DESIGN AND EXPERIMENT OF A SPOON-CLAMP TYPE GARLIC SEED METERING DEVICE
/
勺夹式大蒜排种器设计与试验

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ABSTRACT
To reduce miss-seeding and improve the stability of single-clove pickup in garlic seed metering devices, a spoon-clamp type garlic seed metering device was designed. The proposed mechanism combined spoon-type seed pickup with spring-assisted clamping, so garlic cloves with irregular surfaces could be picked up, carried, cleaned, and discharged more stably. Based on the geometric characteristics of three garlic varieties, the key parameters of the seed plate, seed pickup spoon, and opening-closing mechanism were determined by theoretical analysis. A three-dimensional model of the seed metering device and garlic-clove models were established using the discrete element method. Single-factor simulations were then performed to analyze the effects of seed plate speed and seed pickup spoon diameter on the qualified seeding index, reseeding index, and miss-seeding index. The suitable simulated operating range was 1–7 r/min for seed plate speed and 25–35 mm for seed pickup spoon diameter. Bench tests showed that the suitable parameter combination for "Acheng Purple Garlic" and "Nong'an Purple Garlic" was a seed plate speed of 4 r/min and a seed pickup spoon diameter of 32 mm. For "Zhaozhou White Garlic", the suitable combination was 5.5 r/min and 28 mm. These results showed that the spoon-clamp mechanism was feasible for improving single-clove garlic metering stability under controlled bench-test conditions.

摘要
针对大蒜蒜瓣形状不规则导致排种器漏播率高、单粒取种稳定性不足等问题，本文设计了一种勺夹式大蒜排种器。该装置将取种勺取种与弹簧辅助夹持相结合，使蒜瓣在取种、携种、清种和投种过程中保持较稳定的约束状态。基于三种大蒜蒜瓣的几何特性，通过理论分析确定排种盘、取种勺及开合机构等关键参数。采用离散元法建立排种器三维模型和蒜瓣颗粒模型，并通过单因素仿真分析排种盘转速和取种勺直径对合格指数、重播指数和漏播指数的影响。仿真结果表明，排种盘转速为 1–7 r/min、取种勺直径为 25–35 mm 时排种性能较优。台架试验结果表明，"阿城紫皮蒜"和"农安紫皮蒜"的适宜参数组合为排种盘转速 4 r/min、取种勺直径 32 mm；"肇州白皮蒜"的适宜参数组合为排种盘转速 5.5 r/min、取种勺直径 28 mm。研究结果说明，勺夹式取种机构在受控台架条件下具有提高大蒜单粒取种稳定性的可行性。

INTRODUCTION
Garlic is one of the main specialty cash crops in China. Precision garlic seeding technology is important for improving the quality and efficiency of mechanized garlic sowing *(Wei et al., 2022; Xie et al., 2015)*. Garlic cloves have irregular curved surfaces and differ greatly in variety, shape, and size. These characteristics can easily cause miss-seeding, reseeding, and unstable seed carrying during mechanical sowing. Improving the stability of single-clove pickup and transport is therefore an important issue in the development of garlic seed metering devices. Existing garlic seeding devices mainly include spoon-chain, spoon-belt, cell-type, and pneumatic seed metering devices *(Liu et al., 2019; Zhang et al., 2014)*. Reviews and recent studies have also emphasized the need for improved single-clove pickup, directional control, and adaptability *(Cui et al., 2018; Fang et al., 2024; Jiang, 2018; Shao et al., 2025)*. These devices can meet some agronomic requirements, but their performance is still limited by seed leakage, unstable single-clove pickup, high structural complexity, or poor adaptability to different garlic varieties.

Previous studies have improved garlic seed metering performance through different technical routes. *Li et al. (2020)* designed a wheel-spoon type single-clove seed picking device, but different spoon structures were needed for different garlic grades. *Li et al. (2017)* and *Geng et al. (2016)* designed seed-box delivery mechanisms, but manual replanting was still required when serious miss-seeding occurred. Other mechanical garlic planting devices were reported by *Choi et al. (2003)*, *Dong et al. (2015)*, *Han (2011)*, and *Kang (2000)*. *Bakhtiari et al. (2009)* developed a precision garlic seeder with good performance, although the sensors and control system increased the manufacturing cost. *Xie et al. (2022)* proposed a tooth-assisted pneumatic garlic seed metering device, and *Hou et al. (2024)* designed a multi-disturbance seed-cleaning device. These studies indicate that seed pickup stability, miss-seeding control, and structural adaptability remain important problems. Most spoon-type mechanisms mainly depend on passive seed filling or spoon carrying, and the clove is not actively constrained during transport. A clove may slip, fall, or be picked up together with other cloves under shape variation and collision disturbance. A metering mechanism that combines spoon pickup with controlled clamping is therefore needed to improve carrying stability while reducing seed damage.

Accordingly, this study aimed to: (1) design a spoon-clamp type garlic seed metering device that combines spoon pickup with spring-assisted clamping; (2) determine the key structural parameters of the seed plate, seed pickup spoon, and opening-closing mechanism based on garlic-clove dimensions and theoretical analysis; (3) analyze the effects of seed plate speed and seed pickup spoon diameter using DEM simulation; and (4) verify the suitable parameter combinations through bench tests with three garlic varieties. This study provides a basis for further optimization and field validation of garlic precision seeding devices.

MATERIALS AND METHODS

Dimensional Measurement

The geometric characteristics of garlic cloves are the basis for designing the key components and selecting the control parameters of the seed metering device. The axial dimension method is commonly used to measure seed materials *(Liu et al., 2018)*. In this study, clove morphology was described by length L, width W, thickness H, and tail length T. As shown in Fig. 1, a three-axis spatial coordinate system XYZ was established with the centroid of the garlic clove as the origin O. The length, width, and thickness directions were defined as the X-, Y-, and Z-axes, respectively. To keep the design parameters consistent, garlic cloves with similar moisture content and intact appearance were selected. Each dimension was measured using a Vernier caliper with an accuracy of 0.01 mm.

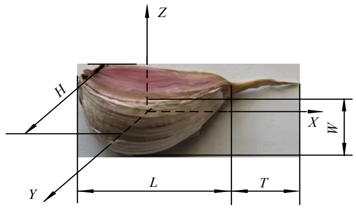


Fig. 1 – Determination of the geometric dimensions of garlic cloves

A total of 300 cloves were randomly selected from each variety, including “Acheng Purple Garlic”, “Zhaozhou White Garlic”, and “Nong’an Purple Garlic”. Each dimension was measured three times with equal precision. The probability density distribution of garlic dimensions was analyzed using Excel *(Tang, 2018)*, and the mean and standard deviation were calculated, as shown in Table 1.

Table 1

Geometrical dimensions of three garlic varieties

Tested varieties	Length [mm]		Width [mm]		Thickness [mm]		Tail Length [mm]	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Acheng Purple Garlic	28.43	0.93	16.95	0.82	17.05	0.97	10.71	1.02
Zhaozhou White Garlic	32.80	2.94	14.34	1.31	10.13	0.70	12.04	0.99
Nong’an Purple Garlic	25.37	1.61	16.26	0.79	15.93	0.78	12.40	0.82

Table 1 shows clear differences in the geometric dimensions of the three garlic varieties. The average length, width, thickness, and tail length of “Acheng Purple Garlic” were 28.43, 16.95, 17.05, and 10.71 mm, respectively. The corresponding values for “Zhaozhou White Garlic” were 32.80, 14.34, 10.13, and 12.04 mm. For “Nong’an Purple Garlic”, the values were 25.37, 16.26, 15.93, and 12.40 mm. These data provide a basis for designing the seed pickup spoon parameters.

Overall Structure and Working Principle of the Seed Metering Device

The spoon-clamp garlic seed metering device mainly consists of seed pickup spoons, torsion springs, a seed plate, limit rods, and other components, as shown in Fig. 2. The working process of the device includes four zones: seed pickup, seed clamping, seed cleaning, and seed discharge.

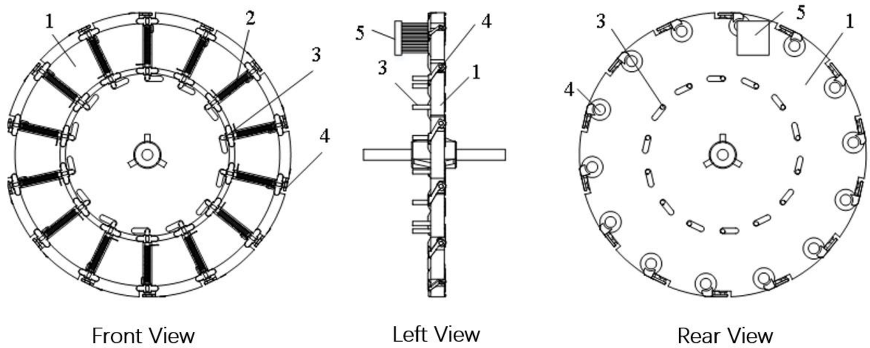


Fig. 2 – Overall structure of spoon-clamp garlic seed metering device

1 – Seed Plate; 2 – Torsion Spring; 3 – Limit Rod; 4 – Seed Pickup Spoon; 5 – Seed Cleaning Brush

During operation, the seed plate rotates around the main shaft and drives the seed pickup spoons, torsion springs, and clamping components. When a seed pickup spoon reaches the seed pickup zone, the limit rod opens the spoon through the torsion spring shaft. After the spoon passes the limit block, the elastic force of the torsion spring closes the spoon and clamps a garlic clove. The clamped clove then moves with the seed plate. When the spoon passes through the seed cleaning brush, excessive or unstable cloves are removed. At the seed discharge position, the second limit rod opens the spoon and releases the clove. This process integrates seed pickup, clamping, cleaning, and discharge. It is also the main structural difference between the proposed mechanism and ordinary spoon-type carrying devices.

Design of Key Components

Design of Seed Plate

The seed plate of the precision garlic seed metering device adopts a disc structure. Its main parameters include seed plate diameter, rotational speed, and the number of seed pickup spoons. A relationship among seed plate diameter, rotational speed, forward speed, and the number of seed pickup spoons was therefore established.

A larger seed plate diameter and more seed pickup spoons can reduce angular velocity and increase the curvature radius at the seed drop point, which helps stabilize seed pickup. Increasing the seed plate diameter can also increase spring deformation and improve control of the squeezing force during seed carrying. However, an excessive diameter increases the size, weight, and power consumption of the metering mechanism. Considering the relationship among seed plate radius, rotational speed, and forward speed, the seed plate diameter was set to 400 mm in the prototype design.

The linear speed of the seed plate refers to the linear speed at the seed pickup spoon. As the rotational speed increases, the time for the seed pickup spoon to pass through the seed area decreases. This may increase miss-seeding and cause picked cloves to fall under collision disturbance. Therefore, the linear speed of the seed pickup spoon should generally not exceed 0.35 m/s.

The maximum linear speed was set to 0.35 m/s, and the maximum rotational speed of the seed plate was calculated according to Equation (1).

$$\frac{d_p n_p \pi}{60} = 0.35 m/s \tag{1}$$

where d_p is the seed plate diameter, [m]; and n_p is the seed plate rotational speed, [r/min].

During operation, the garlic seeder mainly relies on ground-wheel transmission. According to the coordination between seed metering and forward movement, the time required for a garlic clove to rotate through the arc distance between adjacent seed pickup spoons should be equal to the time required for the seeder to move forward by one hill spacing. The relationship between seed pickup spoon spacing and garlic plant spacing is expressed as follows:

$$S_p = r\theta = \frac{n_p d_p \pi t}{60} \tag{2}$$

$$(1+\delta)\ \upsilon_c t = S_c \tag{3}$$

where S_p is the arc distance between adjacent seed pickup spoons on the seed plate, [m]; r is the seed plate radius, [m]; θ is the angular displacement, [rad]; n_p is the seed plate rotational speed, [r/min]; d_p is the seed plate diameter, [m]; t is the travel time, [s]; δ is the ground-wheel slip rate; υ_c is the forward speed of the machine, [m/s]; and S_c is the garlic plant spacing, [m].

By combining the above two formulas, the expression for the seed pickup spoon spacing can be obtained as follows:

$$S_p = \frac{S_c n_p d_p \pi}{(1+\delta)60\upsilon_c} \tag{4}$$

According to the agronomic requirements for garlic planting, the plant spacing S_c is 80–120 mm, the forward speed of the seeder υ_c is 0.2–0.4 km/h, and the ground-wheel slip rate δ is 0.05–0.12. When δ = 0.08, the calculated arc distance S_p between adjacent seed pickup spoons on the seed plate is 58–116 mm.

$$n_s = \frac{\pi d_p}{S_p} \tag{5}$$

where n_s is the number of seed pickup spoons, [pcs]; d_p is the seed plate diameter, [m]; and S_p is the arc distance between adjacent seed pickup spoons, [m].

The calculation showed that the arc distance between adjacent seed pickup spoons on the seed plate was 116 mm, and the number of seed pickup spoons was 14.

Design of Seed Pickup Spoon

A spoon-clamp seed pickup structure was proposed because garlic cloves differ greatly in three-dimensional morphology and have uneven curved surfaces. The seed pickup spoon is used for seed pickup and carrying. During seed plate rotation, the spoon should carry the garlic clove to the discharge position without damage or falling. A larger spoon can reduce miss-seeding, but an excessively large spoon may increase reseeding. The spoon size was therefore determined according to the external dimensions of the garlic cloves. The three-dimensional shape of garlic cloves was approximately regarded as an ellipsoid. The spoon opening was initially designed as a circular opening similar to a small hemisphere. To reduce miss-seeding and reseeding, the diameter of the spoon opening should be greater than the average clove width and smaller than the average clove length. The initial diameter was set to 30 mm. The minimum and maximum diameters were 16 mm and 36 mm, respectively, and the spoon depth was about 4 mm, which was about two-thirds of the maximum clove thickness. The structure of the seed pickup spoon is shown in Fig. 3.

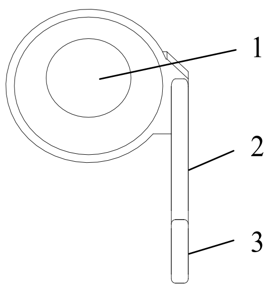


Fig. 3 – Structure diagram of seed pickup spoon
1 – Spoon Body; 2 – Spoon Handle; 3 – Fixing Hole

Design of Opening and Closing Mechanism

The seed pickup process of the precision garlic seed metering device mainly depends on the opening and closing mechanism. The fixed end contacts the limit rod and continuously opens the seed pickup spoon. As the seed plate rotates, the elastic potential energy of the torsion spring increases. When the fixed end is separated from the limit rod, the stored elastic potential energy is released, and the seed pickup spoon closes rapidly under the action of the torsion spring. The operating performance of this mechanism directly affects seed clamping, transport, and discharge. It is therefore an important component for precision seed pickup in garlic planting. The opening and closing mechanism are shown in Fig. 4.

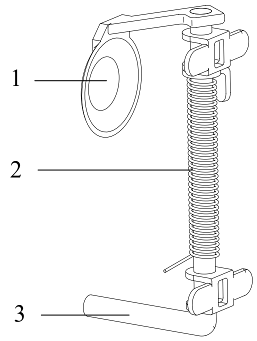


Fig. 4 – Opening and closing mechanism of the garlic seed metering device
1 – Seed Pickup Spoon; 2 – Torsion Spring; 3 – Limit Rod

The opening-closing mechanism realizes the opening and closing movement of the seed pickup spoon through the combined action of the torsion spring and limit rod. During opening, elastic potential energy is stored in the torsion spring and then released to generate the clamping force of the seed pickup spoon. The clamping force affects both seed pickup stability and clove damage. Because the clamping force is difficult to adjust directly during operation, different spring wire diameters were used as equivalent clamping force levels in the experiment. The relationship between spring wire diameter and clamping force is expressed by Eq. (6).

$$\begin{cases} P = k\Delta s \\ k = \dfrac{1000 d_w}{\left(\dfrac{d}{d_w}\right)^3} \end{cases} \tag{6}$$

where P is the clamping force of the seed pickup spoon, [N]; k is the spring stiffness coefficient, [N/mm]; Δs is the spring deformation, [mm]; d_w is the spring wire diameter, [mm]; and d is the mean spring diameter, [mm].

"Acheng Purple Garlic" was selected for the single-factor test on clamping force to clarify its effect on seed damage rate. The spring wire diameters were set to 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 mm. For each spring wire diameter, 300 garlic cloves were selected and evenly divided into three groups for repeated seed pickup tests. The seed damage rate was determined according to visible damage to the garlic body after the skin was peeled off. Considering the practical requirements of agricultural production and the adjustable range of the mechanism, the spring wire diameter was set within 0.5–1.0 mm. The number of damaged cloves among the effectively clamped cloves was counted, and the seed damage rate was used as the evaluation indicator. The test plan and results are shown in Table 2.

Table 2
Single-factor test scheme and results for spring wire diameter

Spring Wire Diameter [mm]	0.5	0.6	0.7	0.8	0.9	1.0
Seed Damage Rate [%]	0	0	0	5.33	6.66	8.00

The single-factor results showed that the seed damage rate was 0% when the spring wire diameter was 0.5–0.7 mm. Visible damage began to appear when the spring wire diameter exceeded 0.7 mm. The spring wire diameter was therefore set to 0.7 mm, corresponding to a clamping force of approximately 2.401 N. This value was selected to maintain clamping stability while reducing garlic-clove damage.

Determination of Seed Discharge Port Position

The position of the seed discharge port directly affects the falling height and initial state of the garlic clove, and is therefore an important parameter for device coordination.

Fig. 5 shows the seed pickup process and the falling process from the discharge port.

To determine the discharge port position, the seed pickup process was assumed to be uniform. The horizontal and vertical coordinates of the garlic clove during movement with the seed plate are denoted as x and y. When the garlic clove falls from the discharge port, its initial horizontal and vertical velocities are denoted as v_x and v_y. The horizontal and vertical displacements after falling are denoted as X and Y. The expressions for these variables are given in Equation (7).

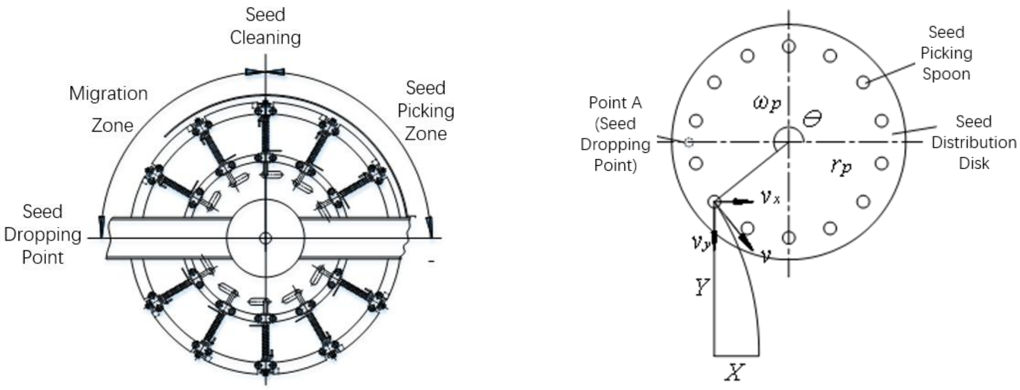


Fig. 5 – Motion analysis of seeding process

$$\begin{cases} x = r_p \cos\theta \\ y = r_p \sin\theta \\ \dot{x} = -r_p \sin\theta \\ \dot{y} = r_p \cos\theta \\ X = r_p \omega_p t \cos\theta \\ Y = r_p \omega_p t \sin\theta + \dfrac{gt^2}{2} \end{cases} \tag{7}$$

where x and y are the horizontal and vertical coordinates of the garlic clove, [m]; $\dot{x}$ and $\dot{y}$ are the corresponding velocity components, [m/s]; X and Y are the horizontal and vertical falling displacements, [m]; r_p is the seed plate radius, [m]; θ is the garlic-clove discharge angle, [rad]; ω_p is the angular velocity of the seed plate, [rad/s]; t is the falling time, [s]; and g is the gravitational acceleration, [m/s²].

To reduce the horizontal velocity during discharge and obtain zero horizontal displacement after the garlic clove falls from the discharge port, the discharge position was determined according to the motion relationship in Equation (7). Among the solutions, −90° corresponds to the initial seed pickup position. Therefore, point A in Fig. 5 was selected as the seed discharge port position.

Discrete Element Simulation

A model of the precision garlic seed metering device and garlic-clove models were constructed using the discrete element method (DEM), and simulation experiments were then conducted *(Hu, 2010)*. The control-variable single-factor method was used to clarify the independent effects of seed plate speed and seed pickup spoon diameter at the prototype design stage. The qualified seeding index, reseeding index, and miss-seeding index were selected as evaluation indicators. EDEM software was used for the virtual simulation tests, which provided data support for structural improvement and operational parameter selection of the precision garlic seed metering device.

Establishment of Seed Metering Device Geometric Model

The geometric model of the seed metering device is an important factor affecting the accuracy of seed pickup simulation. The precision garlic seed metering device was modeled using NX/UG 3D software *(Bertrand et al., 2005; Cundall and Strack, 1979; Hou et al., 2019; Li et al., 2003; Qian, 2008; Sakaguchi et al., 2001; Sharma et al., 2011; Yang and Hsiau, 2000; Yu et al., 2005)*, as shown in Fig. 6. To improve calculation efficiency while preserving the main contact boundaries, small fillets, threaded holes, and other non-critical details were simplified before importing the model into EDEM.

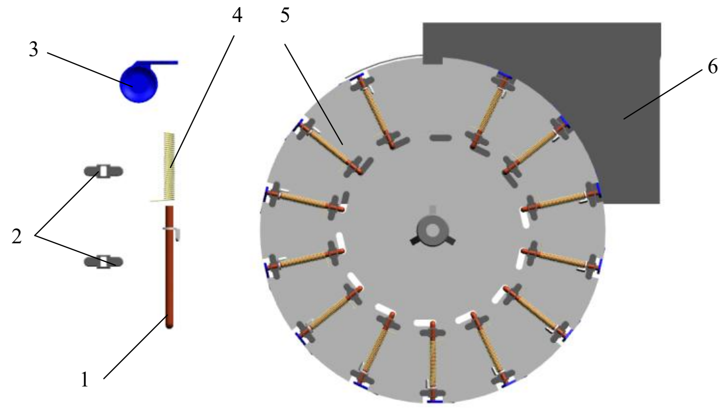
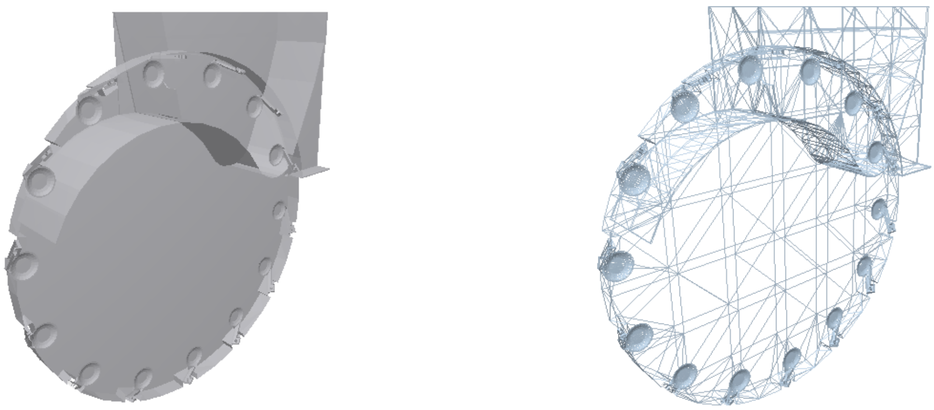


Fig. 6 – Three-dimensional model of garlic seed metering device
1 – Opening and Closing Limit Rod; 2 – Fixing Washer; 3 – Seed Pickup Spoon; 4 – Spring; 5 – Seed Plate; 6 – Seed Box

According to the requirements of prototype development and preliminary material property measurements, the seed pickup spoon was set as 65 Mn steel, with a Poisson's ratio of 0.40, a shear modulus of 7.85×10^9 Pa, and a density of 7800 kg/m^3. The seed plate and seed box were set as aluminum alloy, with a Poisson's ratio of 0.42, a shear modulus of 1.7×10^{10} Pa, and a density of 2700 kg/m^3.



a) Garlic seed metering device in filled format *b) Garlic seed metering device in mesh format*

Fig. 7 – Virtual simulation model of spoon-clamp garlic precision seed metering device

Establishment of Discrete Element Model for Garlic Cloves

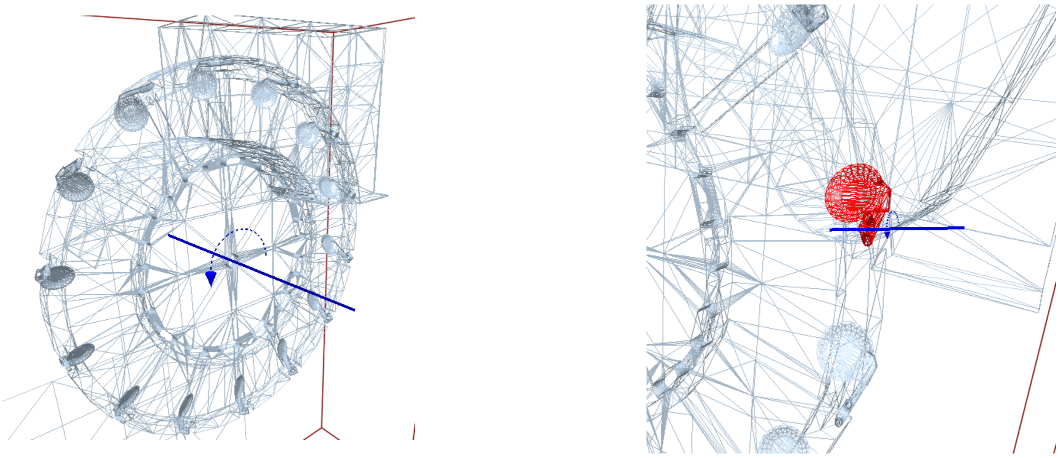
The shape and size of garlic cloves are important factors affecting the seeding performance of the seed metering device. In this study, the seeding performance of three garlic varieties was analyzed. According to the morphological and dimensional characteristics of the three varieties, the clove shapes were divided into two categories. "Acheng Purple Garlic" and "Nong'an Purple Garlic" were classified as drum-shaped, while "Zhaozhou White Garlic" was classified as slender. Based on the parameters measured in previous material property studies, multi-sphere filling was carried out for the two clove shapes. The filled garlic-clove particles are shown in Fig. 8.

a) Drum-shaped *b) Slender*

Fig. 8 – Filling condition of two kinds of garlic cloves

Numerical Simulation Test of Seed Metering Device Performance

The seeding performance of the garlic seed metering device is affected by garlic variety and size, seed plate speed, and seed pickup spoon diameter. In this study, seed plate speed and seed pickup spoon diameter were selected as the main design variables. The qualified seeding index, reseeding index, and miss-seeding index were used as evaluation indicators. A single-factor control-variable simulation was adopted to determine the suitable parameter range before bench-test validation. The possible interaction between factors was not the focus of this prototype-stage study and should be further analyzed in later optimization work.



a) Rotation direction of the seed plate and seed pickup spoon *b) Self-rotation direction of the seed pickup spoon*

Fig. 9 – Simulation of component motion settings

Factors and Evaluation Indicators for Virtual Simulation Experiments

The rotational speed of the seed plate was matched with the revolution speed of the seed pickup spoons. A rotating model was used to set the rotational speed of the seed plate and each seed pickup spoon, and the self-rotation motion of the seed pickup spoons was also added. A factory model was used to establish a virtual particle factory above the seed box for dynamic particle generation. The operating parameters of the spring were set through the Application Programming Interface, as shown in Fig. 9.

Virtual simulation experiments were conducted using the same structural parameters of the spoon-clamp precision garlic seed metering device. The effects of seed plate speed and seed pickup spoon diameter on seeding performance and the suitable parameter range were analyzed for drum-shaped and slender garlic cloves. Based on theoretical analysis, preliminary tests, agronomic requirements, and actual operating conditions, the seed plate speed was set to 1–13 r/min, and the seed pickup spoon diameter was set to 15–45 mm. Single-factor virtual simulation experiments were conducted separately for the two garlic-clove types.

Referring to the national standards GB/T 6973–2005 "Test Methods for Single Seed (Precision) Planters" and NY/T 503–2015 "Quality of Single Seed (Precision) Planter Operations," the qualified seeding index, reseeding index and miss-seeding index were selected to evaluate the operational performance, suitable parameter range and stability of the precision garlic seed metering device. Considering the differences between simulation and bench tests and the operability of the virtual statistics, the calculation formulas for each simulation indicator were defined as follows:

$$S_f = \frac{n_{0f}}{N_f} \times 100\% \tag{8}$$

$$D_f = \frac{n_{1f}}{N_f} \times 100\% \tag{9}$$

$$M_f = \frac{n_{2f}}{N_f} \times 100\% \tag{10}$$

where S_f is the simulation qualified seeding index, [%]; D_f is the simulation reseeding index, [%]; M_f is the simulation miss-seeding index, [%]; n_{0f} is the single-seed pickup count, [pcs]; n_{1f} is the count of two or more seeds picked up, [pcs]; n_{2f} is the no-seed pickup count, [pcs]; and N_f is the theoretical seed pickup count, [pcs].

Bench-Test Materials and Equipment

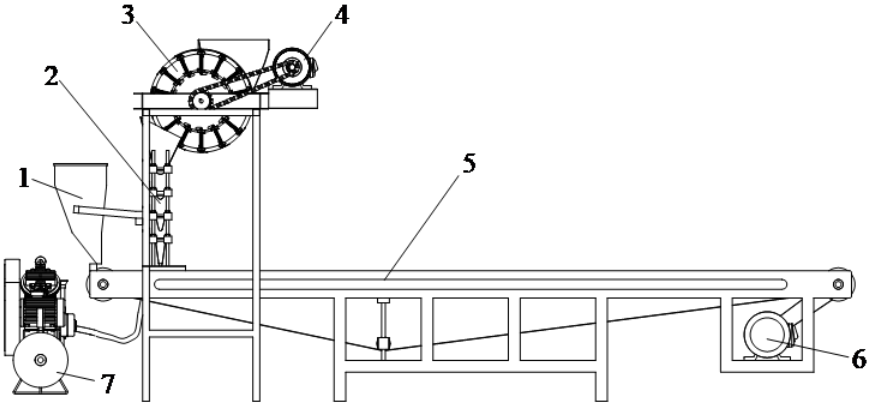


Fig. 10 – Test-bed of spoon-clamp garlic precision seeding device

1 – Soil Spreading Device; 2 – Three-stage Alignment Mechanism; 3 – Spoon-clamp Precision Garlic Seed Plate; 4 – Speed-regulating Motor for Seed Metering Device; 5 – Conveyor Belt; 6 – Speed-regulating Motor for Conveyor Belt; 7 – Air Pump

The test materials were three garlic varieties widely planted in the Heilongjiang region: “Acheng Purple Garlic”, “Zhaozhou White Garlic”, and “Nong’an Purple Garlic”. The cloves were manually graded and screened to ensure a moisture content of 55%–65%, plump and symmetrical shapes, and no scars, rot, or pest damage. Garlic cloves with similar specifications were selected for single-factor performance testing and validation of the seeding device.

A self-made spoon-clamp precision garlic seeding test bench was used, and its overall structure is shown in Fig. 10. The bench mainly consisted of a spoon-clamp precision garlic seed metering device, a seed alignment mechanism, a soil spreading device, a conveyor belt, and a speed-regulating motor. The seed metering device and alignment mechanism completed seed pickup and alignment. The positioning bowl in the alignment mechanism was opened and closed by an air pump. The soil spreading device mainly consisted of a soil box and adjustable baffles. It spread soil evenly on the conveyor belt, allowing the garlic cloves to fall into the soil on the conveyor belt after alignment.

The motors of the seed metering device and conveyor belt were controlled by frequency converters, which adjusted the working speeds and improved the operability of the test bench. The JPS-12 frequency converter was selected to ensure precise motor speed adjustment and stable bench operation. According to the agronomic requirements for garlic seeding spacing, a conversion relationship between the working speed of the seed metering device and the forward speed of the machine was needed. During the experiment, the forward speed of the machine was represented by the forward speed of the conveyor belt. The conversion relationship is expressed as follows:

$$N_P = \frac{60V_D}{S_Q N_Q} \cdot 1000 \tag{11}$$

where N_P is the rotational speed of the seed plate, [r/min]; V_D is the conveyor-belt speed, [m/s]; S_Q is the theoretical plant spacing, [mm]; and N_Q is the number of seed pickup spoons, [pcs].

Based on the mechanism analysis, DEM simulation, and production requirements, the main factors affecting the operational quality and suitable seeding range of the spoon-clamp precision garlic seeding device are seed plate speed and seed pickup spoon diameter. Bench tests were conducted to verify the effects of these two structural and operational parameters and to determine suitable parameter combinations for the tested garlic varieties.

Division of Sections and Variable Calculation

The measured spacing between adjacent garlic cloves was recorded as x_i, and the reference (theoretical) plant spacing was recorded as X_{ref}. The samples were divided into intervals with a step of $0.1X_{ref}$. The dimensionless spacing ratio for each observation was calculated using Equation (12).

$$X_i = \frac{x_i}{X_{ref}} \tag{12}$$

where X_i is the dimensionless spacing ratio; x_i is the measured spacing between adjacent garlic cloves, [mm]; and X_{ref} is the reference (theoretical) plant spacing, [mm].

The spacing of the tested garlic seed samples was divided into qualified intervals, reseeding intervals, and miss-seeding intervals. The division methods for each interval are as follows:

$$\begin{cases} \boldsymbol{n}_1' = \sum \boldsymbol{n}_i(\boldsymbol{X}_i \in \{0.0 - 0.5\}) \Rightarrow Reseeing\ Interval \\ \boldsymbol{n}_2' = \sum \boldsymbol{n}_i(\boldsymbol{X}_i \in \{0.5 - 1.5\}) \Rightarrow Qualified\ Interval \\ \boldsymbol{n}_3' = \sum \boldsymbol{n}_i(\boldsymbol{X}_i \in \{1.5 - 2.5\}) \Rightarrow Miss - Seeding\ Interval \\ \boldsymbol{n}_4' = \sum \boldsymbol{n}_i(\boldsymbol{X}_i \in \{2.5 - 3.5\}) \\ \boldsymbol{n}_5' = \sum \boldsymbol{n}_i(\boldsymbol{X}_i \in \{3.5 - +\infty\}) \\ \boldsymbol{N} = \boldsymbol{n}_1' + \boldsymbol{n}_2' + \boldsymbol{n}_3' + \boldsymbol{n}_4' + \boldsymbol{n}_5' \quad \Rightarrow Number\ of\ Interval \end{cases} \tag{13}$$

The qualified count, reseeding count, and miss-seeding count of the measured garlic seed hill spacing can be expressed by Equation (14) as follows:

$$\begin{cases} \text{Qualified Count:}\ n_1 = N - 2n_2 \\ \text{Reseeding Count:}\ n_2 = n_1' \\ \text{Miss-seeding Count:}\ n_0 = n_3' + 2n_4' + 3n_5' \\ \text{Number of Intervals:}\ N' = n_2' + 2n_3' + 3n_4' + 4n_5' \\ \text{Average Qualified Spacing:}\ \bar{X} = \dfrac{\sum n_i X_i}{n_2} \qquad Xi \in \{> 0.5 \sim \le 1.5\} \end{cases} \tag{14}$$

where n'_j ($j = 1,\ldots,5$) is the number of observations in the j-th spacing interval; n_i is the frequency in interval i; X_i is the dimensionless spacing ratio; N is the total number of observations; n_1, n_2, and n_0 are the qualified, reseeding, and miss-seeding counts, respectively; N' is the equivalent total interval count; and $\bar{X}$ is the mean qualified spacing ratio.

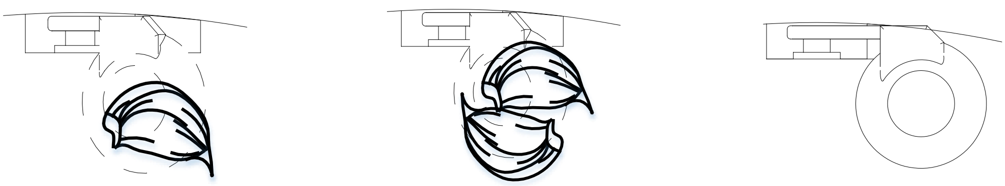
Calculation Methods for Seeding Performance Evaluation Indicators

Qualified Seeding Index, Miss-seeding Index, Reseeding Index, and Qualified Plant Spacing Index. The calculation methods for each performance indicator of the garlic seeding device in this study are shown in Equation (15) as follows:

$$\begin{cases} Qualified\ Seeding\ Index:\ \boldsymbol{S}_0 = \dfrac{\boldsymbol{n}_n}{\boldsymbol{N}'} \times 100\% \\ Qualified\ Plant\ Spacing\ Index:\ \boldsymbol{S} = \dfrac{\boldsymbol{n}_1}{\boldsymbol{N}'} \times 100\% \\ Reseeding\ Index:\ \boldsymbol{D} = \dfrac{\boldsymbol{n}_2}{\boldsymbol{N}'} \times 100\% \\ Miss\text{-}seeding\ Index:\ \boldsymbol{M} = \dfrac{\boldsymbol{n}_0}{\boldsymbol{N}'} \times 100\% \end{cases} \tag{15}$$

where S_0 is the qualified seeding index, [%]; S is the qualified plant spacing index, [%]; D is the reseeding index, [%]; M is the miss-seeding index, [%]; n_n is the single-seed pickup count, [pcs]; n_1 is the qualified single-seed discharge count, [pcs]; n_2 is the count of two or more seeds discharged, [pcs]; n_0 is the miss-seeding count, [pcs]; and N' is the total number of hill-spacing intervals in the sample, [pcs].

The evaluation criteria were as follows. In the single-factor tests of seed plate speed and seed pickup spoon diameter, the seed pickup spoon was judged as qualified if it held only one garlic clove after passing through the seed box, as shown in Fig. 11(a). If it held two or more garlic cloves, it was judged as reseeding, as shown in Fig. 11(b). If it did not hold any garlic clove, it was judged as miss-seeding, as shown in Fig. 11(c).



a) Qualified *b) Reseeding* *c) Miss-seeding*

Fig. 11 – Seed collection judgment: qualified, reseeding, and miss-seeding

RESULTS

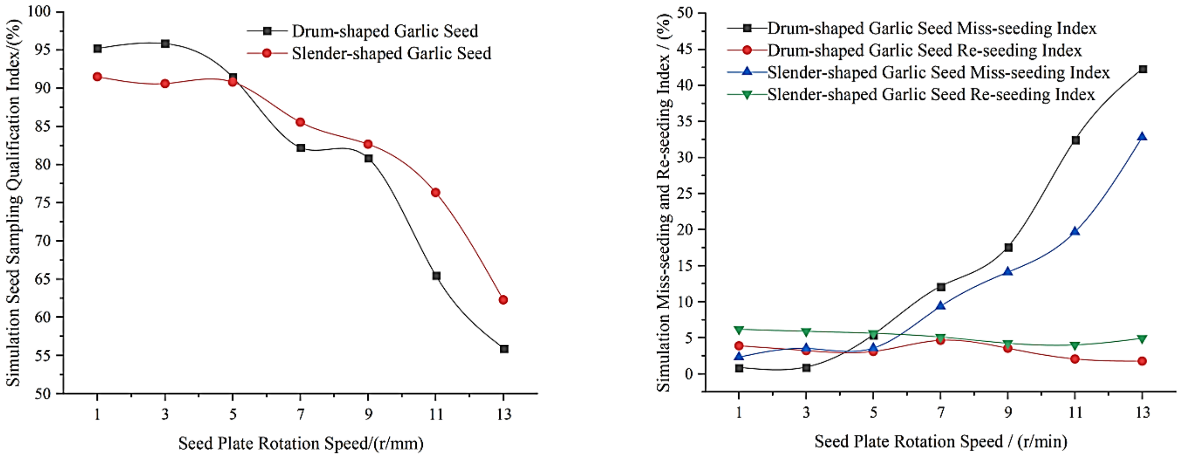
Simulation Results and Analysis

Seed plate speed and seed pickup spoon diameter were used as experimental factors, while qualified seeding index, reseeding index, and miss-seeding index were used as evaluation indicators. Single-factor DEM simulations were conducted for drum-shaped garlic cloves, represented by “Acheng Purple Garlic” and “Nong’an Purple Garlic”, and slender garlic cloves, represented by “Zhaozhou White Garlic”. These simulations were used to analyze the effect of each factor on seeding performance. Based on the structural dimensions of the seed metering device and the agronomic requirements for garlic seeding, the seed plate speeds were set to 1, 3, 5, 7, 9, 11, and 13 r/min. The seed pickup spoon diameter was fixed at 30 mm for the single-factor simulation on seed plate speed. The simulation results are shown in Table 3.

Table 3

Virtual simulation scheme and results for seed plate speed

Test Number	Operating Speed [r/min]	Drum-shaped			Slender		
		Qualified Index [%]	Reseeding Index [%]	Miss-seeding Index [%]	Qualified Index [%]	Reseeding Index [%]	Miss-seeding Index [%]
1	1	95.21	3.89	0.90	91.51	6.17	2.32
2	3	95.84	3.22	0.94	90.60	5.89	3.51
3	5	91.46	3.10	5.44	90.81	5.63	3.56
4	7	82.23	4.64	13.13	85.55	5.10	9.35
5	9	80.85	3.55	15.60	81.67	4.24	14.09
6	11	65.50	2.06	32.44	76.33	4.00	19.67
7	13	55.96	1.77	42.27	62.27	4.93	32.80



a) Simulation of qualified index *b) Simulation of reseeding and miss-seeding indices*

Fig. 12 – Single-factor simulation test of the rotation speed of seed metering plate

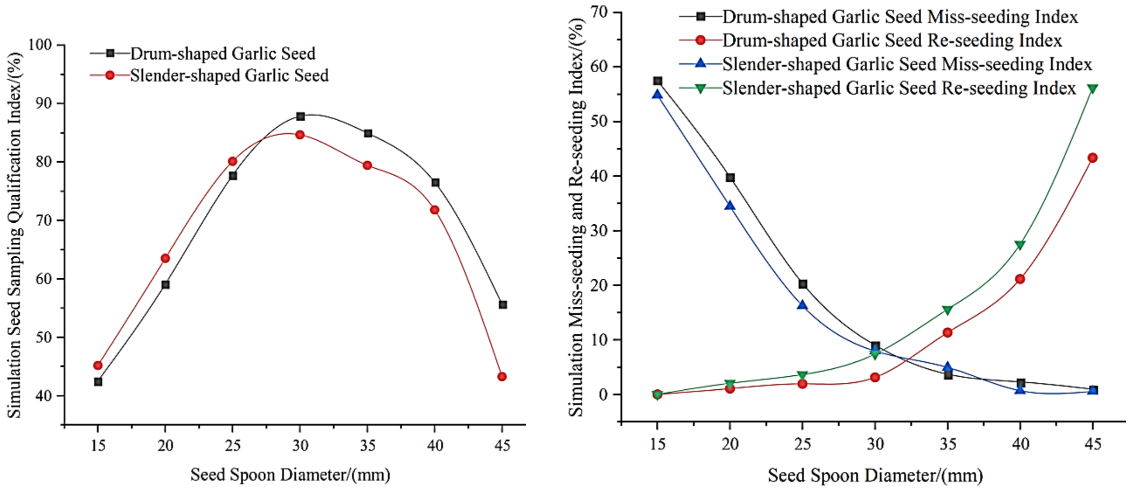
As shown in Fig. 12, the virtual simulation results showed that the qualified seeding index of both garlic-clove types first remained relatively stable and then decreased as seed plate speed increased. At low to medium speeds, the seed pickup spoon had sufficient contact time with the seed population, and the clamping mechanism could complete stable pickup and carrying. When the speed exceeded the suitable range, the contact time between the spoon and garlic cloves decreased. Collision disturbance also increased, which led to unstable pickup and higher miss-seeding. Under simulation conditions, the qualified seeding index was relatively high within 1–7 r/min, while the miss-seeding index increased continuously at higher speeds. The reseeding index was less affected by seed plate speed.

The seed pickup spoon diameters were set to 15, 20, 25, 30, 35, 40, and 45 mm. Other experimental conditions were fixed at a seed plate speed of 5 r/min for the single-factor simulation on seed pickup spoon diameter. The simulation results are shown in Table 4.

Table 4

Virtual simulation scheme and results for seed pickup spoon diameter

		Drum-shaped			Slender		
Test Number	**Seed pickup spoon diameter [mm]**	**Qualified Index [%]**	**Reseeding Index [%]**	**Miss-seeding Index [%]**	**Qualified Index [%]**	**Reseeding Index [%]**	**Miss-seeding Index [%]**
1	15	42.52	0	57.48	45.18	0	54.82
2	20	59.1	1.08	39.82	63.5	2.05	34.45
3	25	77.7	1.94	20.36	80.12	3.63	16.25
4	30	87.85	3.12	9.03	84.66	7.39	7.95
5	35	84.96	11.34	3.7	79.44	15.6	4.96
6	40	76.55	21.14	2.31	71.8	27.52	0.68
7	45	55.68	43.36	0.96	43.25	56.18	0.57



a) Simulation of qualified index *b) Simulation of reseeding and miss-seeding indices*

Fig. 13 – Single-factor simulation test of seed pickup spoon diameter

As shown in Fig.13, the qualified seeding index first increased and then decreased as seed pickup spoon diameter increased. A smaller spoon diameter reduced the effective contact area between the spoon and garlic clove, which resulted in a higher miss-seeding index. As the spoon diameter increased, the clove was more easily captured and carried. However, an excessively large spoon increased the probability of holding two or more cloves, and the reseeding index increased. The seed pickup spoon diameter should therefore match the size distribution of each garlic variety. Based on the single-factor simulation results, the suitable parameter range under DEM conditions was 1–7 r/min for seed plate speed and 25–35 mm for seed pickup spoon diameter.

Experimental Results and Analysis

"Acheng Purple Garlic", "Zhaozhou White Garlic", and "Nong'an Purple Garlic" were used as test materials to verify the influence of the selected factors on metering performance. Seed plate speed and seed pickup spoon diameter were taken as experimental factors. The qualified seeding index, miss-seeding index, reseeding index, and qualified plant spacing index were used as test indicators *(Xing et al., 2015)*. The seed plate speed ranged from 1 r/min to 10 r/min, and the seed pickup spoon diameter ranged from 20 mm to 44 mm.

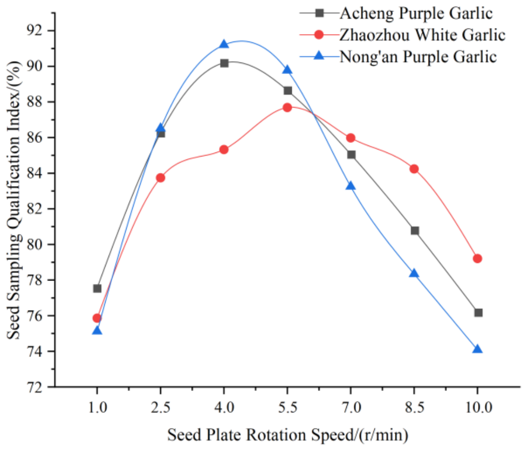
Influence of Seed Plate Working Speed on Seeding Performance

With the seed pickup spoon diameter fixed at 32 mm, the seed plate speed was set to seven levels: 1, 2.5, 4, 5.5, 7, 8.5, and 10 r/min. Each level was tested three times. The average values of the qualified seeding index, miss-seeding index, and reseeding index were used for analysis. The single-factor bench-test plan and results for seed plate speed with the three garlic varieties are shown in Table 5.

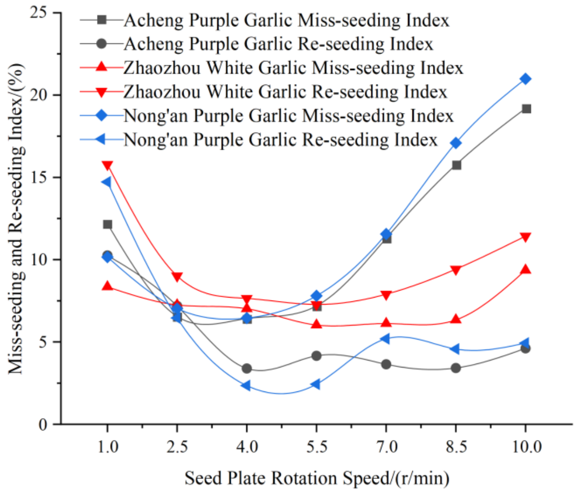
Table 5

Single-factor test scheme and results for seed plate speed

Garlic Variety	Test Number	Seed Plate Rotation Speed [r/min]	Test Indicators [%] Qualified seeding Index	Miss-seeding Index	Reseeding Index
Acheng Purple Garlic	1	1	77.56	12.18	10.26
	2	2.5	86.26	6.55	7.19
	3	4	90.19	6.42	3.39
	4	5.5	88.65	7.19	4.16
	5	7	85.06	11.3	3.64
	6	8.5	80.81	15.77	3.42
	7	10	76.21	19.19	4.61
Zhaozhou White Garlic	8	1	75.86	8.35	15.79
	9	2.5	83.74	7.25	9.01
	10	4	85.33	7.02	7.65
	11	5.5	87.69	6.03	7.28
	12	7	85.98	6.12	7.9
	13	8.5	84.24	6.34	9.42
	14	10	79.21	9.36	11.43
Nong'an Purple Garlic	15	1	75.12	10.16	14.72
	16	2.5	86.51	7.03	6.46
	17	4	91.20	6.45	2.35
	18	5.5	89.77	7.80	2.43
	19	7	83.25	11.56	5.19
	20	8.5	78.34	17.09	4.57
	21	10	74.08	20.99	4.93



a) Influence of seed plate rotation speed on qualified seeding index



b) Influence of seed plate rotation speed on miss-seeding and reseeding indices

Fig. 14 – Single-factor test result curve of the rotation speed of the seed metering plate

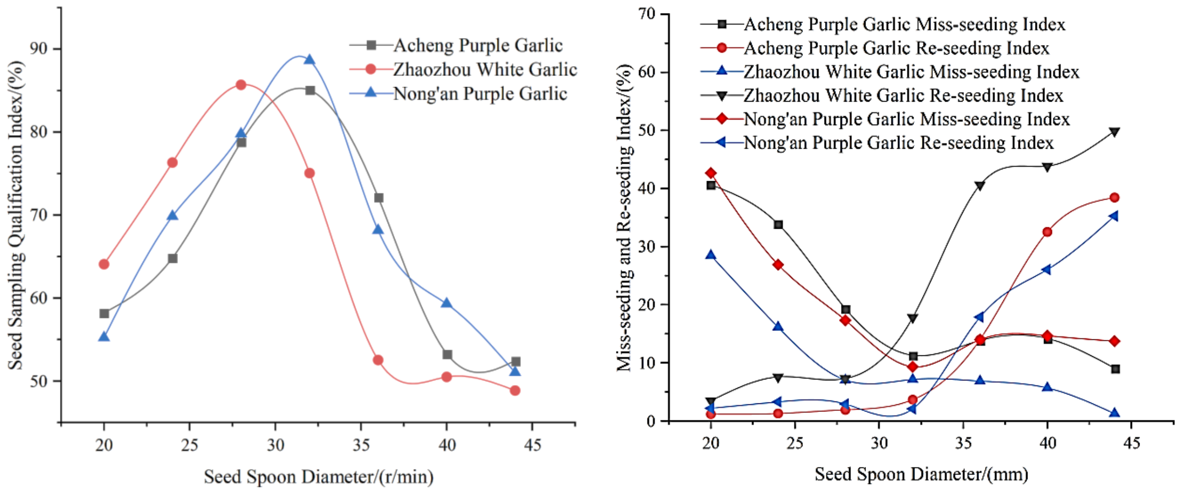
As shown in Fig. 14, the qualified seeding index of all three garlic varieties first increased and then decreased as seed plate speed increased. For “Acheng Purple Garlic” and “Nong’an Purple Garlic”, the qualified index reached its maximum at 4 r/min. For “Zhaozhou White Garlic”, the maximum value was obtained at 5.5 r/min. At a very low speed, the disturbance to the seed population was insufficient, which reduced the probability of stable single-clove pickup. At an excessively high speed, the spoon passed through the seed zone too quickly, and the cloves were more easily affected by collision and vibration. As a result, the miss-seeding index increased. The difference among varieties was mainly related to clove shape. The slender “Zhaozhou White Garlic” required a slightly higher speed to improve pickup probability, while the two drum-shaped varieties reached their suitable speed at 4 r/min.

Influence of Seed Pickup Spoon Diameter on Seeding Performance

Table 6

Single-factor test scheme and results for seed pickup spoon diameter

Garlic Variety	Test Number	Seed pickup spoon diameter [mm]	Test Indicators [%] Qualified seeding Index	Miss-seeding Index	Reseeding Index
Acheng Purple Garlic	1	20	58.21	40.64	1.15
	2	24	64.84	33.89	1.27
	3	28	78.78	19.32	1.9
	4	32	85.06	11.3	3.64
	5	36	72.15	13.84	14.01
	6	40	53.29	14.19	32.52
	7	44	52.46	9.1	38.44
Zhaozhou White Garlic	8	20	64.07	28.47	3.46
	9	24	76.32	16.12	7.56
	10	28	85.69	7.03	7.28
	11	32	75.05	7.14	17.81
	12	36	52.52	6.86	40.62
	13	40	50.49	5.66	43.85
	14	44	48.85	1.25	49.9
Nong'an Purple Garlic	15	20	55.21	42.64	2.15
	16	24	69.84	26.89	3.27
	17	28	79.78	17.32	2.9
	18	32	88.62	9.3	2.08
	19	36	68.15	13.99	17.86
	20	40	59.29	14.66	26.05
	21	44	51.02	13.72	35.26



a) Influence of seed pickup spoon diameter on qualified seeding index

b) Influence of seed pickup spoon diameter on miss-seeding and reseeding indices

Fig. 15 – Single-factor test result curve of seed pickup spoon diameter

As shown in Fig.15, the qualified seeding index of all three garlic varieties first increased and then decreased as seed pickup spoon diameter increased. The miss-seeding index decreased with increasing spoon diameter because the effective clamping and carrying area became larger. However, the reseeding index increased when the spoon diameter was too large, because two or more cloves could be picked up at the same time. The qualified seeding index reached its maximum at a spoon diameter of 32 mm for “Acheng Purple Garlic” and “Nong’an Purple Garlic”, and at 28 mm for “Zhaozhou White Garlic”. These results were consistent with the garlic-clove size differences measured in Table 1. Compared with the simulation results, the bench-test qualified indexes were lower because the real cloves had irregular surfaces, skin deformation, and non-uniform contact states. Therefore, the DEM simulation was used to determine the suitable parameter range, while the final parameter combination was verified by bench tests. Because the validation was conducted on a laboratory bench, field conditions such as vibration, soil resistance, ground-wheel slip, and non-uniform seed supply may affect the actual sowing performance. Further field validation and multi-factor optimization are needed in future work.

CONCLUSIONS

A spoon-clamp type garlic seed metering device was designed to improve the stability of single-clove pickup and carrying. The device integrates spoon pickup, spring-assisted clamping, seed cleaning, and controlled discharge. This structure is suitable for garlic cloves with irregular shapes and size variation.

DEM simulations were conducted to analyze the effects of seed plate speed and seed pickup spoon diameter. The qualified seeding index decreased at excessive seed plate speeds because seed pickup time was reduced and collision disturbance increased. Under simulation conditions, the suitable parameter range was 1–7 r/min for seed plate speed and 25–35 mm for seed pickup spoon diameter.

Bench tests verified the feasibility of the proposed mechanism under controlled test conditions. The suitable parameter combination was 4 r/min and 32 mm for “Acheng Purple Garlic” and “Nong’an Purple Garlic”, and 5.5 r/min and 28 mm for “Zhaozhou White Garlic”. Future work should focus on field validation, vibration adaptability, and multi-factor optimization of the garlic seed metering device.

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