the other terms were insignificant. The contribution of test factors to the qualifying rate as the test index is determined by the *F*-value. The higher the *F*-value, the greater the effect on the test index. The influence order of all test factors on the qualifying rate of cabbage harvesting is: rotating speed of the cutter-head (x_4) > advancing speed (x_1) > rotating speed of the conveyor belt (x_3) > rotating speed of the pulling roller (x_2).

Analysis of the Two-Factor Interaction Effect

Since the interaction item x_3x_4 had a significant effect on the qualifying rate of cabbage harvesting, according to the regression model (21), a response surface between the rotating speed of the conveyor belt, x_3, and the rotating speed of the cutter-head, x_4, based on the regression model (21), is shown in Figure 15.
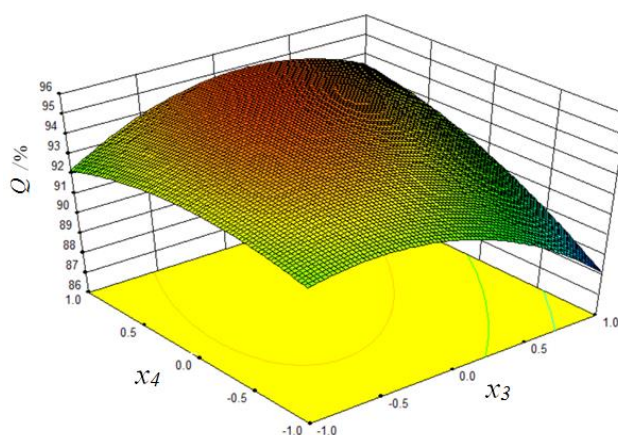

Figure 15. Influence of the interaction factors on the qualifying rate of cabbage harvesting.

Figure 15 shows that when the advancing speed and the rotating speed of the pulling roller were fixed at zero-level (actual value: the advancing speed was 1.2 km/h and the rotating speed of the pulling roller was 100 r/min), the rotating speed of the cutter-head was 300–350 r/min, with an increase in the rotating speed of the conveyor belt, the qualifying rate of cabbage harvesting showed a tendency to continuously decrease. When the rotating speed of the cutter-head rose to 350–400 r/min, with the increase in the rotating speed of the conveyor belt, the qualifying rate first increased, then went down slightly. The reason was that when the cutter-head rotated at a low speed, the rotating speed of the conveyor belt was relatively high, and the per unit time for the cutter-head to cut the cabbage roots became shorter; therefore, the roots would not be totally cut off, reducing the qualifying rate of cabbage harvesting. When the cutter-head rotated at a high speed, the cutting power was also high, so that it could cut off cabbage roots rapidly, showing a higher qualifying rate of cabbage harvesting. When the rotating speed of the conveyor belt was 160–200 r/min, with the increase in the rotating speed of the cutter-head, there was little variation in the qualifying rate of cabbage harvesting. When the rotating speed of the conveyor belt increased to 200–240 r/min, with the increase in the cutter-head, the qualifying rate of cabbage harvesting increased linearly. The reason for this was that when the conveyor belt was kept at a low speed, the rotating speed of the cutter-head was at the lowest level of −1 (actual value at 300 r/min), thus realizing the effective root-cutting of cabbages, increasing the qualifying rate of cabbage harvesting. In this range, solely increasing the rotating speed of the cutter-head would not obviously increase the qualifying rate. With the continuous increase in the rotating speed of the conveyor belt, the conveyed cabbages per unit time also increased, and the relatively low rotating speed of the cutter head could not

cut the cabbage roots rapidly; cases of incomplete root cutting may occur, greatly reducing the qualifying rate of cabbage harvesting. Therefore, the rotating speed of the conveyor belt was at the $-0.5\sim0.5$ level (actual value of 180–220 r/min), and the rotating speed of the cutter-head was at the $0.5\sim1$ level (actual value of 350–400 r/min); these values could result in a high qualifying rate of cabbage harvesting.

Figure 15 shows that when the advancing speed and rotating speed of the pulling roller were kept at zero level (actual value, 1.2 km/h, and rotating speed of the pulling roller, 100 r/min), and the rotating speed of the cutter-head at 300–350 r/min, with the increase in the conveyor belt speed, the qualifying rate of cabbage harvesting reduced continuously. When the rotating speed of the cutter-head increased to 350–400 r/min, with the increase in the rotating speed of the conveyor belt, the qualifying rate first increased and then reduced slightly. The reason was that when the cutter-head rotated at a lower speed, the rotating speed of the conveyor belt was relatively high, the per unit time of the cutter-head cutting cabbage roots became shorter, and the cabbage roots could barely be cut off, thus reducing the qualifying rate of cabbage harvesting. When the cutter-head rotated at a high speed, it gained great cutting power and could rapidly cut off the cabbage roots and improve the qualifying rate of cabbage harvesting. When the rotating speed of the conveyor belt was at 160–200 r/min, with the increase in cutter-head speed, there was little change variation in the qualifying rate of cabbage harvesting. When the rotating speed increased to 200–240 r/min, with the increase in cutter-head speed, the qualifying rate of cabbage harvesting increased linearly. The reason was that when the conveyor belt rotated at a low speed, the rotating speed of the cutter-head remained at the lowest level of -1 (actual value at 300 r/min), and the roots of cabbages could be totally cut off, increasing the qualifying rate of cabbage harvesting. In this range, only increasing the rotating speed of the cutter-head could not obviously increase the qualifying rate. With the continuous increase in the speed of the conveyor belt, the number of cabbages per unit time increased, the low cutter-head speed could not achieve an effective effect of root cutting, and the roots were not totally cut off, greatly undermining the qualifying rate of cabbage harvesting. Therefore, the rotating speed of the conveyor belt at the $0.5\sim0.5$ level (actual value at 180–220 r/min) and the cutter-head speed at the $0.5\sim1$ level (actual value at 350–400 r/min), a high qualifying rate of cabbage harvesting can be achieved.

4.5. Parameter Optimization and Validation Test

4.5.1. Parameter Optimization and Analysis

In order to obtain the optimal parameter combination for the qualifying rate of the 4GCSD-1200 type cabbage harvester, considering the boundary conditions of each factor, a constrained optimization was made on the objectives above, based on the cabbage operation quality requirements and actual operation conditions; the objective function and restrained condition are [27]:

$$\begin{cases} y = 90 \leq maxy(x_1, x_2, x_3, x_4) \leq 100 \\ \text{s.t.} \begin{cases} 1.0 \leq x_1 \leq 1.4 \\ 80 \leq x_2 \leq 120 \\ 160 \leq x_3 \leq 240 \\ 300 \leq x_4 \leq 400 \end{cases} \end{cases} \tag{21}$$

After optimizing and solving the objective function, the following results were obtained: when the advancing speed was 1.12 km/h, the rotating speed of the pulling roller was 88.29 r/min, the rotating speed of the conveyor belt was 203.52 r/min, the rotating speed of the cutter-head was 394.91 r/min, the qualifying rate of cabbage harvesting was 95.5%, which could meet the requirements of cabbage harvesting.

4.5.2. Field Verification Test

Figures **??**C and S1

The field verification test was carried out on the optimized theoretical values. Considering convenience in measurement and test, the values of the combined optimized

parameters were rounded up. The parameters of the cabbage harvester were set as follows: the advancing speed was 1.1 km/h, the rotating speed of the pulling roller was 90 r/min, the rotating speed of the conveyor belt was 205 r/min, and the rotating speed of the cutter-head was 395 r/min. Under the same testing conditions (referring to Sections 4.1 and 4.2), the field verification test was repeated 5 times; the operation effect of the test is shown in Figure 16. The test results showed that the sample machine showed good performance in the field verification test, with uniform roots after cutting and a low damage rate. The average value of the qualifying rate of cabbage harvesting after five times of tests was 96.3%, which was basically in line with the optimized parameter combination in the regression coefficients. In conclusion, the 4GCSD-1200 type cabbage harvester showed a stable working performance, with the characteristics of a sophisticated structure, easy operation, and high efficiency. The cabbage harvester can achieve the standard for mechanized cabbage harvesting, in which two rows of cabbages with a sphere diameter of 150–250 mm and row spacing of 400–500 mm are planted. The machine has been certified by a third-party testing agency and is conducive to the realization of integrated support of the operations of cabbage production in China and the reduction in labor input.

(**a**) (**b**)

Figure 16. Field test. (**a**) Harvesting in progress. (**b**) After harvesting.

5. Discussion

(1) In this study, the influence of the advancing speed of the cabbage harvester, the rotating speed of the pulling roller, the rotating speed of the conveyor belt, and the rotating speed of the cutter-head on the qualifying rate of cabbage harvesting was analyzed. When the walking speed is 1.2 km/h, the speed of the plucking roller is 100 r/min, the speed of the conveyor belt is 180–220 r/min, and the speed of the cutter is 350–400 r/min, a high qualifying rate of kale harvesting can be obtained. Further studies will be made on the influence of the angle of the pulling roller, the material of the flexible conveyor belt, the structure of the tensioning mechanism, and the cutting methods on harvesting performance in the future.

(2) It was found in the test that there is the problem of the failure of harvesting due to the skewing or lodging of cabbages, thus undermining the qualifying rate of cabbage harvesting. To solve this problem, subsequent studies will adopt an automatic row-alignment mechanism. By installing an angle sensor and developing an automatic row-alignment system, this problem will be solved.

(3) At present, China has imported mature machine types from European and American countries in terms of mechanized cabbage harvesting. They are mainly large-scale mechanized equipment designed for large pieces of land, and harvest cabbages in single rows with a unilateral harvester hung on a tractor, the power of which is over 120 hp and the harvesting efficiency is 0.07–0.10 hectare/h. They are suitable for the conventional planting of cabbages and are not suitable for the agronomic requirements of cabbage planting in China, especially in terms of ridge planting. Thus, they showed a poor harvesting effect and required 2–6 workers to cut roots or strip leaves at the same time. The self-propelled cabbage harvester designed in this paper has improved harvesting quality, saved labor costs, and reduced labor

intensity; however, its marketability should be further improved. Further research should be made into high-efficiency and low-loss harvesting technologies, to realize commercialized harvesting.

6. Conclusions

(1) Through an in-depth analysis of the status of the cabbage industry in China and the requirement of harvesting technologies, the 4GCSD-1200 type cabbage harvester was designed. It includes a crawler walking chassis and cabbage harvesting header; the header is composed of the pulling mechanism, the flexible clamping and conveying mechanism, and the double-disk root-cutting mechanism. The harvester can realize low-loss cabbage pulling, conveying, and precision root-cutting.

(2) Based on the theoretical analysis and single-factor test, following the design principles of the Box–Behnken test, by taking the advancing speed, rotating speed of the pulling roller, rotating speed of the conveyor belt, rotating speed of the cutter-head as influencing factors, a four-factor three-level response surface analysis was adopted to carry out a test of the working parameter optimization of the cabbage harvester. Moreover, a mathematical regression model between the influencing factors and the qualifying rate of cabbage harvesting was established; the influence order of the factors on the qualifying rate of cabbage harvesting was: rotating speed of the cutter-head > advancing speed > rotating speed of conveyor belt > rotating speed of the pulling roller.

(3) By taking the optimal qualifying rate of cabbage harvesting as the objective, the optimal working parameters for the harvester were obtained: the advancing speed was 1.1 km/h, the rotating speed of the pulling roller was 90 r/min, the rotating speed of the conveyor belt was 205 r/min; the rotating speed of the cutterphead was 395 r/min. A verification test showed that the qualifying rate of cabbage harvesting was 96.3%, with high root-cutting uniformity and low loss. It shows that optimizing the working parameters could reduce the loss during the mechanized harvesting of cabbages and improve the qualifying rate of harvesting, and its operation effect could meet the marketization requirements of cabbage harvesting.

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