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Research Article

Development and Test of 4S-6 Garlic Combine Harvester

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Abstract

Garlic harvesting involves digging, soil removal, bulb separation, and collection. Many problems, such as poor coordination between links, high garlic damage rate, and inability to complete bulb separation, are found in the existing combine harvesting. In this study, the parameters of key components, such as digging, clamping, and bulb transportation were determined, and a 4S-6 type self-propelled garlic combine harvester was proposed to improve the effect of garlic digging and the uniformity of bulb separation, reduce the damage rate of garlic, and improve the level of combine harvesting through theoretical analysis and calculation. A field experiment was conducted using an orthogonal test method to verify the effectiveness of each component and the influence of operating parameters on garlic harvesting performance. The optimal operation parameters were determined, and the reliability of the prototype was verified through variance analysis of test data on SPSS software. Results demonstrate that the optimum working parameters of 4S-6 self-propelled garlic combine harvester are digging shovel angle (25°), machine working speed (0.5m/s), and conveying speed of clamping belt (0.9m/s). Field experiment results show that the garlic loss rate, garlic damage rate, impurity rate, and success rate of bulb separation are 3.57%, 1.22%, 3.95%, and 89.34%, thereby meeting the requirements of garlic harvesting in lightly cohesive soil of Cangshan, China. This study provides a certain reference for the development and performance optimization of rhizome crop combine harvesters.

Keywords: Garlic, Combine harvester, Design, Orthogonal test, Parameter optimization

1. Introduction

The garlic planting area and yield in the world have steadily increased in recent years, where the total garlic yield of China, India, and South Korea accounts for more than 85 % of the total garlic yield worldwide. However, garlic harvesting in the three countries is still dominated by pure manpower and semi mechanization because of the influence of planting scale, mode, and local economic level.

Relevant enterprises and scientific research units have developed various garlic stage-harvesting machineries that mainly complete automatic excavation and have conducted relevant research on reducing the garlic damage rate and power consumption to improve harvest efficiency. However, the excavated garlic still needs manpower for collection, soil removal, bulb separation, and other operations. Problems, such as high labor intensity and low operation efficiency, are still found, making it unable to meet the current production requirements and seriously limiting the development of local garlic industrialization[1-2]. Garlic combined harvesting requires good coordination, consistency, stability, and reliability during excavation, transportation, bulb separation, and other operation links, otherwise, the entire machine will not work or seriously affect the harvest quality. Therefore, the digging principle and garlic stage-harvesting machinery [3] cannot be applied to combine harvesting, and the working mode of single-row combine harvester cannot meet the requirements of multirow planting patterns in the main garlic production countries, such as China. Many key components are used in multirow garlic combine harvester that require high assembly accuracy and work coordination, thereby causing great challenges to the development of combine harvesters.

Scholars have conducted many studies on garlic harvesting technology [4-6]. The feasibility and reliability of these research results have not been tested and verified because of many factors, such as garlic planting mode and scale, early mechanical design and processing level, and government support. Therefore, the utilization of theory and means of modernized design and test means and the development of garlic combine harvesters with high reliability and generality have become the key factors to the development of the garlic industry.

In this study, a 3D model of self-propelled garlic combine harvester is proposed through 3D modeling and simulation. The structural characteristics and forced characteristics of the key components of the proposed model, such as excavation, clamping, and bulb transportation, are optimized and analyzed, and a prototype is developed. The reliability of the prototype is verified through field testing, and the key parameters of harvesting operation are collected.

2. State-of-the-art

Many studies have been conducted on garlic harvesting equipment. The garlic harvester studied in the United States belongs to stage-harvesting operation[7]. The machine

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developed by Ramaswamy et al. can complete garlic digging and laying operation[8]. Combining with the digging and laying machine, the garlic picker developed by Churchill et al. can complete the entire garlic harvesting but has high power consumption and damage rate[9]. Krishna et al. developed a four-row garlic harvester towing by tractor with a good harvest effect, but the field harvest rate is only 68.7 %, the garlic damage rate is high, and cannot achieve garlic root removal and bulb separation [10, 11]. Barman et al. conducted a bench test utilizing electric cutting of roots and bulbs, with an operating efficiency of 90.08 %, to solve the technical problems of garlic root cutting and bulb separation but it was not applied to garlic combine harvesters[12]. Myunghee et al. performed simulation analysis of garlic conveying on EDEM software to determine the theoretical speed of garlic conveying and conducted simulation analysis of yield strength of garlic digging shovel on ANSYS software; however, these proposed theoretical studies were not verified through experiments [13, 14]. Borkar et al. designed a six-row swinging garlic harvester to increase the field harvest rate to 80 % for solving the problems of low efficiency and high damage rate of garlic harvesting; however, the machine operation is extremely wide to meet the garlic planting patterns and economic requirements of China[15]. Sharma et al. proposed a single-row traction garlic harvester and conducted software simulation to meet the garlic harvesting needs of small farmers. However, the machine was not verified through experiments and was unsuitable for large-scale harvesting operations in plain areas[16]. Masami et al. studied the vibration pullout multirow garlic harvester mainly designed for the harvesting of middle and small blocks and indicated that is low working efficiency and cannot meet the requirements of large area harvesting[17-20]. Xing et al. conducted virtual simulation design and theoretical analysis of garlic bulb header and bulb digging device and ignored prototype trial production[21]. Wang et al. proposed a handheld section baling harvester that can complete three rows of garlic harvesting and improve the garlic harvest efficiency to a certain extent, but the traction type handheld operation is unsuitable for large-area harvesting [22]. Peng et al. designed a half-feed and self-propelled garlic combine harvester that can accurately excavate, clear soil, clamp, transport, cut, and collect. The harvester meets the operational requirements of garlic harvesters but only remains at the design stage and is not put into production [23]. Yu X. T. et al. designed a 4DLB-2 self-propelled garlic combine harvester on the basis of existing studies [24]. The field performance test results of the harvester meet the requirements of garlic harvesting, but the effect of garlic bulb separation effect is poor. Yu Z. Y. et al. conducted a bench test for the root fibril cutting problem of garlic combined harvesting. Garlic root fibril cutting is realized by floating root cutting mechanism, but is not applied to production[25]. Han et al. designed a 4DS-6 garlic combine harvester with refitting tractor that can complete the excavation, clamping and transportation, bulb separation, collection, and other operations of garlic harvesting; however, its stability is poor, and garlic pseudostem is easy to be blocked when it is thrown, thereby causing it to be shut down for many times to manually remove the garlic pseudostem[26].

The above studies show that garlic stage-harvesting technology in different countries is mature. Garlic harvesting technology in Europe and America is relatively mature, but the planting patterns and harvesting requirements are different from those in Asia. Studies in Europe and America cannot meet the requirements of row spacing and plant spacing of garlic in Asian countries and do not have the function of bulb separation. Therefore, few studies are available about combine harvesters that can meet the needs of multi row harvesting, row spacing adjustment, and economic purchasing power of developing countries. In this study, a 3D model of 4S-6 garlic combine harvester is proposed through digital modeling and field tests. The theoretical optimization analysis of key components, such as excavation, clamping, and bulb transportation is conducted, and the reliability and universality of the proposed model are verified through field testing. This study provides a reference for the development and performance optimization of rhizome crop combine harvesters.

The remainder of this study is organized as follows. Section 3 describes the structure of 4S-6 garlic combine harvester and presents and analyzes the proposed model of 4S-6 garlic combine harvester. Section 4 verifies the reliability and generality of 4S-6 garlic combine harvester through field test data collection and relevant data analysis software and obtains the optimal operation combination parameters of the machine. Section 5 summarizes the study and provides the relevant conclusions.

3. Methodology

3.1 Entire structure and working principle

The 4S-6 garlic combine harvester structure is shown in Fig. 1, which is mainly composed of the caterpillar base plate, digging device, clamping and conveying device, bulb separation device, bulb conveying device, and pseudostem conveying device, etc.

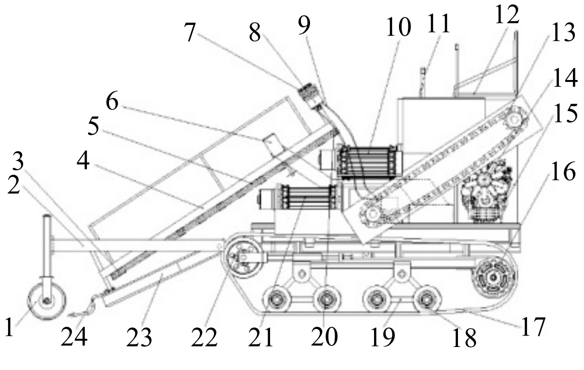

Fig. 1 Schematic of self-propelled garlic combine harvester structure
1-depth wheel 2-prepositive rod 3-clamping driven belt wheel 4-clamping bracket 5-clamping belt 6-cutting off motor 7-clamping chain 8-hydraulic motor 9-hydraulic tubing 10-garlic pseudostem conveyor 11-operating lever 12-seat 13-garlic upper conveyor 14-exhaust fan 15-engine 16-caterpillar base plate 17-track 18-bearing wheel 19-bearing wheel bracket 20-clamping drive belt wheel 21-garlic left conveyor 22-guide wheel 23-digging shovel bracket 24-digging shovel

During operation, the garlic clamping position is first adjusted in accordance with the row spacing of garlic in the field. The engine then provides power for the machine operation through the hydraulic pump, and the digging device performs reciprocating vibration excavation and scarification of garlic. The clamping and conveying device conducts clamping and conveying of dug garlic through the chain drive. During clamping and conveying, garlic is cut through a bulb device composed of a DC motor and a blade. The cut garlic bulb is collected and sent to the conveying device, and the cut garlic pseudostem is thrown into the field through the conveying device[27].

Combined with the current situation of garlic planting agriculture, mechanized harvesting parameter requirements, and mating power requirements in China[28, 29], the main technical indexes of 4S-6 self-propelled garlic combine harvester are determined, as shown in Table 1.

Table 1. Main technical parameters

Items	Parameters
Size of the entire machine (length×width×height)/(mm×mm×mm)	3900×1710×1730
Entire machine quality/kg	1440
Rated power/kW	15
Structure	Self-propelled
Operation mode	Row harvest
Working width/mm	960–1320
Steering control	Differential steering
Variable grade	Continuously variable
Maximum working speed/($m \cdot s^{-1}$)	0.55
Digging depth/mm	0–100
loss rate/%	≤5
Impurity rate/%	≤5
Damage rate/%	≤1.5
The success rate of bulb separation /%	≥85
Working productivity/($hm^2 \cdot h^{-1}$)	0.05–0.1

3.2 Design and research of key components

3.2.1 Structure and key parameter design of digging device

The digging device structure is shown in Fig. 2, which is mainly composed of transmission shaft, eccentric sleeve, connecting rod, high support, V-type digging shovel, suspension rod, low support, and pulley. The hydraulic oil pump provides power for the pulley rotation and then drives the transmission shaft rotation. The eccentric sleeve on the two sides of the transmission shaft is firmly connected with the connecting rod to realize the up and downswing of the connecting rod. The high and low supports realize the up and down rapid vibration of the suspension rod and the vibration and scarification of the digging shovel [30-32].

The digging shovel adopts a V-shaped shovel structure, the width of the digging device is 1.4 m, and six digging shovels are used. The spacing of digging shovels can be adjusted in accordance with the planting row spacing of different garlic to realize flexible operation [33, 34].

The opening angle of the shovel surface affects the excavating resistance of the digging shovel, and the digging shovel surface has a triangular shape. The stress analysis of the soil at the edge of the digging shovel during excavation is shown in Fig. 3. When the digging shovel can complete the excavation, the soil after excavation can overcome the friction and move along the edge of the digging shovel, and the following formulas can be obtained:

$$f_2 \le F_2 cos\frac{\beta}{2} \tag{1}$$

$$f_2 = F_{N2}\, tan\gamma_2 \tag{2}$$

$$F_{N2} = F_2 \, sin\frac{\beta}{2} \tag{3}$$

where f_2 is the friction between the soil and the digging blade, F_2 is the force required to move the excavated soil along the side edge of the digging shovel, F_{N2} is the support force of the soil after the excavation of the digging blade, β is the opening angle of the shovel surface, and γ_2 is the friction angle between the soil and the digging shovel.

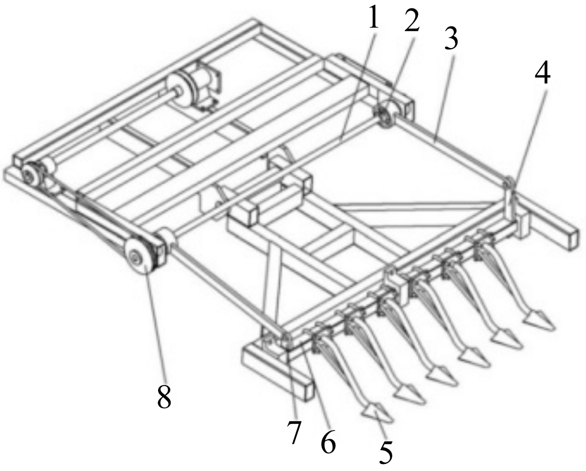

Fig. 2 Schematic of digging device structure
1-transmission shaft 2-eccentric sleeve 3-connecting rod 4-high support 5-V-type digging shovel 6-suspension rod 7-low support 8-pulley

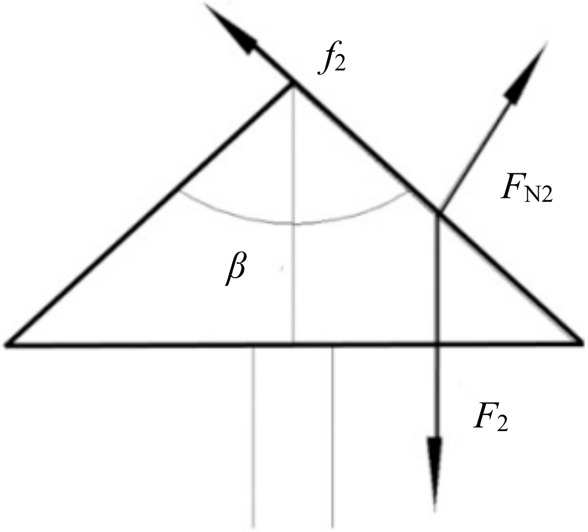

Fig. 3 Stress analysis diagram of digging shovel
Note: f_2 is the friction between the soil and the digging blade, N. F_2 is the force required to move the excavated soil along the side edge of the digging shovel, N. F_{N2} is the support force of the soil after excavation of the digging blade, N. β is the opening angle of the shovel surface, (°).

γ_2 is set to 34° in accordance with the growth of garlic and field operation of digging shovel. Combining Eqs. (1)–(3) yields:

$$\beta \le 0° \sim 112° \tag{4}$$

As shown in Eq. (4), the theoretical maximum opening angle of the digging shovel is 112°. The width of soil excavation is insufficient when the opening angle of the excavation surface is extremely small, thereby affecting the excavation effect. This condition also accelerates the consumption of the excavation surface and seriously wears the digging device to increase the resistance of the excavation handle, making it easy to bend. Therefore, a large opening angle of the shovel surface should be selected, and the opening angle of the shovel surface is $112°$.

Excavating resistance is an index used to measure the working efficiency of digging shovel that affects the digging power. The formula of digging resistance is expressed as:

$$F_{\mathrm{dig}} = [Sl_1\rho \pm g\tan\left(\alpha+\gamma_1\right) + KS + K_{\mathrm{p}}m_{\mathrm{m}}g]\times 6 \tag{5}$$

where S is the cutting area of soil, and its value is $0.25\mathrm{m}^2$. ρ is the density of soil, where tested ρ=$1200\,\mathrm{kg}\cdot\mathrm{m}^{-3}$. K is the plowing specific resistance, and the value of K is $20000\,\mathrm{N}\cdot\mathrm{m}^{-2}$ in accordance with the soil properties and plow structure. K_{p} is the resistance coefficient of machine drive, and its value is 0.22.

The digging resistance of the digging shovel is calculated using Eq. (5):

$$F_{\mathrm{dig}} = 6542.6\,\mathrm{N} \tag{6}$$

The formula of power required by six digging shovels to overcome digging resistance is expressed as:

$$P_{\mathrm{dig}} = F_{\mathrm{dig}} \times v_{\mathrm{dig}} \tag{7}$$

The known working speed of garlic combine harvester $v_{\mathrm{dig}} = 0.25\,\mathrm{m/s}$ by combining (6) and (7) is:

$$P_{\mathrm{dig}} = 9.81\,\mathrm{kW} \tag{8}$$

The total power of the self-propelled garlic combine harvester is $14.7\,\mathrm{kW}$, and the total power consumed by the combine harvester in the excavation work is 66.76%, which meets the requirements of 50%-70%[35].

3.2.2 Structure and key parameter design of clamping device

The clamping device structure is shown in Fig. 4, which is mainly composed of universal joint, clamping frame, driven belt wheel, tensioning device, clamping belt, drive belt wheel, hydraulic motor, drive sprocket, adjusting slide, suspension bracket, driving chain, and driving chain wheel. Six suspension brackets are connected with the main body of the harvester to form a clamping unit, and the adjustable slider on the suspension brackets can meet the requirements of different garlic planting row space. The sprocket is installed in the groove, and the tightness of the transmission chain is adjusted through the position adjustment. The universal joint is used to transfer power for the operation of the clamping conveying device, and the transmission chain is installed on each transmission sprocket in S-shape to complete the clamping conveying operation. The tensioning device completes the clamping tension function[36].

The clamping operation speed is analyzed to determine the appropriate clamping conveying speed, and the speed analysis diagram is established, as shown in Fig. 5.

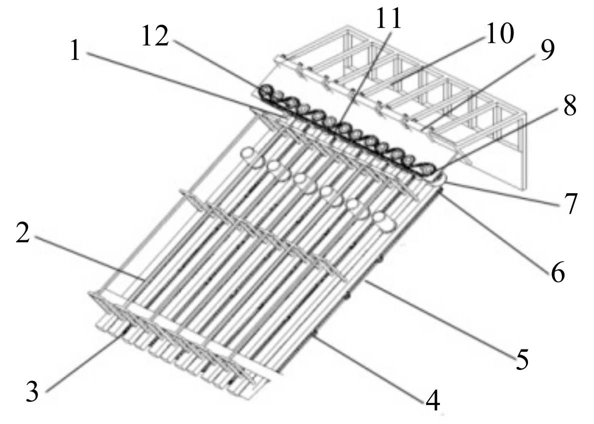

Fig. 4 Schematic of clamping device structure
1-universal joint 2-clamping frame 3-driven belt wheel 4-tensioning device 5-clamping belt 6-drive belt wheel 7-hydraulic motor 8-drive sprocket 9-adjusting slide 10-suspension bracket 11-driving chain 12-driving chain wheel

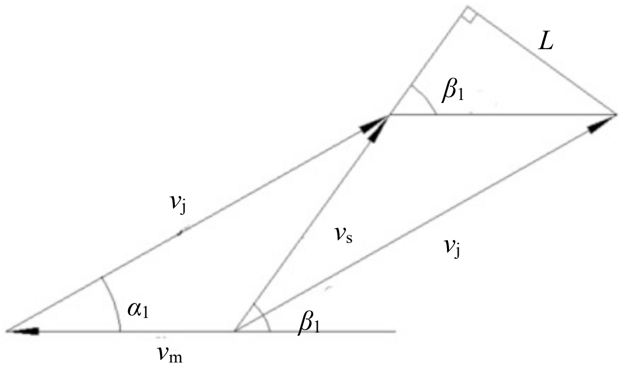

Fig. 5 Velocity analysis chart of garlic clamping operation
Note: v_{s} is the combined harvesting speed of garlic clamped by the clamping device, $\mathrm{m}\cdot\mathrm{s}^{-1}$. v_{m} is the forward speed of the garlic combine harvester, $\mathrm{m}\cdot\mathrm{s}^{-1}$. v_{j} is the clamping belt speed, $\mathrm{m}\cdot\mathrm{s}^{-1}$. α_1 is the angle between the clamping device and the ground, (°). β_1 is the angle between the garlic holding speed and the ground, (°).

As shown in Fig. 5, the speed vector is analyzed.

$$\vec{v}_{\mathrm{s}} = \vec{v}_{\mathrm{m}} + \vec{v}_{\mathrm{j}} \tag{9}$$

On the basis of cosine theorem, combining Fig. 5 and Eq. (9) yields:

$$v_{\mathrm{s}} = \sqrt{v_{\mathrm{m}}^2 + v_{\mathrm{j}}^2 - 2v_{\mathrm{m}}v_{\mathrm{t}}\cos\alpha_1} \tag{10}$$

where

$$v_{\mathrm{m}}\sin\beta_1 = v_{\mathrm{j}}\sin\left(\beta_1-\alpha_1\right) = L \tag{11}$$

Then, we have

$$\frac{v_{\mathrm{j}}}{v_{\mathrm{m}}} = \frac{\sin\beta_1}{\sin\left(\beta_1-\alpha_1\right)} \tag{12}$$

when $\beta_1 > \frac{\pi}{2}$, that is, the driving speed of garlic combine harvester is greater than the clamping speed of clamping belt, thereby making it difficult to complete the effective clamping harvesting operation of garlic, so $\beta_1 \le \frac{\pi}{2}$. On the basis of the requirements of garlic harvesting agronomy and relevant research, when $\alpha_1 \approx 22°$, $K = 2\text{-}3.1$ which is suitable for the normal harvesting operation of garlic combine harvester clamping device. The clamping device is taken as $\alpha_1 = 22°$, $K = 2$, and $\beta_1 = 41°$ in accordance with the actual situation[37].

The forward speed of the self-propelled garlic combine harvester under normal condition is:

$$v_m = 0.46\,\mathrm{m/s} \tag{13}$$

The clamping belt conveying speed is calculated as:

$$v_j = 0.92\,\mathrm{m/s} \tag{14}$$

The harvesting speed of garlic with the clamping device using Formula (10) is:

$$v_s = 0.52\,\mathrm{m/s} \tag{15}$$

3.2.3 Structure and key parameter design of garlic bulb conveyor

The garlic bulb conveying device structure is shown in Fig. 6, which is mainly composed of hydraulic motor, internally-driven chain, internally-driven sprocket, bearing, transmission shaft, externally-driven sprocket, externally-driven chain, internally-driven sprocket, camshaft, delivery steel pipe, and plastic hose installed outside the delivery steel pipe[38].

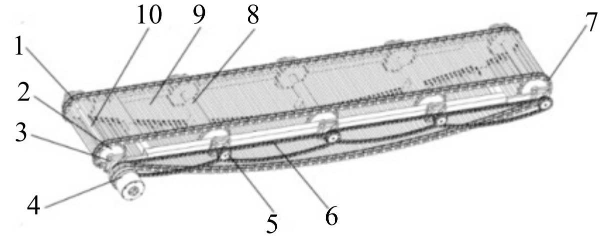

Fig. 6 Schematic of garlic bulb conveying device structure
1-internally-driven chain 2-internally-driven sprocket 3-bearing 4-hydraulic motor 5-externally-driven sprocket 6-externally-driven chain 7-internally-driven sprocket 8-camshaft 9-delivery pipe 10-transmission shaft

As an essential working device of the garlic combine harvester, the garlic bulb conveyor should be designed with full consideration of its size and installation position in the self-propelled garlic combine harvester and the relative position of other devices to prevent damaging or leaking the garlic.

The garlic bulb conveyor frame is welded with 45 carbon steel, with a thickness of 15 mm. In accordance with the size and installation position of the clamping device and chassis, width B_s is 410 mm, height H_S is 250 mm, and the vertical height from bulb separating device H_1 is 350 mm.

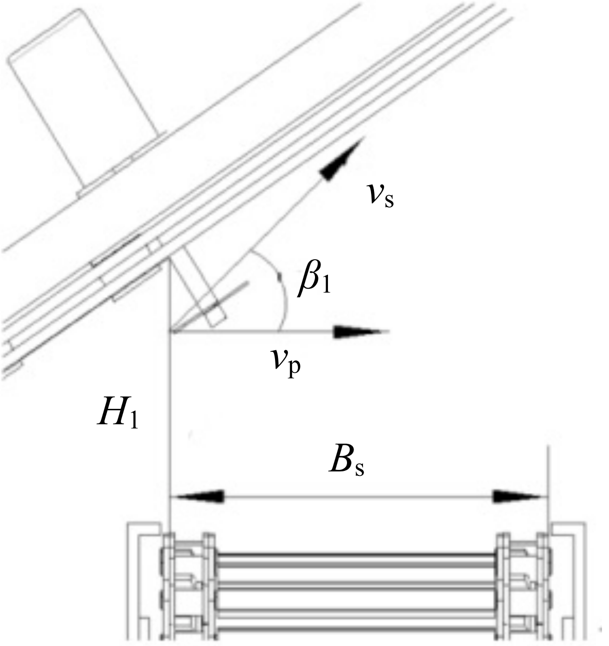

Fig. 7 Velocity analysis chart of garlic
Note: v_s is the combined harvesting speed of garlic clamped by the clamping device, $\mathrm{m \cdot s^{-1}}$. v_p is the speed of garlic bulb in the horizontal direction, $\mathrm{m \cdot s^{-1}}$. β_1 is the angle between the garlic holding speed and the ground, (°). B_s is the horizontal width of the garlic bulb conveyor frame, mm. H_1 is the vertical height between the garlic bulb conveyor and the pseudostem removal device, mm.

Harvesting speed v_s of garlic clamped by the clamping device is $0.52\,\mathrm{m/s}$. As shown in Fig. 7, the garlic bulb speed in the horizontal direction is expressed as:

$$v_p = v_s \cos\beta_1 \tag{16}$$

The time when the cut garlic bulb falls to the garlic bulb conveyor is expressed as:

$$t_1 = \sqrt{\frac{2H}{g}} \tag{17}$$

where t_1 is the time when the cut garlic bulb falls to the garlic bulb conveyor, and H is the vertical distance between the garlic bulb cutting position and the garlic bulb conveying device. The value of H is 350 mm in accordance with the actual situation.

The falling distance of garlic bulb in the horizontal direction is:

$$L_s = v_p \times t_1 = 105\ \mathrm{mm} \tag{18}$$

The garlic bulb will not lose when it falls on the conveyor because $L_s < B_s$. The garlic bulb conveyor parameters are determined, as shown in Table 2.

Table 2. Parameters of garlic bulb conveying device

Length×Width×Height/（mm×mm×mm）	Sprocket speed/($r \cdot min^{-1}$)	Chain type	Conveyingdevice material	Quality/kg
1300×410×250	34	12A	45 carbon steel	6

4 Result analysis and discussion

The field experiment was conducted at the Cangshan garlic planting base in Lanling County, China. The experimental site is a plain area, and the soil is light clay. The plant spacing of garlic is $160\ \text{mm}$, and the row spacing of garlic is $180\ \text{mm}$. The environmental temperature is $30.5\,℃$, the relative humidity is $43\,\%$, and the soil moisture content is $28.2\,\%$. The testing field is shown in Fig. 8.

Fig. 8 Field experiment

4.1 Orthogonal test

4.1.1 Test scheme and results

This research studied the comprehensive influence of three factors, namely, digging shovel angle, conveying speed of clamping belt, and forward speed of garlic combine harvester, on the performance indexes (loss rate, damage rate, impurity rate, and success rate of bulb separation) of garlic harvester through testing and verification of the prototype parameters. The optimal operation parameter combination of the garlic combine harvester is determined. Each group of test machines has a harvesting operation stroke of 20 m, repeats three tests, and takes the average value. Each harvest index is calculated in accordance with Table 3, and the average value of the three work trips is calculated. The calculation formulas of garlic loss rate, garlic damage rate, garlic impurity rate, and success rate of garlic bulb separation are expressed as follows:

$$P_1 = \frac{W_1}{W} \times 100 \tag{19}$$

$$P_2 = \frac{W_2}{W} \times 100 \tag{20}$$

$$P_3 = \frac{W_3}{W} \times 100 \tag{21}$$

$$P_4 = \frac{W_4}{W} \times 100 \tag{22}$$

where P_1 is the garlic loss rate, P_2 is the garlic damage rate, P_3 is the garlic impurity rate, P_4 is the success rate of garlic bulb separation, W is the total weight of garlic, W_1 is the weight of garlic lost, W_2 is the weight of damaged garlic, W_3 is the weight of impurities in garlic, and W_4 is the weight of garlic after bulb separation.

The test factors and levels selected in the three-factor and three-level orthogonal field test are shown in Table 3. The digging shovel angle can be adjusted using the lifting cylinder of the digging device. The machine working speed and the conveying speed of clamping belt are adjusted by controlling the displacement of each hydraulic motor[39]. The test scheme and results are shown in Table 4.

Table 3. Test factors and levels

Levels	Digging shovel angle A/(°)	Machine working speed B/($m \cdot s^{-1}$)	Conveying speed of clamping belt C/($m \cdot s^{-1}$)
1	20	0.40	0.7
2	25	0.45	0.8
3	30	0.50	0.9

Table 4 .Test scheme and results

Serial Number	Factors			Indexes			
	A	B	C	P_1/%	P_2/%	P_3/%	P_4%
1	1	1	1	3.67	1.44	3.62	90.32
2	1	2	2	3.98	1.49	3.31	92.15
3	1	3	3	3.37	1.31	3.36	89.51
4	2	1	2	2.97	1.09	3.69	93.18
5	2	2	3	2.59	1.07	3.82	94.28
6	2	3	1	2.67	1.03	4.06	86.37
7	3	1	3	3.07	1.18	4.31	87.10
8	3	2	1	3.19	1.22	4.61	86.87
9	3	3	2	3.43	1.32	3.98	90.29

4.1.2 Test analysis and verification

Table 5 shows the analysis of test results, where m_{11}-m_{13}, m_{21}-m_{23}, m_{31}-m_{33}, and m_{41}-m_{43} represent the average values of measurement indexes (P_1, P_2, P_3, P_4) under various factors and levels, respectively, and R_1 , R_2 , R_3 , R_4 represent the ranges. The orthogonal test results are analyzed on SPSS software[40, 41], as shown in Table 6.

As shown in Table 5, the primary and secondary orders of influence of test factors on the garlic loss rate are provided as follows: digging shovel angle > conveying speed of clamping belt > machine working speed, and the better combination is $A_2B_3C_3$. The primary and secondary order of influence of test factors on the garlic damage rate is as follows: digging shovel angle > conveying speed of the clamping belt > machine working speed, the better combination is $A_2B_3C_3$. The primary and secondary orders of influence of test factors on the garlic impurity rate are provided as follows: digging shovel angle > conveying speed of clamping belt > machine working speed, and the better combination is $A_1B_3C_2$. The primary and secondary orders of influence of test factors on the success rate of garlic bulb separation are provided as follows: conveying speed of clamping belt > digging shovel angle > machine working speed, and the better combination is $A_3B_3C_1$. In actual garlic harvesting, the damage and loss rates evidently influence the harvesting operation, and the impurity rate and success rate of bulb separation can be obtained through artificial treatment in the later stage. Therefore, the optimal combination is determined as $A_2B_3C_3$, that is, digging shovel angle ($25°$), machine working speed ($0.5\,\mathrm{m/s}$) and conveying speed of clamping belt ($0.9\,\mathrm{m/s}$) in accordance with the principle that the damage and loss rates are the primary factors and by considering the impurity rate and success rate of bulb separation.

Table 5. Analysis of test results

Serial Number	Factors			Indexes
	A	*B*	*C*	
m_{11}	3.67	3.24	3.18	P_1
m_{12}	2.74	3.25	3.46	
m_{13}	3.23	3.16	3.01	
R_1	0.93	0.097	0.45	
Primary and Secondary factors	$A > C > B$			
Optimal combination	$A_2B_3C_3$			
m_{21}	1.41	1.24	1.23	P_2
m_{22}	1.06	1.26	1.30	
m_{23}	1.24	1.22	1.19	
R_2	0.35	0.04	0.11	
Primary and secondary factors	$A > C > B$			
Optimal combination	$A_2B_3C_3$			
m_{31}	3.43	3.87	4.10	P_3
m_{32}	3.86	3.91	3.66	
m_{33}	4.3	3.80	3.83	
R_3	0.87	0.11	0.44	
Primary and secondary factors	$A > C > B$			
Optimal combination	$A_1B_3C_2$			
m_{41}	90.66	90.20	87.85	P_4
m_{42}	91.28	91.10	91.87	
m_{43}	88.09	88.72	90.30	
R_4	3.19	2.38	4.02	
Primary and secondary factors	$C > A > B$			
Optimal combination	$A_3B_3C_1$			

ANOVA from Table 6: Under the significance level of 0.05, the factor value *Sig* of the digging shovel angle is 0.005, which has a significant impact on the garlic loss rate index. The factor value *Sig* of the conveying speed of clamping belt is 0.022, which has a significant impact on the garlic loss rate index. The factor value *Sig* of machine working speed is 0.303, which has no significant impact on the garlic loss rate index. Under the significance level of 0.05, the factor value *Sig* of digging shovel angle is 0.039, which has a significant impact on the garlic damage rate index. The factor value *Sig* of conveying speed of clamping belt is 0.756, which has no significant impact on the garlic damage rate index. The factor value *Sig* of machine working speed is 0.276, which has no significant impact on the garlic damage rate index. Under the significance level of 0.05, the factor value *Sig* of digging shovel angle is 0.012, which has a significant impact on the garlic impurity rate index. The factor value *Sig* of the conveying speed of clamping belt is 0.413, which has no significant impact on the garlic impurity rate index. The factor value *Sig* of machine working speed is 0.046, which has a significant impact on the garlic impurity rate index. Under the significance level of 0.05, the factor value *Sig* of digging angle, conveying speed of clamping belt, and conveying speed of clamping belt are all greater than 0.05, which have no significant effect on the success rate of garlic bulb separation.

The performance test of the prototype is conducted in accordance with the Chinese garlic harvesting national standards and related papers[42]. Three work strokes are detected, and the test distance of each working stroke is $20\,\mathrm{m}$ in the test area in accordance with the determined optimal harvest parameters. The garlic loss rate, garlic damage rate, garlic impurity content rate, and success rate of garlic bulb separation are calculated using Eqs. (19)–(22), respectively. The average value of the three working trips is calculated.

Table 6 ANOVA

Test indexes	Source of variance	Sum of squares	*df*	Mean square	*F*	*Sig*
Loss rate	Correction model	1.625a	6	0.271	77.869	0.013
	Intercept	93.058	2	93.058	26757.942	0
	A	1.298	2	0.649	186.655	0.005
	B	0.016	2	0.08	2.304	0.303
	C	0.311	2	0.155	44.649	0.022
	Error	0.007	2	0.003		
	Total correction	1.632	8			
Damage rate	Correction model	0.206a	6	0.034	9.160	0.102
	Intercept	13.814	1	13.814	3689.095	0
	A	0.184	2	0.092	24.537	0.039
	B	0.002	2	0.001	0.323	0.756
	C	0.020	2	0.010	2.620	0.276
	Error	0.007	2	0.004		
	Total correction	0.213	8			
Impurity rate	Correction model	1.446a	6	0.241	34.538	0.028
	Intercept	134.251	1	134.251	19239.771	0

	A	1.135	2	0.568	81.365	0.012
	B	0.020	2	0.010	1.420	0.413
	C	0.291	2	0.145	20.830	0.046
	Error	0.014	2	0.007		
	Total correction	1.460	8			
Success rate of bulb separation	Correction model	50.43a	6	8.406	1.165	0.530
	Intercept	72912.601	1	72912.601	10106.054	0
	A	17.178	2	8.589	1.191	0.457
	B	8.639	2	4.320	0.599	0.626
	C	24.616	2	12.308	1.706	0.370
	Error	14.629	2	7.215		
	Total correction	64.863	8			

The test results are shown in Table 7. The average loss rate of the self-propelled garlic combine harvester is 3.57%, meeting the requirements of $\leq 5\%$. The average garlic damage rate is 1.22%, meeting the requirements of $\leq 1.5\%$. The average impurity rate is 3.95%, meeting the requirements of $\leq 5\%$. The average success rate of garlic bulb separation is 89.34%, meeting the requirements of $\geq 85\%$.

Table 7. Prototype test results

Stroke	Total weight/kg	Loss weight/kg	Loss rate/%	Damage weight/kg	Damage rate/%	Impurity weight/kg	Impurity rate/%	Bulb separation weight/kg	Success rate of bulb separation/%
1	78.3	3.17	4.05	0.987	1.26	2.71	3.46	7.11	90.80
2	71.7	2.59	3.61	0.671	0.94	2.54	3.55	6.28	87.59
3	76.2	2.33	3.06	1.12	1.47	3.68	4.83	6.83	89.63
Mean	75.4	2.70	3.57	0.926	1.22	2.98	3.95	6.74	89.34

5. Conclusions

In this study, a multirow garlic combine harvester with stable performance and complete functions was proposed to serve as reference for the structural improvement and operation parameter optimization of garlic combine harvesters and promote the development of the garlic industry. A 3D model of garlic harvesting was presented, the combination of digital design and experimental research was adopted, and the key components of the garlic combine harvester, such as digging, clamping, and bulb transportation were theoretically analyzed and verified through field testing. The conclusions are summarized as follows:

1）The self-propelled garlic combine harvester designed on SolidWorks software can complete the excavation, clamping and transportation, bulb separation, and collection of six rows of garlic. The structural and operation parameters of the key components, such as digging, clamping, and garlic bulb conveying devices are determined through theoretical analysis and experiments, thereby improving the level of mechanized garlic harvesting.

2）A three-factor and three-level orthogonal field test is established. The optimal combination is determined as $A_2B_3C_3$, that is, digging shovel angle ($25°$), machine working speed ($0.5\,\mathrm{m/s}$), and conveying speed of clamping belt ($0.9\,\mathrm{m/s}$) in accordance with the principle that the damage and loss rates are the primary factors and by considering the impurity rate and success rate of bulb separation.

3）Under the optimal operation parameters, the self-propelled garlic combine harvester is used to harvest garlic, the garlic loss rate is 3.57%, the garlic injury rate is 1.22%, the garlic impurity rate is 3.95%, and the success rate of bulb separation is 89.34%, thereby meeting the requirements of relevant standards.

In this study, a 4S-6 garlic combine harvester with strong reliability and good versatility is proposed through theoretical analysis and experimental verification, thereby meeting the requirements of mechanized garlic harvesting in China. This study has a certain reference for the structural improvement design and operation parameter optimization of garlic combine harvesters. Field experiments and data collection are only conducted on Cangshan garlic. In future studies, field test data collection will be conducted on other varieties of garlic, and the prototype will be optimized to enhance its universality.

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