DESIGN AND EXPERIMENT OF A CLAW-CHAIN GARLIC CLOVE METERING DEVICE
/
爪链式大蒜播种机取种装置设计与试验

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ABSTRACT
To solve the problems of multiple picking and missed picking in garlic planter, single-seed picking has become a critical technology that urgently needs improvement. In response, a claw-chain mechanism for single garlic seed picking was developed. Based on theoretical analysis of the clove picking claw's motion, the feasible ranges of claw speed (v), minimum clove-holding length (S_2), and sprocket inclination angle (θ) were determined. Using the EDEM simulation platform, the single-seed picking rate and missed picking rate under different parameter combinations were obtained. A Box–Behnken central composite design was used to conduct a three-factor, three-level quadratic regression experiment involving claw speed, minimum clove-holding length, and sprocket inclination angle. Design-Expert software was employed to establish a response surface model and optimize the key parameters affecting the single-seed picking rate. The optimal parameter combination was a claw speed of 0.05 m/s, a minimum clove-holding length of 32.4 mm, and a sprocket inclination angle of 5.6°. Under these conditions, the single-seed picking rate reached 91.7%, and the missed picking rate was 4.4%, meeting the technical requirements for garlic single-seed planting.

摘要
为解决大蒜种植过程中存在多取漏取问题，单粒取种成为了亟需解决的关键技术。针对此问题，设计了一种爪链式单粒取种装置。通过对取种爪运动状态进行理论分析，确定取种爪速度（v）、取种爪最小容种长度（S_2）及两链轮倾角（θ）的取值范围。利用 EDEM 仿真平台得到单粒取种率、漏取率的相应指标值。运用 Box-Benhnken 中心组合试验方法对取种爪速度、取种爪最小容种长度、两链轮倾角进行三因素三水平二次回归试验设计，采用 Design-expert 软件建立响应面数学模型，对影响单粒取种率的关键参数进行了综合优化，得到最优工作参数组合为取种爪速度为 0.05m/s，取种爪最小容种长度为 32.4mm，两链轮倾角为 5.6°，在此条件下进行试验得到单粒取种率为91.7%，漏取为4.4%，满足大蒜种植的单粒取种率要求。

INTRODUCTION
Garlic is a major economic crop with extensive applications in culinary, medicinal, and health-related fields. China has long maintained the largest garlic cultivation area worldwide, stabilized at approximately 11 million mu (≈ 733.000 ha), mainly in Shandong, Henan, and Jiangsu provinces *(Yang et al., 2019; Qin et al., 2019; Zhang et al., 2022)*. Annual exports reach approximately 2.8 million tons, covering over 160 countries and regions. With ongoing agricultural modernization, garlic sowing now demands greater efficiency and precision. However, sowing in China still relies heavily on manual labor, leading to high labor intensity, low efficiency, and issues such as uneven distribution and poor clove placement *(Chen et al., 2021; Wei et al., 2022)*. These challenges raise production costs and reduce crop yield. Garlic planters can enhance sowing quality and efficiency, reduce labor, and support large-scale farming. Yet, current machines often suffer from multiple pickups and missed cloves, compromising sowing performance. Therefore, developing a high-efficiency, high-precision single-seed metering device is of great practical significance and urgent necessity *(Zhang et al., 2022; Furuhata et al., 2015; Manjunatha et al., 2014)*.

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Currently, common garlic clove picking methods include socket type, spoon-clip type, and claw-chain type *(Xie et al., 2022; Xue et al., 2024; Suryakant et al., 2024; Smita et al., 2019)*. The socket type utilizes holes on a rotating disc to pick cloves but suffers from low efficiency. The spoon-clip type uses a clove plate to drive the picking spoon, but it often damages cloves. The claw-chain type uses claws installed on a chain to achieve continuous picking and has a relatively simple structure *(Im et al., 2023; Kim et al., 2020; Lee et al., 2023; Gyoung et al., 2018)*. However, due to the large variation in garlic clove shape and size, these methods still frequently result in missed or multiple clove placement, failing to meet agronomic requirements, and a significant gap remains in achieving high-efficiency and high-precision single-seed picking. Therefore, it is necessary to optimize and improve the structural parameters of the picking device to increase accuracy and operation quality *(Yang et al., 2015; Lai et al., 2022; Elwakeel et al., 2025; Marey et al., 2011)*.

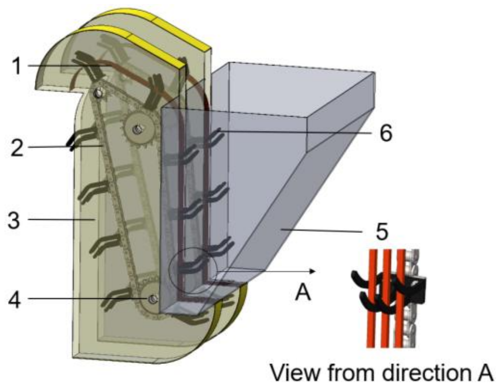
To address the low single-seed picking rate of existing garlic clove picking devices, this study investigates the structural design and working principle of the picking mechanism. A simulation model of the picking process is developed using EDEM software to analyze the interaction between the device and garlic cloves. Key factors influencing the single-seed picking rate and seed-missing rate are identified. A Box–Behnken experimental design is employed to conduct multi-factor optimization trials, from which the optimal parameter combination is determined. Finally, field experiments are performed to validate the accuracy and reliability of the simulation results. The findings provide a theoretical foundation and technical reference for optimizing the structure and enhancing the performance of single-seed picking devices in garlic planters.

MATERIALS AND METHODS

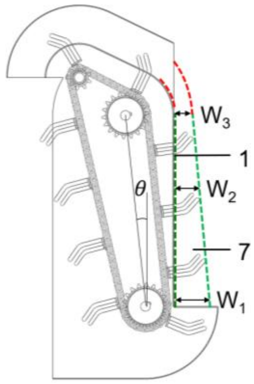
Structure of the Clove Metering Device

The claw-chain clove picking device is shown in Fig. 1. It consists of clove picking claws, chain, sprockets, clove box, guide plate, and outer shell. The claws are fixed on the chain. The sprockets rotate to drive the claws on the chain.

As shown in Fig. 1(b), the two sprockets are installed at an angle. The claws and the guide plate form a clove holding space. As the claws move upward, the internal clove holding space gradually decreases, following the trend shown by the green dashed line. The space relationship is W1 > W2 > W3. When the claw reaches the point where the green slant line meets the red arc, the clove holding space inside the claw remains unchanged.



(a) Clove metering device



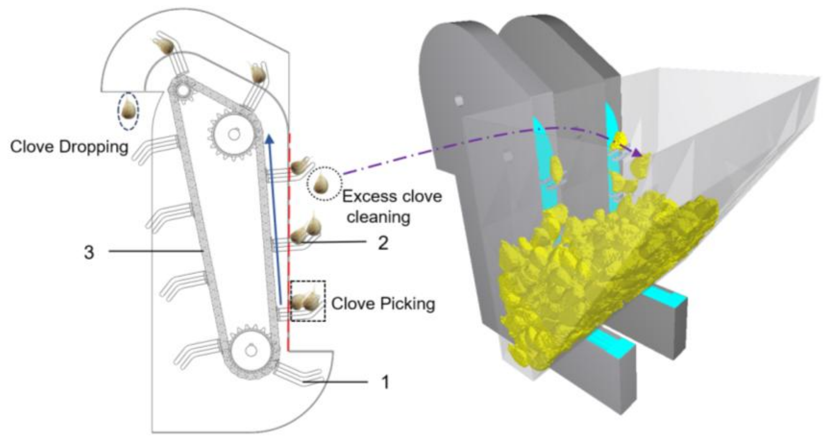
(b) Structure of the clove metering mechanism

Fig. 1 - Structural schematic diagram of the clove picking device

1. Guide plate; 2. Clove picking chain; 3. Housing; 4. Clove picking sprocket; 5. Clove box; 6. Clove picking claw; 7. Clove holding chamber.

Working Principle of the Clove Metering Device

As shown in Fig. 2, the clove picking process includes three stages: picking, cleaning, and dropping. First, garlic cloves are added into the clove box. The chain drives the claws to move upward along the guide plate from the bottom of the box, grabbing several cloves during the ascent. As the claws rise, the internal holding space W gradually decreases. When the clove center of gravity exceeds the claw edge, excess cloves fall off by gravity, completing the cleaning. Since the space reduces to W_3 and remains unchanged, only one clove stays in the claw. Finally, the claw completes clove dropping at the end of its stroke. Throughout the motion, the claw maintains a tilt angle with the horizontal, promoting clove fallback and reducing missed picking.



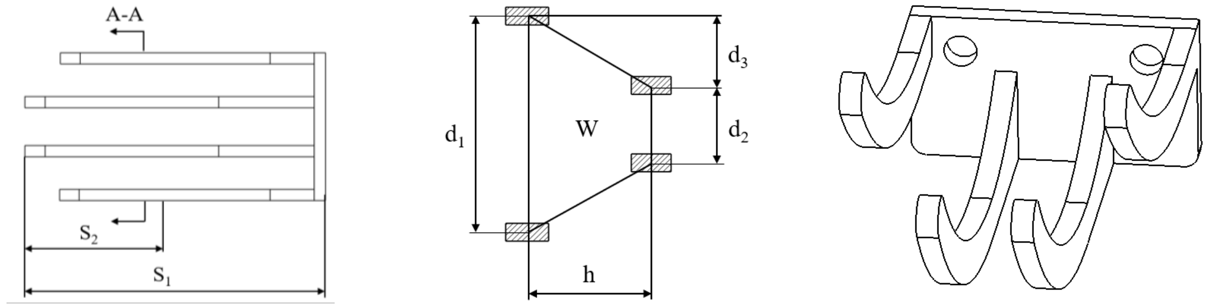
(a) 2D schematic of the clove-picking device (b) 3D diagram of the clove-picking process

Fig. 2 - Working Principle Diagram of the Clove Picking Device

1. Clove picking sprocket; 2. Garlic clove; 3. Clove picking chain; The blue arrow indicates the movement direction of the clove-picking claw; The red dashed line represents the guide plate; The purple dashed line illustrates the excess-clove cleaning process.

Design of Key Components of the Clove Picking Claw

The clove picking claw is the core component for achieving single-seed picking. Its geometry directly affects the performance of the clove picking device. The design must meet several key conditions: firstly, there must be spacing between claws to prevent garlic cloves from falling and to fit with the guide plate; secondly, the internal space must hold at least one garlic clove; thirdly, the shape should closely match the garlic clove to keep it stable inside the claw. To meet these requirements, a four-claw clove picking claw was designed, as shown in Fig. 3. The claws are installed alternately at two high and two low positions.



(a) Top view (b) Section view A-A (c) Axonometric View

Fig. 3 Structure of the clove picking claw

S1 represents the length of the clove picking claw; S2 is the minimum clove holding length; h denotes the height of the claw; d1 and d2 refer to the spacing between the upper and lower clove picking claws respectively; d3 is the spacing between the upper and lower claws; W indicates the cross-sectional area of the clove picking claw.

To ensure a high single-seed picking rate, the claw size must be reasonable. The minimum clove holding length S_2 mainly determines the minimum clove space W_3. Garlic cloves lie horizontally, vertically, inclined, or upright in the clove box. The design is based on the common horizontal position. The claw width should be larger than the maximum clove length and less than twice the minimum clove width. The claw height should be more than half the maximum clove width and less than half the minimum clove length. The claw length should be between twice the maximum clove width and twice the minimum clove length. In the cleaning stage, the minimum clove holding length must be greater than the maximum clove length and less than twice the minimum clove width. Also, the claw's minimum clove holding length should be less than the minimum clove width.

$$\begin{cases} L_{max} \le \mathrm{d}_1 \le 2B_{min} \\ \dfrac{B_{max}}{2} \le h \le \dfrac{L_{min}}{2} \\ 2B_{max} \le S_1 \le 2L_{min} \\ L_{min} \le S_2 \le 2B_{min} \end{cases} \tag{1}$$

where: L_{max} is the Maximum length of garlic; L_{min} is the Minimum length of garlic; B_{max} is the Maximum width of garlic; B_{min} is the Minimum width of garlic.

According to Equation (1), the clove picking claw width is set at the midpoint of the parameter range, 33.3 mm. The claw height is chosen as the median value, 13.8 mm. The maximum clove holding space S_1 ranges from 53 mm to 57.8 mm, and the minimum clove holding space S_2 ranges from 28.64 mm to 34 mm.

Maximum Inclination Angle Between the Two Sprockets

During the cleaning stage, garlic cloves are confined within a narrowing space between the clove picking claw and the guide plate. This causes cloves to contact or be squeezed by the guide plate. If the tilt angle θ is set improperly, the resistance on the cloves during lifting will increase, which may cause clove damage. To prevent this, the compression force on the cloves during the entire lifting process must be less than their minimum crushing force. The force analysis is illustrated in Fig. 4.

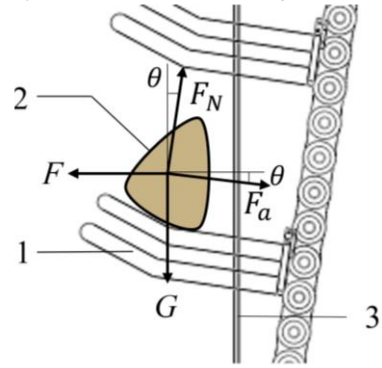


Fig. 4 - Force analysis of garlic cloves during cleaning process
1. Clove picking claw; 2. Garlic clove; 3. Guide plate

$$\begin{cases} F = F_a \cos\theta + F_N \sin\theta \\ G + F_a \sin\theta = F_N \cos\theta \\ F_a = \mu F_N \end{cases} \quad (2)$$

where: F is the thrust, (N); F_N is the support force, (N); F_a is the friction force, (N); G is the Weight of the garlic clove, (N); μ is the friction coefficient between the clove-picking claw and garlic clove; θ is the Inclination Angle Between the Two Sprockets.

From Equation (2), we obtain:

$$\theta = \arctan\left(\frac{F - \mu G}{\mu F - G}\right) \quad (3)$$

The clove picking claw is made of metal, and the coefficient of friction between the garlic clove and the metal material is 0.33. Moreover, the thrust force F must be less than the minimum destructive force of the garlic clove. Substituting into equation (3) yields θ is less than or equal to 18.22°.

Speed of the Clove Picking Claw

When the clove picking claw moves to the circular section of its path, the centrifugal force on the garlic cloves inside reaches its maximum. If this force is too large, the cloves may fly out of the claw, affecting picking performance. Therefore, a force analysis is needed to determine the claw's maximum speed and prevent clove ejection caused by excessive centrifugal force. The force analysis diagram is shown in Fig. 5.

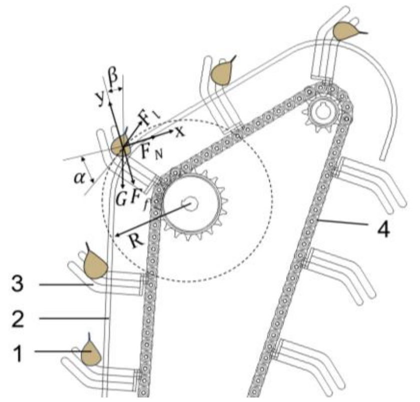


Fig. 5 - Force Analysis Diagram of Garlic Clove
1. Garlic clove; 2. Guide plate; 3. Clove picking claw; 4. Clove picking chain;

Taking the center of gravity of the garlic clove as the origin, the direction opposite to friction force as the y-axis, and the direction of support force as the x-axis, a force analysis of the clove inside the claw is conducted. The equilibrium equation is shown in Equation (4).

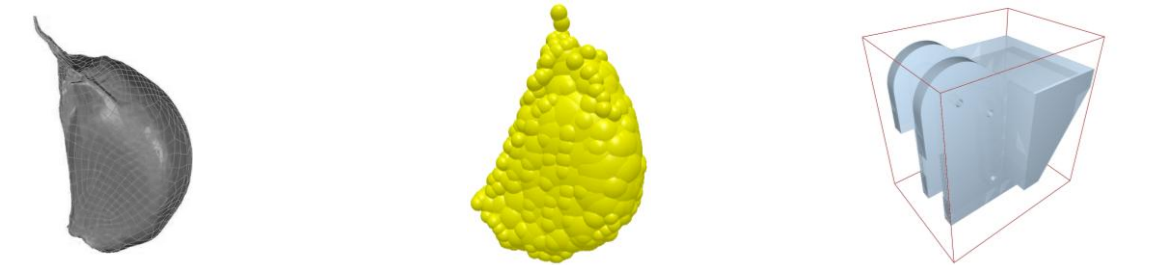
$$\begin{cases} F_l \cos\alpha + F_N = G\sin\beta \\ G\cos\beta + F_f = F_l \sin\alpha \\ F_f = \mu F_N \\ F_{l=} \dfrac{mv^2}{R\times 10^{-3}} \end{cases} \tag{4}$$

where: F_l is the Centrifugal force on the garlic clove, (N); G is the Weight of the garlic clove, (N); F_N is the Support force from the clove picking claw, (N); F_f is the Friction force from the clove picking claw, (N); α is the Angle between centrifugal force and the x-axis, (°); β is the Angle between gravity and the y-axis, (°); v is the Movement speed of the clove picking claw, (m/s); R is the distance between the sprocket center and the center of mass of the garlic clove.

According to equation (4), garlic cloves in the clove spoon will slide out along the tangential direction, resulting in clove leakage, when the component of gravity is less than the centrifugal force. Through calculation, the critical velocity *v* is less than or equal to 1.274 m/s.

Clove Picking Process EDEM Virtual Simulation and Analysis

Due to the irregular shape of garlic, 3D scanning technology was used to obtain its model. The model was then optimized using Geomagic Wrap to refine the garlic clove contour, as shown in Fig. 6. The model was saved in STL format. Finally, the 3D models of the clove picking device and garlic clove were imported into EDEM.



(a) Garlic scanning image (b) Garlic EDEM model (c) Clove picking device EDEM model

Fig. 6 - Simulation Models of Garlic Particles and Clove Picking Device

Model Parameters

Based on the materials used for the clove picking device, the clove picking claw, clove box, and clove guide plate are all made of medium carbon steel, Grade 45 (Chinese standard). The main simulation parameters are shown in Table 1.

Table 1

Garlic Clove Picking Simulation Parameters

Parameters	45 Steel	Garlic Clove
Density(kg/m³)	7850	1033
Poisson's Ratio	0.26	0.23
Elastic Modulus (MPa)	2.06×10^5	26.27
Coefficient of Restitution (with particles)	0.511	0.487
Static Friction Coefficient (with particles)	0.473	0.503
Dynamic Friction Coefficient (with particles)	0.117	0.102

A total mass of 10 kg of garlic cloves was generated per group in the particle factory at a rate of 3 kg/s. The cloves were initialized with a downward velocity of 2 m/s and zero angular velocity. To reflect realistic geometric variability, clove orientations were randomized, and a random distribution was used for generation. The size distribution coefficient was set between 0.95 and 1.08 times the measured clove dimensions to simulate actual screening effects.

Simulation Analysis

As shown in Fig. 7, to facilitate performance statistics of the clove picking device, a Grid Bin Group was set at the end of the picking area using EDEM post-processing to monitor cloves picked by the claw. Based on the results, and referring to GB/T 6973-2005 “Test Methods for Single-Seed (Precision) Seeders” and NY/T 503-2015 “Operation Quality of Single-Seed (Precision) Seeders”, the single picking rate Y_1, multiple picking rate Y_2, and missed picking rate Y_3 are calculated by the formulas in Equation (5).

$$\begin{cases} Y_1 = \dfrac{n_1}{N} \times 100\% \\ Y_2 = \dfrac{n_2}{N} \times 100\% \\ Y_3 = \dfrac{n_3}{N} \times 100\% \end{cases} \tag{5}$$

where: n_1 is the number of single garlic cloves picked; n_2 is the number of two or more cloves picked together; n_3 is the number of missed picks; N is the total number of picking attempts.

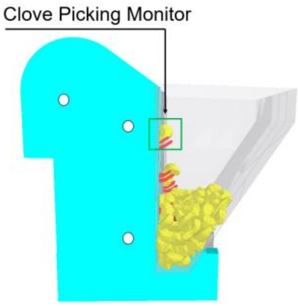


Fig. 7 - Clove Filling Monitor

RESULTS

Effect of Clove-Holding Length of Picking Claw on Filling Performance

Under the conditions of a picking claw speed of 0.05 m/s and a sprocket inclination angle of 7°, the picking claw length (S_1) was set to 53, 54, 55, 56, and 57 mm, and the minimum clove-holding length (S_2) was set to 29, 30, 31, 32, 33, and 34 mm. For each parameter combination, 50 picking operations were conducted, and the test was repeated five times, with the average value taken as the final result. The results, shown in Fig. 8, indicate that when S_1 is kept constant, a smaller S_2 (29~30 mm) results in insufficient clove-holding space after the cleaning stage, causing larger garlic cloves to be removed during cleaning and thus increasing the missed-picking rate. When S_2 is increased to 31–33 mm, the clove-holding space after cleaning is sufficient to accommodate garlic cloves of different sizes, leading to a higher single-seed picking rate. However, when S_2 exceeds 33 mm, the excessive clove-holding space after cleaning tends to retain two smaller cloves simultaneously, increasing the multiple-picking rate and reducing the single-seed picking rate. This demonstrates that S_2 is a key factor affecting clove-filling performance. In contrast, variations in S_1 have little influence on the single-seed picking rate when S_2 is fixed. Therefore, an S_1 of 53 mm within the feasible range and an S_2 of 31–33 mm can achieve optimal single-seed picking performance.

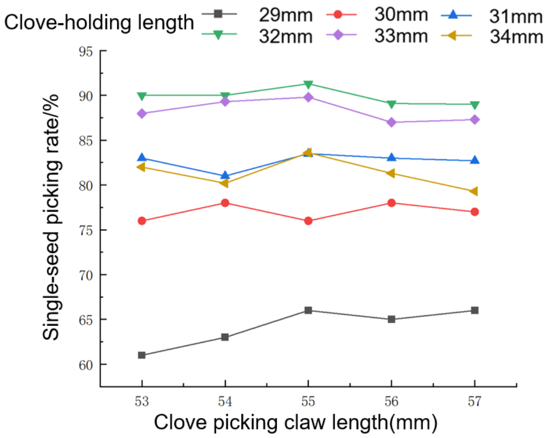


Fig. 8 - Effect of Clove Claw Cavity Length on Clove Filling Performance

Effect of dual sprocket tilt angle on clove filling performance.

The picking claw speed was set to 0.05 m/s, with a minimum clove-holding length of 32 mm. Simulations were run at sprocket angles of 4°, 6°, 8°, and 10°, with 50 picks per trial, repeated five times, resulting in a total of 250 picks for each angle. Statistical analysis was conducted using one-way ANOVA, and differences between sprocket angles were found to be statistically significant ($p < 0.05$). Results are shown in Fig. 9. At small angles, clove space changes little, causing poor cleaning, high multiple picking, and low single-seed picking rate. As the angle increases, cleaning improves and multiple picking decreases. When the angle exceeds 8°, the clove space is too large, causing cloves to be fully cleared and miss rate to rise. Overall, the best filling performance occurs between 5° and 7°, showing sprocket angle affects filling performance.

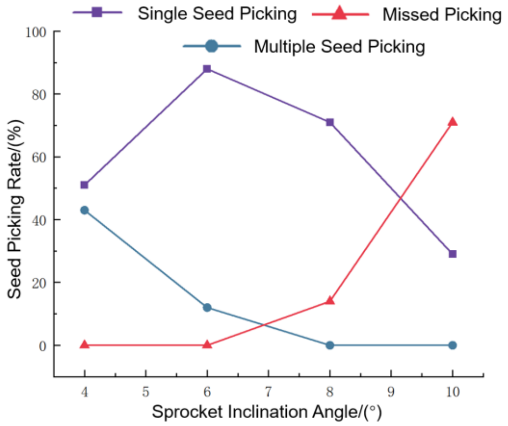
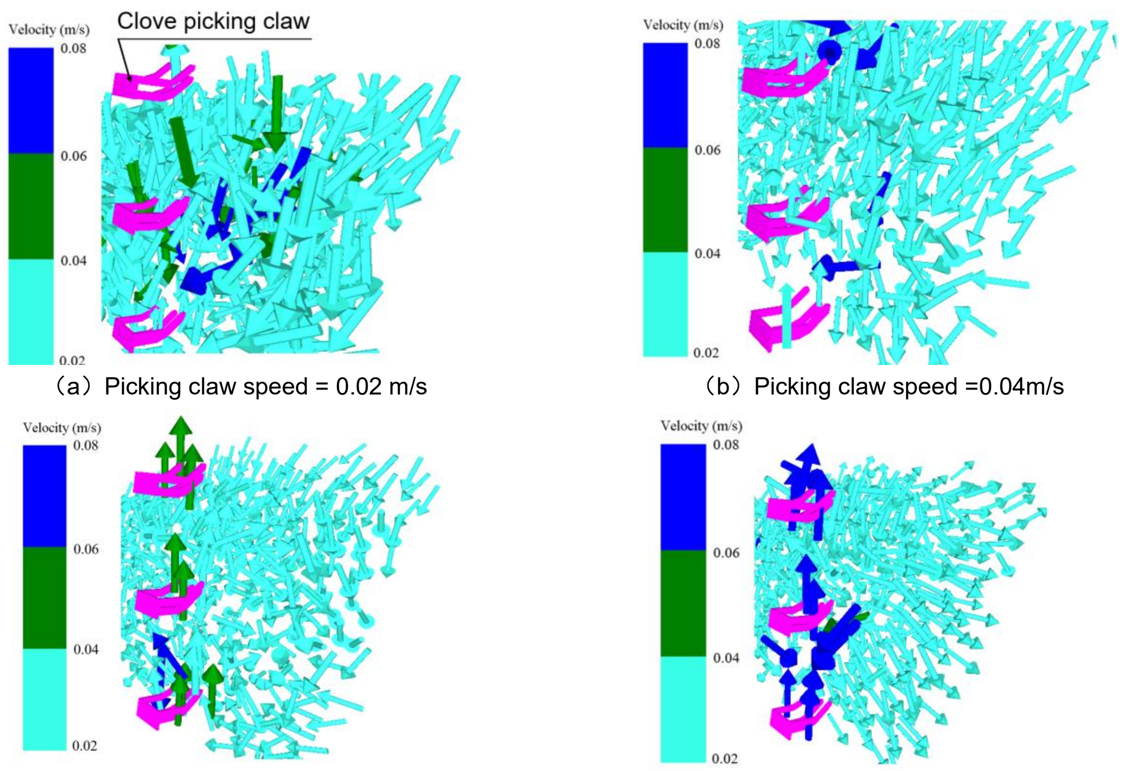


Fig. 9 - Effect of Sprocket Inclination Angle on Filling Performance

Effect of picking claw speed on clove filling performance

With the minimum clove-holding length of the picking claw set to 32 mm and the sprocket angle at 7°, simulation tests were conducted at claw speeds of 0.02, 0.04, 0.06, and 0.08 m/s. Each speed condition involved 50 picking cycles, repeated five times, and the average was taken as the final result. Fig. 11 shows the garlic clove velocity vector diagrams at different speeds, with the arrow indicating the direction of clove movement.



（a）Picking claw speed = 0.02 m/s （b）Picking claw speed =0.04m/s

（c）Picking claw speed =0.06m/s （d）Picking claw speed =0.08m/s

Fig. 10 - Velocity Vector Diagram of the Clove Picking Process

Different colored vector arrows indicate garlic clove velocity direction and magnitude; arrows in the claw show claw velocity, others show clove velocity in the clove box.

When the picking claw moves slowly (Fig. 10a, 10b), its speed is less than or equal to the garlic clove refill speed, resulting in longer contact time and fewer collisions, which leads to a higher multiple picking rate. As speed increases (Fig. 10c, 10d), the claw speed exceeds the refill speed, contact time shortens, collisions increase, and the claw has less time to pick cloves, causing a lower multiple picking rate and higher miss rate. Fig. 11 shows the effect of speed on filling performance. Considering both performance and efficiency, the optimal claw speed is 0.05~0.07 m/s.

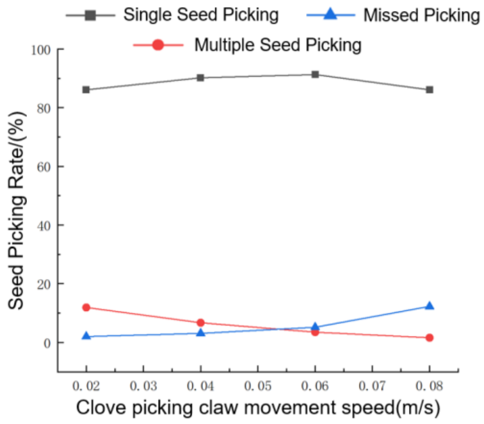


Fig. 11 - Effect of Clove Picking Claw Speed on Filling Performance

Analysis of three-factor, three-level orthogonal experiment

To find the optimal values of the three factors, the Box-Behnken design was used for testing. Based on single-factor tests, the picking claw speed range was set to 0.05~0.07 m/s, minimum clove-holding length to 31~33 mm, and sprocket angle to 5°~7°. The factors and levels for the clove picking device are shown in Table 2, where X_1, X_2 and X_3 are the factor code values of the Picking Claw Speed, Minimum Clove-Holding Length of Picking Claw and Angle Between Two Sprockets.

Table 2

Experimental Factors and Levels

Level	X_1 (m/s)	X_2 (mm)	X_3 (°)
-1	0.05	31	5
0	0.06	32	6
1	0.07	33	7

Experimental Results

Based on the Box-Behnken design, a three-factor, three-level experiment was conducted for the clove picking device. The experience plan and response values are shown in Table 3, where X_1, X_2, and X_3 represent the coded values of each factor.

Table 3

Experimental Design and Results

No.	Influencing Factors			Response Values	
	X_1/(m/s)	X_2/(mm)	X_3/(°)	Y_1/%	Y_2/%
1	-1	-1	0	75.30	12.90
2	1	-1	0	86.30	7.70
3	-1	1	0	78.10	11.80
4	1	1	0	90.10	5.40
5	-1	0	-1	75.80	13.40
6	1	0	-1	85.80	7.80
7	-1	0	1	75.80	13.40
8	1	0	1	92.10	5.70
9	0	-1	-1	80.20	10.90
10	0	1	-1	85.90	8.10
11	0	-1	1	90.20	6.40
12	0	1	1	91.00	5.80
13	0	0	0	87.90	6.90
14	0	0	0	85.70	8.80
15	0	0	0	85.80	8.80
16	0	0	0	85.70	8.80
17	0	0	0	85.70	8.80

Regression Equation and Significance Test

Based on Table 3, a multiple regression fitting analysis was performed using Design-Expert software to establish a quadratic polynomial response surface model of the single-seed picking rate with respect to picking claw speed, minimum clove-holding length, and the angle of the two sprockets, as shown in equations (6) and (7), These are dimensionless coded values and response variables.

$$Y_1 = 91.62 - 1.16x_1 + 6.98x_2 + 0.7875x_3 + 0.85x_1x_2 + 0.825x_1x_3 + 0.25x_2x_3 - 4.72x_1^2 - 8.45x_2^2 - 3.42x_3^2 \quad (6)$$

$$Y_2 = 7.24 + 2.26x_1 - 2.98x_2 + 2.83x_3 + 0.9025x_1x_2 - 0.415x_1x_3 + 0.6825x_2x_3 + 0.13x_1^2 + 4.1x_2^2 + 1.56x_3^2 \quad (7)$$

According to the analysis of variance for the regression equation shown in Table 4, the models for the single seed picking rate(Y_1) and missing picking rate(Y_2) are both highly significant (p<0.01), indicating that the regression models for single seed picking rate and missing picking rate are highly significant. The lack-of-fit tests for both models show p-values greater than 0.05, suggesting the models fit the data well. Based on the p-values, it can be concluded that in the single seed picking rate model, the regression terms X_2, X_1^2, X_2^2 and X_3^2 have extremely significant effects on the model, and the regression terms X_1, X_3, X_1X_2, X_1X_3 have significant effects. The order of influence of factors on the single seed picking rate is: minimum clove-holding length of the picking claw, picking claw speed, and the angle of the two sprockets. In the missing picking rate model, X_1, X_2, X_3 and X_2^2 have extremely significant effects on the model, while X_1X_2 and X_3^2 have significant effects. The order of influence of factors on the missing picking rate is: minimum clove-holding length of the picking claw, angle of the two sprockets, and picking claw speed.

By removing the insignificant influencing factors, the regression equations are optimized as shown in Equations (8) and (9), These are dimensionless coded values and response variables.

$$Y_1 = 91.62 - 1.16x_1 + 6.98x_2 + 0.7875x_3 + 0.85x_1x_2 + 0.825x_1x_3 - 4.72x_1^2 - 8.45x_2^2 - 3.42x_3^2 \quad (8)$$

$$Y_2 = 7.24 + 2.26x_1 - 2.98x_2 + 2.83x_3 + 0.9025x_1x_2 + 4.1x_2^2 + 1.56x_3^2 \quad (9)$$

Table 4

Variance Analysis of Regression Equations

Source	Single seed picking rate				Missed seed rate			
	Sum of squares	Degrees of Freedom	F-Value	P-Value	Sum of squares	Degrees of Freedom	F-Value	P-Value
Model	897.12	9	231.39	<0.0001***	266.67	9	54.63	<0.0001***
X_1	10.81	1	25.10	0.0015***	40.91	1	75.42	<0.0001***
X_2	389.21	1	903.48	<0.0001***	70.92	1	130.77	<0.0001***
X_3	4.96	1	11.52	0.0115***	64.01	1	118.03	<0.0001***
X_1X_2	2.89	1	6.71	0.0359**	3.26	1	6.01	0.0440**
X_1X_3	2.72	1	6.32	0.0402**	0.6889	1	1.27	0.2969
X_2X_3	0.2500	1	0.5803	0.4711	1.86	1	3.44	0.1062
X_1^2	93.90	1	217.98	<0.0001***	0.0712	1	0.1312	0.7279
X_2^2	300.46	1	697.48	<0.0001***	70.87	1	130.66	<0.0001***
X_3^2	49.32	1	114.49	<0.0001***	10.25	1	18.89	0.0034**
Residual	3.02	7			3.80	7		
Lack of Fit	1.03	3	0.6891	0.6044	1.45	3	0.8205	0.5465
Error	1.99	4			2.35	4		
Sum total	900.14	16			270.47	16		
	R=0.9966 ;Adjusted R^2=0.9923; Adeq Precision=44.0164				R=0.9860 ;Adjusted R^2=0.9670 ; Adeq Precision=25.8506			

Note: *** indicates $P < 0.001$ (extremely significant), ** indicates $P < 0.01$ (highly significant).

Effect of Interaction Terms Among Factors on the Single Seed Picking Rate

Fig. 12(a) shows the effect of interaction between clove picking claw speed and minimum clove-holding length on the single seed picking rate when the sprocket angle is at the medium level. As the claw speed increases, the single seed picking rate increases first and then decreases. Fig. 12(b) shows the effect of claw speed and sprocket angle when the clove-holding length is at its medium level. When the claw speed is fixed, the picking rate gradually increases with increasing angle. When the claw speed increases to 0.06 m/s, the upward trend due to the larger angle weakens.

Fig. 12(c) shows the interaction between clove-holding length and sprocket angle when the claw speed is at its medium level. When the sprocket angle is fixed, the picking rate first increases and then decreases as the clove-holding length increases.

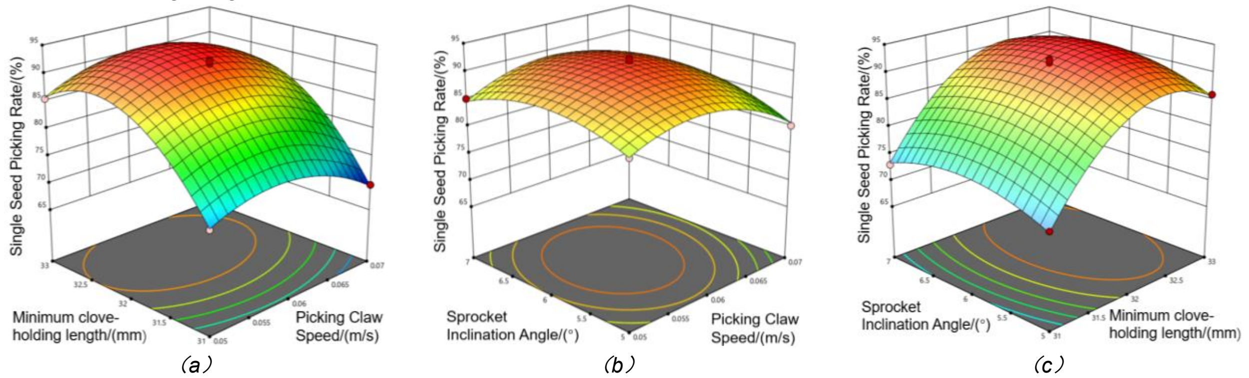


Fig. 12 - Effects of Picking Claw Speed, Minimum Clove-Holding Length, and Sprocket Inclination Angle on Single-Seed Picking Rate

(a)$Y_1(X_1,X_2,6)$;(b)$Y_1(X_1,32,X_3)$;(c)$Y_1(0.06,X_2,X_3)$

The interaction effects of factors on missed picking rate

Fig. 13(a) shows the interaction effect of picking claw speed and minimum clove-holding length on the missed picking rate when the sprocket angle is at its medium level. When the minimum clove-holding length is fixed, the missed picking rate increases with claw speed. When the claw speed is fixed, the missed picking rate decreases as the minimum clove-holding length increases. Fig. 13(b) shows the interaction between claw speed and sprocket angle on the missed picking rate when the minimum clove-holding length is at its medium level. When the claw speed is fixed, the missed picking rate increases with sprocket angle. When the sprocket angle is fixed, the missed picking rate also increases with claw speed. Fig. 13(c) shows the interaction between minimum clove-holding length and sprocket angle on the missed picking rate when the claw speed is at its medium level. When the sprocket angle is fixed, the missed picking rate decreases as the minimum clove-holding length increases. When the minimum clove-holding length is fixed, the missed picking rate increases with sprocket angle.

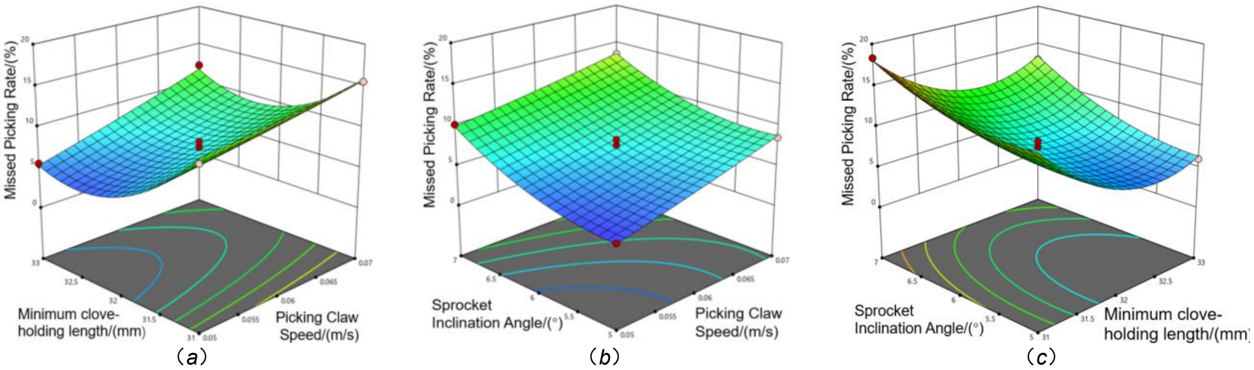


Fig. 13 - Effects of Picking Claw Speed, Minimum Clove-Holding Length, and Sprocket Inclination Angle on Missed Picking Rate

(a)$Y_2(X_1,X_2,6)$;(b)$Y_2(X_1,32,X_3)$;(c)$Y_2(0.06,X_2,X_3)$

Parameter Optimization

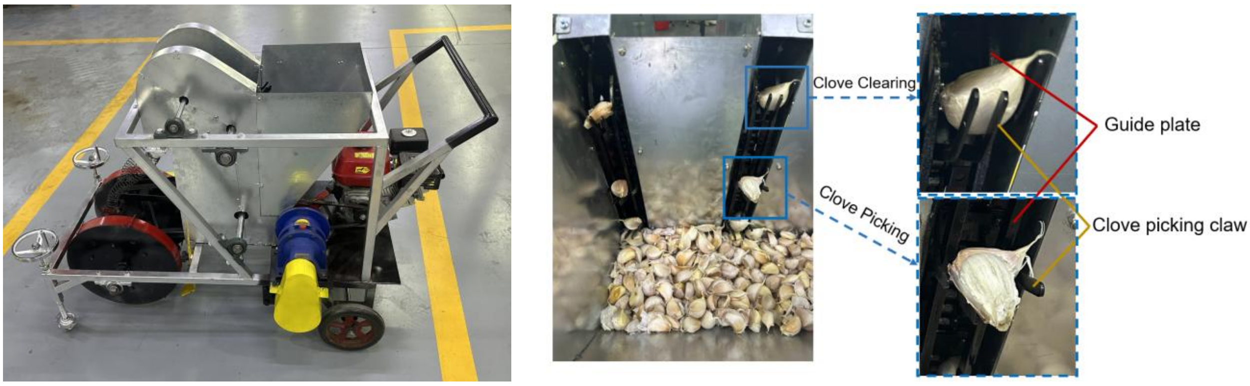
Use Design Expert software to optimize single seed picking rate and missed picking rate. The optimization goal is shown in equation (10):

$$\begin{cases} maxY_1\left(x_1,x_2,x_3\right) \\ minY_2\left(x_1,x_2,x_3\right) \\ 0.05m/s \le x_1 \le 0.07m/s \\ 31\text{mm} \le x_2 \le 33\text{mm} \\ 5° \le x_3 \le 7° \\ 0 < Y_i < 1, i = 1,2,3 \end{cases} \tag{10}$$

From equation (10), the optimal clove picking claw speed is 0.052 m/s, the optimal minimum clove-holding length is 32.413 mm, and the optimal angle between the two sprockets is 5.597°. At this point, the single seed picking rate is 92.342%, and the missed picking rate is 4.2%.

Experimental Process and Results

To verify the consistency between the single-seed picking rate of the clove picking device and the simulation results, and to evaluate the actual operational performance, the experimental procedure is shown in Fig 14. The test subject was Cangshan garlic, with clove sizes consistent with those used in the simulation. The experiment was conducted in a test field at Qingdao Agricultural University, where the plot surface was flat and the soil type was loam. The experiment was carried out under conditions of a picking claw speed of 0.05 m/s, a minimum clove-holding length of 32.4 mm, and a sprocket inclination angle of 5.6°. Five repeated trials were conducted, each involving 200 picking actions, during which the number of single seeds picked and the number of missed picks were recorded.



（a）Overall view of the garlic planter （b）Experiment process

Fig. 14 - Overall view and experimental process

Table 5

Experimental Results

N0.	Number of single seed Picks/Time	Number of Missed Picks/Time	Single Seed Picking Rate/(%)	Missed Picking Rate/(%)
1	184	9	92	4.5
2	185	8	92.5	4
3	183	9	91.5	4.5
4	180	9	90	4.5
5	185	9	92.5	4.5

The experimental results are shown in Table 5. The average single-seed picking rate measured in the tests was 91.7%, with a standard deviation of 1.04%, while the average missed picking rate was 4.4%, with a standard deviation of 0.22%. The average relative errors between the actual test values and the optimized values for the single-seed picking rate and missed picking rate were 0.70% and 4.8%, respectively, with maximum relative errors of 1.8% and 7.14%. These results indicate that the model is feasible and further validate the accuracy and reliability of the simulation data.

CONCLUSIONS

(1) To address the low single seed picking rate of garlic planter, a claw-chain type single seed picking device was designed. During clove picking process, the device initially picks multiple garlic cloves. As the picking claw rises, its internal volume decreases until only one clove is held.

(2) Based on garlic's geometric features, the structure and size of the picking claw were designed: claw width is set to 33.3 mm, height 13.8 mm, maximum clove holding length between 53 mm and 57.8 mm, and minimum clove holding length between 28.64 mm and 34 mm. The claw's moving speed and the angle between the two sprockets were also calculated theoretically.

(3) Single-factor simulation tests were performed using EDEM software, identifying picking claw speed, minimum clove holding length, and sprocket angle as key factors affecting the single seed picking rate. The preliminary ranges were: claw speed 0.4 m/s to 0.6 m/s, minimum clove holding length 31 mm to 33 mm, sprocket angle 5° to 7°. Then, a three-factor three-level orthogonal test was conducted. Using Design Expert software, the optimal parameters were found: claw speed 0.052 m/s, minimum clove holding length 32.413 mm, sprocket angle 5.597°.

(4) Field tests verified the optimal parameter combination. At claw speed 0.05 m/s, minimum clove holding length 32.4 mm, and sprocket angle 5.6°, the single seed picking rate reached 91.7%, and the missed picking rate was 4.4%, close to the simulation results. This proves the device performs well and meets the agronomic requirements for garlic clove picking.

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