Design and experiment of a Chinese chive harvester

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Abstract: Recognizing the labor intensity of current domestic Chinese chive harvesting and the need for its mechanized harvesting, a self-propelled electric Chinese chive harvester is designed. The machine is composed of a control system, supporting mechanism, cutting parts, conveying and clamping mechanisms, frame, and collection system. It can complete Chinese chive feeding, cutting, transmission, and binning operations at one time. It has a cutting width of 0.25 m and wheelbases of 260 mm and 460 mm. Two 12 V, 42 Ah lead-acid batteries were used in series as the power supply. The mechanical properties of Chinese chive were analyzed, and shear and compression tests were carried out to determine that the average value of the maximum shear force on the chives is 129 N. Up to a compressive force of 225 N, Chinese chives are not damaged. According to the physical characteristics of Chinese chives and the requirements of the harvesting operations, design and calculation of the key components of the harvester's transmission mechanism and the strength of the whole machine frame were completed. An embedded control system and Cortex-M3 microprocessor were used to control the harvester and realize its functions of rolling and harvesting while regulating its speed and protecting its motor. Using the Box-Behnken test design method, the machine's operating speed, cutter speed, and cutter height were selected as influencing factors, and the lodging rate and loss rate were evaluated as a test. A mathematical regression model of influencing factors and evaluation indexes was established to analyze the influence of these factors and indexes and optimize test parameters. The optimal parameter combination is determined to be: operating speed, 1.1 km/h; cutter speed, 220 r/min; cutter height 2.0 cm. The parameters were verified from field tests and the results showed that under the optimized parameter combination, the average lodging rate was 3.96% and the average loss rate was 3.23%, indicating that the Chinese chive harvester meets the agronomic requirements of Chinese chive harvesting. This harvester could be modified to harvest other crops such as chrysanthemums and Mongolian Chinese chive.

Keywords: harvester, clamping mechanism, test design, lodging rate, Chinese chive
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1 Introduction

Chinese chive is known as "grass for washing the intestines". It has a spicy flavor that promotes appetite. Not only can it be eaten as a vegetable, it also has medicinal value.

Chinese chive (which, in this paper, it will be usually referred as just chive) is a stalk crop with a water content of more than 90% and is grown widely. In the last decade, new chive products have been appearing, and the techniques of its planting and cultivation are being perfected[1].While open field leek cultivation continues to grow, large areas of anti-seasonal chives are also appearing, and due the increasing market demand and favorable profit margins, fresh chive production areas of over 667 hm² are beginning to appear. Harvesting is the most energy-consuming and time-consuming part of chive farming, accounting for more than 60% of the total costs[2]. Since harvesting directly affects the processing and marketing of the chives, influencing its selling price and the revenue that it generates, it is a crucial step for chive growers. Because of the complexity of its harvesting, the degree of automation of harvesting operations remains quite low. At present, the domestic chive harvesting operation still relies mainly on manual labor, whose cost can be high, indeed sometimes not affordable, so it is important to conduct research on mechanized harvesting technology and to develop practical harvesting machinery[3-5].

Early development of Chinese chive harvesting machinery took place outside of China. For example, the wind-fed-type leafy vegetable harvester made by Kawasaki in Japan uses high-pressure airflow to transport the cut vegetables to a collection bag. This method is suitable for leafy vegetables that are relatively small in size and mass, but the conveyor belt's manufacturing process is complicated, and there is no way to remove the soil, which is picked up on the conveyor belt. The MT-200 semi-automatic harvester developed by the Korean company Podlander is suitable for a variety of leafy-vegetable harvesting, substantially reducing the use of labor and improving harvesting efficiency[6-9]. However, it is normally powered by a gasoline engine, which can cause some pollution of the vegetables and the land during harvesting. Chinese research on mechanization of leafy-vegetable harvesting started relatively late, but is advancing rapidly. Commonly used units include a leafy vegetable harvester with zero stubble cutting rate

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designed by Cheng Yulai, the 4G200 type harvester developed by Shanghai Kangbo Industrial Co., Ltd., and the KS30C-1 type leafy-vegetable harvester developed by Shenyang Liangyan Agricultural Technology Co., Ltd. So far, China does not have a machine specifically for harvesting Chinese chive. Some growers use a large wheat harvester in a greenhouse to harvest chives, but the efficiency is not high; there is considerable waste. Because the height of the chive plant is very low, the serrated shape of a knife for harvesting will often cause the chives to be jumbled, increasing the workload for the subsequent baling work[10,11].

In response to the above, an automatic orderly chives harvester is designed with chives in mind, taking into account the growth characteristics of leafy vegetables. It can complete the chive loading, cutting, transferring, and collecting operations at one time, thus improving the efficiency of chive harvesting and reducing the cost of its production.

2 Mechanical properties of Chinese chives

While being moved on a primary conveyor belt, the chive was clamped. The stem and leaf parts were in a state of extrusion. In order to ensure that the chives were not crushed and broken during harvesting and conveying, a compression test was done by using a texture analyser (TMS-Pro, Food Technology Corpration Inc., America) for the stem and leaf section. Hanzhong wintering Chinese chive grown at an experimental base in the back mountain of Shenyang Agricultural University was used as the test material.

For the compression tests, the stem and leaf parts of the chives, on which the treatment and disinfection were done. The loading rate for this test was 40 mm/min and the compression distance, based on the thickness of the clamping device during harvesting, was set at 13 mm. Each group of trials contained a sample of 20[12]. A test curve is shown in Figure 1.

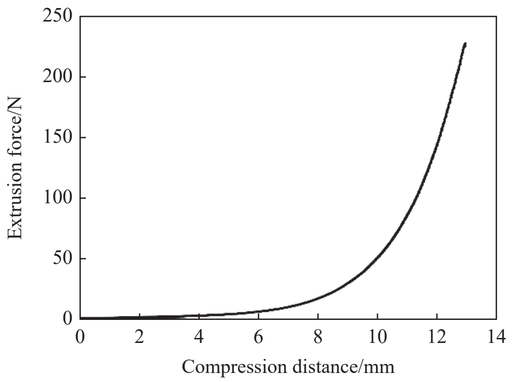


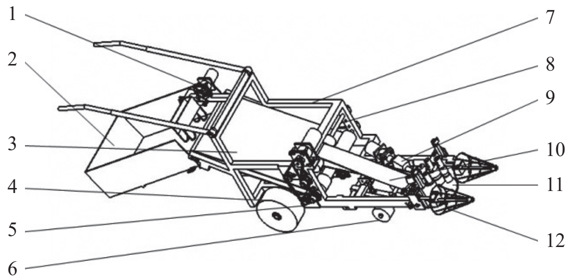
Figure 1 Extrusion force vs. compression distance

During the compression of the stem and leaf parts, the pressure increases with distance to a maximum value of 225 N. The chive did not appear to be broken.

3 Overall structure and working principle

3.1 Structural design of Chinese chive harvester

The structure of our harvester is shown in Figure 2. It contains a power section, a support section, a cutting section, a conveying section, a frame section, and a collection box. Taking account of the external dimensions that the harvester needs to meet during harvesting, SolidWorks software was used to model the whole harvester. The virtual-research-design approach was chosen for developing the harvester, and the ratio of modeled dimensions to actual dimensions was 1:1 to ensure correct processing of the prototype through the drawing size. The three-dimensional model is shown in Figure 3.



1. Rear paddle device 2. Collecting device 3. Secondary conveyor 4. Large walking wheels 5. Collecting device 6. Small walking wheels 7. Rack 8. Primary conveying shaft 9. Cutting moto 10. Primary conveyor belt 11. Cutter device 12. Support device

Figure 2 A drawing of the harvesting machine

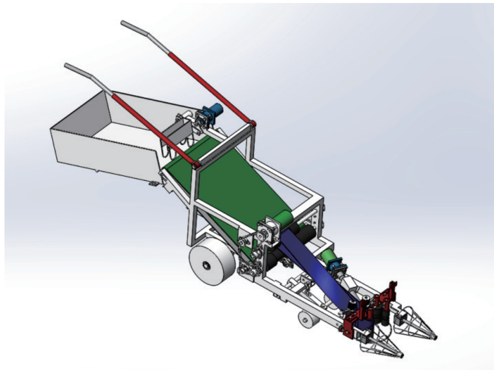


Figure 3 An illustration of the machine

3.2 Working Principle

The harvester uses a rotary cutter to cut the chives with the assistance of a support device. After cutting, the leeks enter upright at the front of the primary conveyor belt and change from a vertical to a horizontal position by clamping. Then they enter the secondary conveyor belt, reaching the front end of the collection box, where they are sent into the collection box by the continuous paddling of the rear paddle. The power is provided by a 24-V DC battery.

3.3 Technical parameters

The main technical parameters of the harvester are listed in Table 1. The overall length, width, and height of the harvester are 2.0 m, 0.5 m, and 1.0 m, respectively, with a single ridge harvesting, an operating width of 0.25 m, a supporting power of 300 W, and an operating speed of 1.44 to 2.16 km/h[13].

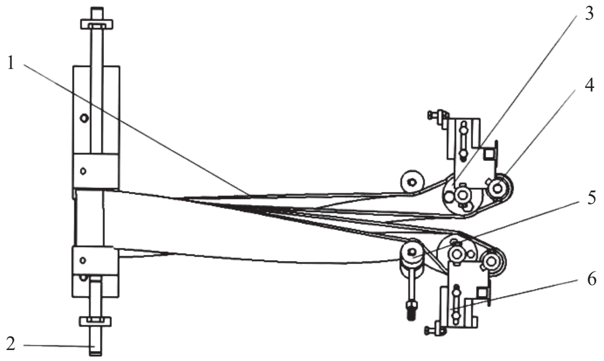
Table 1 Main technical parameters of Chinese chive harvester

Parameter	Value
Size of machine (length×width×height)/mm^3	2000×500×1000
Machine weight/kg	75
Power/W	300
Battery capacity/A·h	40
Wheel base/mm	260
Wheel tread/mm	460
Swath/m	0.25
Working speed/km·h^{-1}	1.44-2.16
Working efficiency/%	85

4 Design and verification of key components

4.1 Design of primary conveying mechanism

The primary conveyor mechanism is shown in Figure 4. It is an important component of the harvester. Its main role is clamping and changing the orientation of the chive after cutting. This mechanism contains a conveyor belt, principal axis, large supporting roller, pre-roller, deflector roller, and distance adjustment device. The clamping transfer entrance angle after cutting the chive can be enlarged by setting the pre-roller. The change-direction press rod gradually changes the conveyor belt from its initial vertical orientation to a horizontal one to avoid misalignment of the cut chives.



1. Conveyor belt 2. Principal axis 3. Large supporting roller 4. Pre-roller 5. Deflector roller 6. Distance adjustment device

Figure 4 Harvester's transport mechanism

4.2 Determination of conveyor belt installation position

Because the stem and leaf parts of Chinese chives are not very resistant to extrusion, in order not to cause damage to the chives, the conveyor belt material is chosen to be relatively soft, and the same material should be used both inside and outside to lengthen its life span. The conveyor belt tension should ensure not only that the chive be closely clamped but also that it is not injured. It is important to choose the right installation angle to ensure that the chive is transferred upward properly but without excessive use of material. For the chive to be driven forward, the pre-roller structure needs to achieve the condition that the entry angle of the chive stalk is less than the friction-limited angle of the conveyor belt. The conveyor-belt installation position is shown in Figure 5.

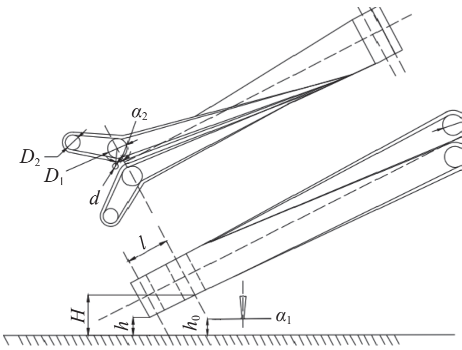


Figure 5 Installation position of conveyor belt

To convey the chive smoothly, the pre-roller diameter must satisfy the following requirement:

$$\alpha_2 = \arccos\frac{D_1}{D_1+d} < \varphi \quad (1)$$

where, α_2 is the entrance angle of the chive stalks, (°); d is the diameter of Chinese chive stem and leaf bundles (5-25 mm); D_1 is the diameter of large supporting roller, mm; φ is the limiting friction angle between chive stems or leaves and the conveyor belt, (°).

The design diameter of the large supporting roller and leaf bundles are 83 mm and 10 mm, respectively. The calculated entrance angle of the chive stalks and calculated limiting friction angle are 27° and 49°, respectively, and the friction coefficient of the chive is 1.19[14].

The entry angle must be less than the limiting friction angle and the roll diameter is selected to meet this requirement.

The installation angle of the primary conveyor belt α_1 (angle with the horizontal) is 30° to 40°. The rollers at the entrance and exit of the conveyor belt must be as close as possible to the ground and close to the rootstock. When the harvester is working, the vertical distance of the stem and leaf section from the ground is H.

$$H = h + \frac{D_2+l}{2}\sin\alpha_2 \quad (2)$$

where, D_2 is pre-roller diameter, mm; l is vertical distance between two pre-rollers (conveyor belt direction), mm; h is height of the leading edge of the conveyor belt roller, mm.

This height ensures that the chive bulbs not be damaged when the collecting area moves above the rootstocks. Its size also takes into account the desired height of the stubble left above and the flatness to the ground.

Designed dimensions are as follows: D_2= 45 mm; l = 65 mm; h = 70 mm. The calculated height H from stem and leaf part to ground is 94 mm.

As these numbers imply, the only way to get the belt as close to the ground as possible is to minimize the diameter of the belt rollers in front. The distance left between primary conveyor belts is Δ_s=5-15 mm. Then Equation (1) can be turned into:

$$\alpha_2 = \arccos\frac{D_1+\Delta_S}{D_1+d} < \varphi \quad (3)$$

The length of the primary conveyor belt is set at 0.5-1.0 m to ensure suitable inclination angles for the configuration of the working parts of the various sections that follow.

4.3 Conveyor belt tension measurement

Measurement of Conveyor belt tension is shown in Figure 6. The values of the compressive force at four different positions on the primary conveyor belt (20 cm, 30 cm, 40 cm, and 50 cm from its front end) were measured using a digital push-pull gauge, scale bar, test sample block (200 mm long, 20 mm wide, and 10 mm high), a thin rope, and other test materials. The test sample was clamped by the conveyor belt. The test sample is connected by a thin rope to a digital push-pull gauge. The pulling distances of the sample block were set at 10 mm, 20 mm, and 30 mm, according to the value of pulling force equaling to the tension value. Experimental results are given in Table 2.

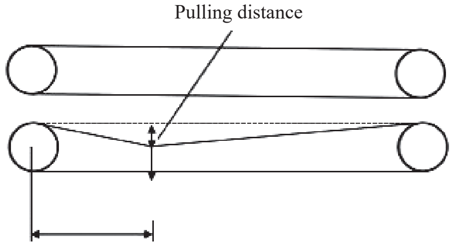


Figure 6 Measurement of the tension of conveyor belt

As this table shows, the maximum value of the compressive force between the primary conveyor belts is 76.2 N, much less than the 225 N that was the maximum compressive force measured in previous Chinese chive compression tests, so the chive did not

Table 2 Forces deflecting the conveyor belt for various tensions

Measuring point from belt axis/cm	Belt tension for different pulling distances/N		
	10 mm	20 mm	30 mm
10	20.6	44.3	76.2
20	16.6	25.1	43.4
30	24.8	38.7	51.2
40	17.5	25.3	35.8
50	16.6	25.1	43.4

break in being clamped and transported. The primary conveyor belt design met the requirements.

4.4 Frame strength analysis and verification

The harvesting machine includes a cutting device, a conveying device, and a transmission device. The profile of the frame structure is a square hollow steel tube. The forces as well as the torques in each part were measured separately for analysis. The vertical forces were the weight of the device plus added load. The lateral force mainly includes inertia and wind. The longitudinal forces were impact and inertial. Torsional loads were also loaded and analyzed. The vertical forces were the load of 300 N and the body weight of 750 N. The torques were calculated according to the power and speed of the paddle part, conveying part, walking wheels, and cutting part, to which finite element analysis was applied, as shown in Figures 7 and 8.

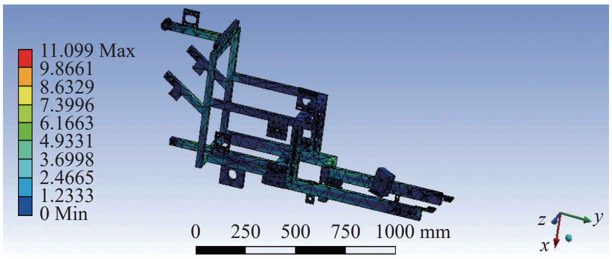


Figure 7 Frame partial stress analysis diagram

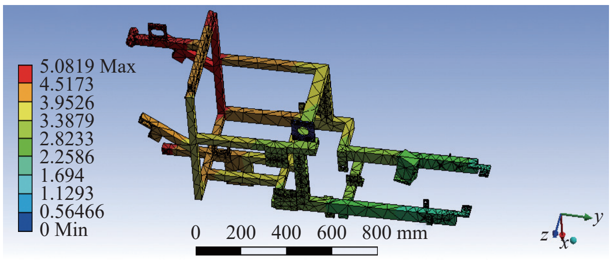


Figure 8 Frame partial strain analysis diagram

$$T_1 = 9\,550\,000\frac{P}{n} = 9\,550\,000\times\frac{10\times10^{-3}}{3000} = 31.83\ (\mathrm{N\cdot mm})$$

$$T_2 = 9\,550\,000\frac{P}{n} = 9\,550\,000\times\frac{150\times10^{-3}}{2650} = 540.56\ (\mathrm{N\cdot mm})$$

$$T_3 = 9\,550\,000\frac{P}{n} = 9\,550\,000\times\frac{60\times10^{-3}}{2800} = 204.64\ (\mathrm{N\cdot mm})$$

$$T_4 = 9\,550\,000\frac{P}{n} = 9\,550\,000\times\frac{80\times10^{-3}}{3340} = 228.74\ (\mathrm{N\cdot mm})$$

Stress concentrations appear in each part of the frame due to the absence of rounded corners. The greatest stress is generated at the big walking wheels, so it is necessary to reduce the weight of the battery as much as possible and to pay attention to the manner of its installation. Because the weights of the parts of the frame are not uniformly distribution, the whole frame leans in the direction of the back walking wheels. In order to reach the goal of a uniform weight distribution of the frame load, reducing the weight of the battery is required. After taking account of the corresponding stress, the maximum stress on the whole machine was 112 MPa, which is less than the material yield strength of 235 MPa. The maximum calculated displacement was 5.08 mm and met the design requirements.

5 Field test

5.1 Test conditions

To verify the working performance of the chive harvester and the reasonableness of its design parameters, a field test was carried out in the greenhouse shed of the experimental base in the back mountain of Shenyang Agricultural University. Hanzhong east Chinese chive was used as the test material. There are a total of 6 ponds, each with 7 ridges, each with a length of 7 m and a width of 0.4 m. A field test is shown in Figure 9.

Figure 9 Field test of this study

5.2 Determination of the test index

According to the analysis of the influence of lodging rate and loss rate during the harvesting operation, there is an interaction between all factors. A ternary quadratic regression orthogonal rotational combination test was designed by selecting operating speed, cutting speed, and cutter height as the test factors, and lodging rate and loss rate as the test indexes[15,16]. The factor level coding table for the harvesting experiment is listed in Table 3.

Table 3 Factor level coding table for the harvesting experiment

Code	Operating speed A/km·h^{-1}	Cutting speed B/r·min^{-1}	Cutter height C/cm
–1.682	0.70	180.0	–4.0
–1.000	0.86	196.0	–2.4
0	1.10	220.0	0
+1.000	1.34	244.0	2.4
+1.682	1.50	260.0	4.0

The main intent of this test was to investigate how the three factors of machine forward speed, cutting speed, and cutter height affect the harvesting quality of the harvester[17]. To date, relevant Chinese institutions and departments have not developed standards on the quality of machine harvesting of Chinese chive. The actual operation of Chinese chive harvesting requires neat and uniform stubble cutting, small loss of rootstock and stems and leaves, and few chives falling on the land. Based on the above conditions, two indicators, the loss rate and the lodging rate of Chinese chives, were selected as the evaluation indicators.

1) Loss rate of Chinese chives

The loss rate is an important indicator of the harvest quality. There is some leaf and stem loss during the cutting by the harvester.

The loss rate X is

$$X = \frac{m_a}{m_c} \times 100\% \quad (4)$$

where, m_a is mass of chives lost during the harvesting process, g; m_c is total mass of the chives, g.

2) Lodging rate of Chinese chives

The lodging rate is also an important index of harvesting quality. Almost all harvesting machines fail to fully supply the product of the harvesting. The lodging rate Z of the chives is

$$Z = \frac{m_b}{m_c} \times 100\% \quad (5)$$

where, m_b is retained mass of the chives during the harvesting process, g; m_c is total mass of the chives, g.

6 Test results and analysis

6.1 Test results

The test program was designed based on the results of the Box-Behnken test. The results of our harvesting test are listed in Table 4.

Table 4 Test results of Chinese chive harvesting

Test No.	Operating speed/km·h^{-1}	Cutting speed/r·min^{-1}	Cutter height/cm	Lodging rate/%	Loss rate/%
1	1	1	1	7.92	7.82
2	1	1	–1	6.24	7.89
3	1	–1	1	8.35	6.56
4	1	–1	–1	7.25	7.49
5	–1	1	1	4.89	7.09
6	–1	1	–1	4.26	6.32
7	–1	–1	1	5.20	6.85
8	–1	–1	–1	4.53	6.28
9	1.682	0	0	9.20	8.21
10	–1.682	0	0	3.62	6.58
11	0	1.682	0	5.92	9.25
12	0	–1.682	0	6.19	8.28
13	0	0	1.682	6.32	5.12
14	0	0	–1.682	5.48	4.53
15	0	0	0	4.21	5.49
16	0	0	0	4.56	4.85
17	0	0	0	3.98	4.75
18	0	0	0	3.79	4.42
19	0	0	0	4.32	4.96
20	0	0	0	4.40	4.88
21	0	0	0	3.88	5.02
22	0	0	0	3.92	4.92
23	0	0	0	4.29	4.68

6.1.1 Regression modeling and significance analysis

The relationships among the lodging rate and loss rate and the operating speed (A), cutting speed (B), and cutter height (C) were obtained by Design-Expert software to get the regression model.

1) Lodging rate

The regression equation for the Lodging rate is as follows.

$$Y_1 = 4.15 + 1.48A - 0.18B + 0.40C - 0.11AB + 0.18AC + 0.068BC + 0.77A^2 + 0.64B^2 + 0.59C^2 \quad (6)$$

The variance analysis of the regression equations is listed in Table 5.

From the analysis of variance in Table 5, a uniformity model p<0.0001 can be obtained, indicating that the model is at a highly significant level. The determination coefficient of the model R^2 is 0.9762, indicating that the uniformity model gives an excellent fit,

Table 5 Analysis of lodging rate model

Source	Coefficient	df	Mean square	F-value	p-value
Model	54.11	9	6.01	59.34	<0.0001
A-operating speed	30.07	1	30.07	296.79	<0.0001
B-cutting speed	0.45	1	0.45	4.42	0.0555
C-cutter height	2.21	1	2.21	21.81	0.0004
AB	0.092	1	0.092	0.91	0.3569
AC	0.27	1	0.27	2.70	0.1241
BC	0.036	1	0.036	0.36	0.5589
A^2	9.31	1	9.31	91.93	<0.0001
B^2	6.51	1	6.51	64.26	<0.0001
C^2	5.44	1	5.44	53.72	<0.0001
Residual	1.32	13	0.10		
Lack of Fit	0.75	5	0.15	2.12	0.1652
Pure Error	0.57	8	0.071		
Cor Total	55.43	22			

with a small test error. The fact that p=0.1652 (>0.05) indicates that the model for the retention rate is valid. The regression equation model is supported, and the working parameters in the model are reliable for the evaluation of the actual operation of the harvester. The operating speed (A), quadratic term of the operating speed (A^2), quadratic term of the cutting speed (B^2), and quadratic term of the cutter height (C^2) are significant in the model, while all other terms are not significant.

2) Loss rate

The regression equation for the loss rate is as follows:

$$Y_2 = 4.89 + 0.44A - 0.26B + 0.098C + 0.17B - 0.29AC + 0.13BC + 0.87A^2 + 1.35B^2 - 0.039C^2 \quad (7)$$

The variance analysis of the regression equation is listed in Table 6.

Table 6 Analysis of the loss rate model

Source	Coefficient	df	Mean square	F-value	p-value
Model	45.66	9	5.07	79.03	<0.0001
A-operating speed	2.60	1	2.60	40.54	<0.0001
B-cutting speed	0.93	1	0.93	14.55	0.0021
C-cutter height	0.13	1	0.13	2.02	0.1783
AB	0.24	1	0.24	3.71	0.0763
AC	0.68	1	0.68	10.66	0.0061
BC	0.14	1	0.14	2.19	0.1629
A^2	12.01	1	12.01	187.15	<0.0001
B^2	29.12	1	29.12	453.73	<0.0001
C^2	0.024	1	0.024	0.38	0.5488
Residual	0.83	13	0.83		
Lack of fit	0.17	5	0.17	0.40	0.8386
Pure error	0.67	8	0.67		
Cor total	46.49	22			

From the analysis of variance in Table 6, a uniformity model p <0.0001 can be obtained, indicating that the model is at a highly significant level. The determination coefficient of the model R^2 is 0.9643, indicating that the uniformity model gives an excellent fit and that the test error is relatively small. The fact that p = 0.8386 (>0.05) indicates that the model for the loss rate gives a good fit. The regression equation model is determined to be suitable, and the working parameters in the model are reliable for the evaluation of the actual operating effect of the harvester. The operating speed (A), quadratic term of operating speed (A^2), and quadratic term of the cutting speed (B^2) are significant in the model, while all other terms are not significant.

6.1.2 Two-factor interaction effect analysis

1) Effect of two factors on lodging rate

The response surface curve for the effect of interaction factors was obtained by applying Design-Expert 8.0 software for analysis[18]. As shown in Figure 10, at an operating speed of 1.1 km/h ,the lodging rate increases with an increase of the operating speed when the cutting speed is fixed, and the lodging rate is minimum when the cutter height is –4.0 cm. However, when the cutter height is –4.0 cm, the cutter is rotating into the ground. Because of the resistance of the earth, when the cutter height is too low, it is easy to damage the cutter and even damage the whole electrical circuit of the machine. When the cutter height is fixed, the lodging rate tends to increase with increasing cutting speed. The influence of cutting speed and cutter height on the lodging rate is not as significant as the effects of cutting speed and operating speed on the lodging rate. In general, the lodging rate of the chives reaches a minimum value near a cutting speed of zero and a cutter height of –1.7. To sum up, the three factors affecting the lodging rate of the harvester are, in order of importance, operating speed (*A*), cutter height (*C*), and cutting speed (*B*).

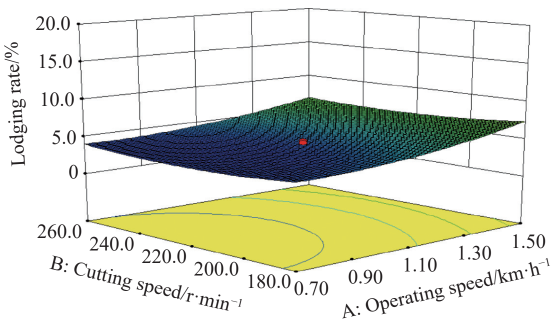


Figure 10 Influence of cutting speed and operating speed on lodging rate

As shown in Figure 11, at an operating speed of 1.1 km/h, the lodging rate increases with an increase of cutter height when the cutting speed is fixed. The lodging rate is minimum when the cutter height is –4.0 cm. However, when the cutter height is –4.0 cm, the cutter is rotating into the ground. Because of the resistance of the earth, when the cutter height is too low, it is easy to damage the cutter and even damage the whole electrical circuit of the machine. When the cutter height is fixed, the lodging rate tends to increase with increasing cutting speed. The influence of cutting speed and cutter height on the lodging rate is not as significant as the effects of cutting speed and operating speed. The lodging rate of Chinese chives reaches a minimum value around a cutting speed of zero and a cutter height of –1.7. To sum up: The three factors affecting the lodging rate of the Chinese chive harvester are, in order of importance, operating speed (*A*), cutter height (*C*), and cutting speed (*B*).

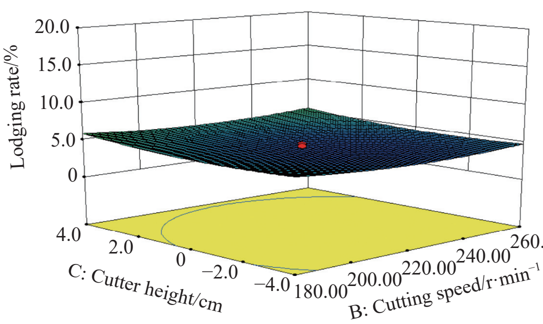


Figure 11 Influence of cutting speed and cutter height on lodging rate

2) Effect of two factors on loss rate

As shown in Figure 12, at a cutter speed of 220 r/min, the loss rate tends to decrease and then increase as the operating speed increases when the cutter height is fixed. The loss rate is minimum when the operating speed is 1.1 km/h and after that it increases rapidly. This is because the machine operates at too low a speed during the leek harvesting process. The machine scrapes the chives causing damage and also easily causing blockages in the collection process. When the machine operating speed is too large, the machine moves ahead before the chives are fully cut, so an appropriate operating speed must be found. When the operating speed is fixed, the loss rate tends to decrease gradually as the height of the cutter increases. This is because it is easier to cut the chives at a higher cutter speed, but for reasons of safety and machine performance the cutter speed cannot be increased indefinitely and must remain below a maximum value. The interaction between cutter height and operating speed has a significant effect on the loss rate, and according to the surface shown in Figure 13, the loss rate is minimal when the operating speed is near zero and the cutter height is around the –1.682 level.

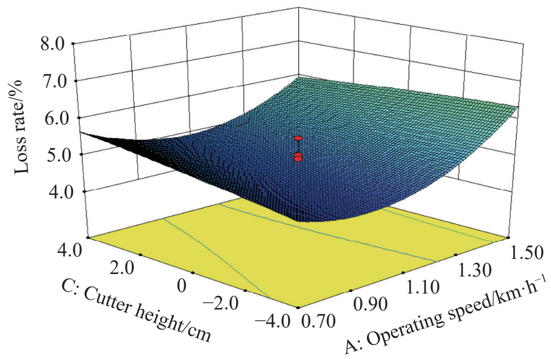


Figure 12 Influence of cutter height and operating speed on loss rate

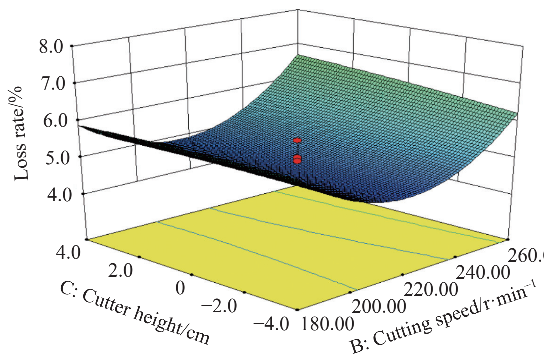


Figure 13 Influence of cutting speed and cutter height on loss rate

As shown in Figure 13, when the operating speed is 1.1 km/h, the loss rate increases with an increase of cutter height when the cutting speed is fixed, and the loss rate is minimum when the cutter height is –4.0 cm. However, when the cutter height is –4.0 cm, the cutter is rotating into the ground and because of the resistance of the earth, when the cutter height is too low, it is easy to damage the cutter and even damage the whole electrical circuit of the machine. The loss rate shows an increasing tendency with increasing cutting speed when the cutting height is fixed. The influence of cutting speed and cutter height on the loss rate is more significant than the effects of cutter height and operating speed. In general, the loss rate reaches a minimum value around a cutting speed of zero and a cutter height at the –1.682 level. To sum up: The three factors affecting the cutting loss rate are, in order of importance, cutting speed (*B*), operating speed (*A*), and cutter height (*C*).

6.2 Model optimization and test validation

6.2.1 Optimization of working parameters

The operating parameters of the Chinese chive harvester were selected on the principle that the loss rate as well as the lodging rate should be below 5% and the loss rate as well as the lodging rate would be between 5% and 10% after carrying out the harvesting operation. The results of the optimization using the Designed-Expert software were as follows: 4.55% lodging rate and 3.24% loss rate when the operating speed was 10 km/h, the cutting speed was 220 r/min and the cutter height was 2.0 cm.

6.2.2 Validation tests

Three tests were carried out by using an operating speed of 1.1 km/h, a cutting speed of 220 r/min and a cutter height of 2.0 cm. The results of the tests are listed in Table 7.

Table 7 Summary of the test results (%)

No.	Lodging rate	Loss rate
1	4.12	3.58
2	3.85	2.99
3	3.92	3.12

According to the results of the validation tests in Table 7, the mean values of 3.96% for the lodging rate and 3.23% for the loss rate are obtained from the three tests and compared with the results of the quadratic regression orthogonal rotational combination tests. The best combination is finally determined to be an operating speed of 1.1 km/h, a cutting speed of 220 r/min, and a cutter height of 2.0 cm.

7 Conclusions

1) This study completed the overall structure design and modelling of a Chinese chive harvester and established its main mechanism, including control system, support mechanism, cutting parts, conveying and clamping mechanisms, frame, and collection system. It can handle the chive feeding, cutting, conveying, and collection-box operation at one time, thereby helping to solve the Chinese chive harvesting problem.

2) The design and verification of the transfer mechanism, rear paddle, and frame were carried. An embedded control system and the Cortex-M3 microprocessor were used for the leafy vegetable harvester and to control the functions of the leafy vegetable harvester such as rolling, harvesting, transferring, speed regulation, and motor protection.

3) The Box-Behnken experimental design method was used to establish a quadratic regression model with lodging rate and loss rate as response indicators. By analyzing the model interaction and response surfaces, the influences of the operating speed, cutting speed, and cutter height of the machine on the response indicators were obtained.

4) The optimization function of Design-Expert 8.0 was applied to optimize the selected model, and the accuracy of the optimization results was verified through tests. The optimum combination of operating parameters was 4.55% collapse and 3.24% loss at an operating speed of 1.1 km/h, a cutter speed of 220 r/min, and a cutter height of 2.0 cm.

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