

ANALYSIS OF THE INTERACTION BETWEEN THE DIBBER, SOIL, AND GARLIC DURING DIRECTIONAL GARLIC SEEDING BASED ON THE DISCRETE ELEMENT METHOD

基于离散元法的大蒜定向播种过程中插播器、土壤和大蒜之间的相互作用的分析

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ABSTRACT

This study investigates the interaction mechanisms between the dibber, soil, and garlic during directional garlic seeding using the Discrete Element Method (DEM), aiming to improve planting uprightiness and planting-depth consistency. A discrete element model of the garlic seeding process was established to analyze the dynamic interactions among the dibber, soil, and garlic from a microscopic perspective, and the reliability of the simulation results was verified through macroscopic experiments. The results show that dibbling depth, lifting height, dibbling speed ratio, and soil-particle surface energy are key factors influencing planting uprightiness and depth consistency. Within a certain range, increasing the dibbling depth and lifting height significantly improves uprightiness, although the effect diminishes beyond critical thresholds. The influence of the dibbling speed ratio on uprightiness exhibits a nonlinear trend, in which both excessively low and excessively high ratios reduce uprightiness. In addition, lower soil-particle surface energy leads to increased uprightiness and improved soil backfilling performance. Experimental validation confirmed strong agreement between the simulation and physical test results, with an average relative error of less than 10%. This study provides a theoretical foundation and numerical simulation tools for optimizing directional garlic seeding technology, offering important guidance for improving planting uprightiness and planting-depth consistency.

摘要

本研究基于离散元法 (DEM) 探究大蒜定向播种过程中取种器、土壤与蒜种之间的相互作用机制, 旨在提高蒜种的种植直立度与播深一致性。通过建立大蒜播种过程的离散元模型, 从微观角度分析了取种器、土壤颗粒与蒜种间的动态相互作用, 并通过宏观试验验证了仿真结果的可靠性。结果表明: 插播深度、提种高度、插播速比以及土壤颗粒表面能是影响大蒜种植直立度和播深一致性的关键因素。在一定范围内, 增大插播深度与提种高度可显著提高直立度, 但超过临界值后效果减弱; 插播速比对直立度的影响呈现非线性关系, 速比过低或过高均会导致直立度下降; 此外, 较低的土壤颗粒表面能有助于获得更高的直立度与更好的土壤回填效果。试验验证表明, 仿真结果与物理试验结果具有高度一致性, 平均相对误差小于 10%。本研究为优化大蒜定向播种技术提供了理论基础与数值模拟工具, 对提高大蒜种植的直立度与播深一致性具有重要指导意义。

INTRODUCTION

Garlic is an essential condiment widely used in the health and pharmaceutical industries (Hong et al., 2023; Lin et al., 2024). Numerous studies have shown that garlic significantly prevents and treats various diseases (Mondal et al., 2022; Oravetz et al., 2023). Garlic is extensively cultivated worldwide, with China leading in both cultivation area and production.

As an important cash crop, enhancing the yield per unit area and the external quality of garlic has always been a focal topic in the agricultural sector. Studies have shown that the adoption of directional seeding technology can significantly improve both the yield and quality of garlic, with the orientation of the garlic clove during seeding having a notable impact on the emergence time, yield metrics, and the external quality of seedlings (Liu et al., 2022; Liu et al., 2018).

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To date, the academic community has conducted extensive and in-depth research on the regulation of garlic clove orientation and has achieved a series of significant results (Li *et al.*, 2020; Fang *et al.*, 2024). However, on the basis of achieving precise single-seed selection and accurate orientation control of garlic cloves, the critical technical challenge of ensuring optimal plant spacing, row spacing, and seeding depth for the cloves, while maintaining the stability of their orientation during the insertion process, remains to be resolved. Effectively addressing this issue not only holds significant theoretical value but also has practical implications for improving the mechanization level and economic efficiency of garlic cultivation.

Directional insertion technology involves complex interactions among soil, soil-engaging components, and garlic. Due to the heterogeneity, discontinuity, and anisotropy of soil particle media, traditional analytical methods struggle to deeply reveal the underlying mechanisms. In recent years, with the advancement of computational capabilities and the development of Discrete Element Method (DEM) simulation technology, DEM has proven to be an effective tool for addressing such problems (Sun *et al.*, 2024; Wang *et al.*, 2024; Yuan *et al.*, 2023). In agricultural technology research, DEM simulation has been widely applied. For instance, scholars have successfully utilized DEM to study the interaction mechanisms between soil-engaging components and soil, achieving significant results (Zhao *et al.*, 2021; Chen *et al.*, 2013; Hang *et al.*, 2017; Sun *et al.*, 2020). Furthermore, DEM technology has been extensively employed in various agricultural fields, including seed metering device optimization, precision fertilization, combined crop harvesting, and feed processing (Ding *et al.*, 2018; Guzman *et al.*, 2020; Keppler *et al.*, 2012; Mao *et al.*, 2020), providing crucial support for the advancement of agricultural mechanization and precision agriculture.

Inspired by these researches, this study proposes a method of applying advanced discrete element simulation technology to investigate the interaction between garlic clove-inserter-soil. Firstly, a discrete element model of the garlic clove insertion process is established and the interaction mechanism between the inserter, the soil and the garlic cloves in the process of directional seeding is analyzed from a microscopic point of view. A test rig was then designed. The interaction mechanism was verified from a macroscopic point of view using a test rig. This method has the advantages of good visualization and rich information. The main contributions of this work are summarized as follows:

(1) Based on an analysis of the structure and operating principle of the inserter, a discrete element model reflecting the interactions between the inserter, soil, and garlic during the directional seeding process was established. Appropriate contact models were determined for soil-soil, inserter-soil, garlic-inserter, and garlic-soil interactions.

(2) The main factors affecting the uprightness of garlic clove planting were analyzed, and the influence law of each factor on the uprightness of insertion was elucidated, while the main factors affecting the consistency of planting depth in the process of insertion were analyzed and the influence law of each factor on the consistency of planting depth was also analyzed.

(3) A test bench based on the LabVIEW platform was constructed, allowing convenient and independent control of each motion parameter of the insertion device. This setup provides favorable conditions and improved convenience for validating the interaction mechanisms obtained through the discrete element model analysis.

In this study, the discrete element model of garlic-inserter-soil was established by using DEM method to analyze the effects of the motion parameters of the inserter and the bonding force of the soil on the index parameters such as the uprightness of garlic planting and the volatility of the planting depth, which can provide a reference and a guide to the related development of improving the uprightness and depth consistency of directional planting of garlic.

MATERIALS AND METHODS

1. Structure and principle of directional inserter

The role of the directional insertion mechanism is to ensure that the seed maintains a stable attitude during planting into the soil. Since seeds are subject to friction and impact during their descent and contact with the soil, resulting in changes in their position and attitude, the inserter needs to control these changes. The double duckbill planter consists of two symmetrical duckbill-type structures that can be rotated open in both directions, and when closed, form a narrow cylinder with a tapered bottom. This design helps to fix the attitude of the seed and ensures that the seed maintains the agronomically required attitude after insertion into the soil. The detailed structure is shown in Fig. 1.

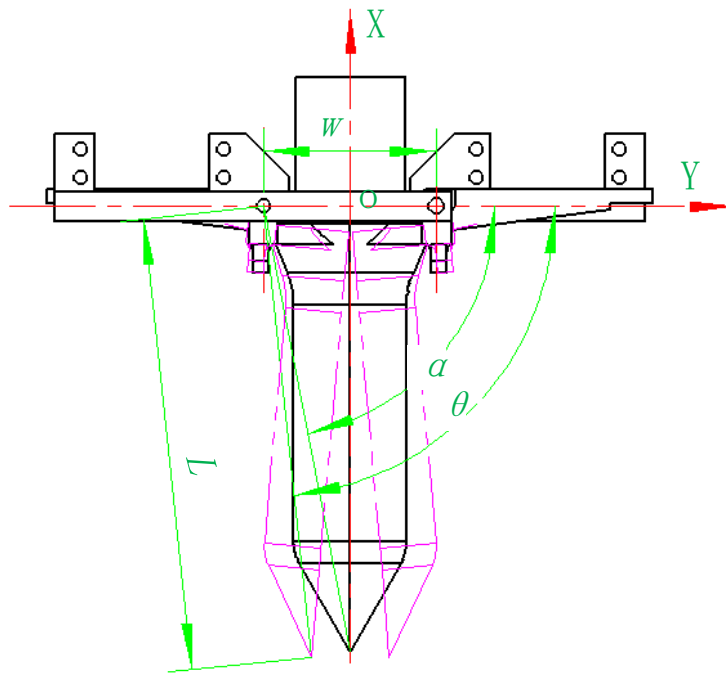


Fig. 1 - Schematic diagram of duckbill directional insertion structure

The principle that enables the double duckbill inserter to achieve directional insertion of garlic cloves is as follows:

(1) Garlic cloves are naturally long and narrow in shape. After falling into the inserter, their posture is constrained by the internal space, allowing them to maintain an adjusted and relatively stable orientation. When a clove reaches the bottom of the duckbill, its posture becomes further stabilized because the bottom is designed with a conical structure.

(2) When the inserter penetrates the soil and reaches the predetermined depth, the two duckbills begin to open, causing the surrounding soil particles to flow around the clove as the opening angle increases. As the duckbills continue to open, the clove gradually loses contact with the inserter. The surrounding soil then flows in and supports the clove, stabilizing its orientation and completing the directional seeding process.

The effectiveness of directional garlic seeding is closely related to the complex interactions among the planter, the garlic clove, and the soil. Soil mobility and the trajectory of the inserter's duckbill directly influence the directional insertion performance. Soil mobility is strongly affected by soil type, moisture content, and compaction. The trajectory of the duckbill is determined by the shape of the cavity it forms, and the resulting seed slot geometry is critical for maintaining the proper orientation of the garlic clove. The motion trajectory of the duckbill tip is expressed in Eq. (1).

$$\begin{cases} \theta = \alpha + \omega(t - t_0) \\ x = \delta \left(\frac{W}{2} + L \sin \left(\frac{\pi}{2} - \theta \right) \right) \\ y = v_y t - L \cos \left(\frac{\pi}{2} - \theta \right) \\ z = v_z t \end{cases} \quad (1)$$

where: (x, y, z) denotes the three coordinate directions of the duckbill tip, W denotes the distance between the rotation centers of the two duckbills, L denotes the distance between the rotation center of the duckbill and the tip, α and θ denote the angles between the Y-axis and the line from the duckbill's rotation center to its tip, corresponding to the two states (closed and open), t denotes the time, and t_0 is the moment when the duckbill starts to open, and (v_x, v_y, v_z) denotes the moving speed of the duckbill in the open-close direction, vertical direction and horizontal direction respectively. The detailed meanings of these parameters are shown in Fig. 1. The ratio of the vertical and horizontal speed of movement, later referred to as the Speed ratio of the inserter, is calculated as shown in Eq. (2).

$$i = \frac{V_{\perp}}{V_{\parallel}} \quad (2)$$

where: $v_{\perp}$ is the vertical insertion speed, m/s; $v_{\parallel}$ is the horizontal insertion speed, m/s.

2. Discrete element simulation modeling and simulation design

2.1. Discrete element contact model selection

The mechanics of the discrete element calculations are based on the interactions between the particles and the instantaneous translational and rotational positions of the particles through the application of Newton's equations, and the relevant kinetic equations are as follows:

$$m \frac{d^2 x}{dt^2} = F_{con} + F_{ext} \quad (3)$$

$$I \frac{d\omega}{dt} = M_{con} + M_{ext} \quad (4)$$

where: F_{con} is the contact force, F_{ext} is the external force, M_{con} is the contact moment, M_{ext} is the external moment, m is the mass, I is the moment of inertia.

Selection of an appropriate discrete element contact model and reasonable material property parameters is crucial to simulate the dynamic behavior between soil and soil-interacting components (Abo-Elnor *et al.*, 2003). For different application scenarios, researchers have proposed a variety of discrete element contact models. Some of these classical models include the Hertz-Mindlin model (Tsuji *et al.*, 1992; Sakaguchi *et al.*, 1993), the Hertz-Mindlin with JKR model (Sakaguchi *et al.*, 1993) Hertz-Mindlin with bonding model (Potyondy *et al.*, 2004), Hertz-Mindlin with RVD Rolling Friction model (Ai *et al.*, 2011), and Hysteretic Spring model (Walton *et al.*, 1986).

Through theoretical analysis and literature review, the Hertz-Mindlin no-slip contact model and the Hertz-Mindlin with JKR model were selected as the contact models. Specifically, the Hertz-Mindlin with JKR model was applied to describe contact between soil particles. Because this model increases inter-particle cohesion, it more accurately captures microscopic deformation and particle mobility. Therefore, using the Hertz-Mindlin with JKR model for soil-soil contact provides a more realistic basis for analyzing clove-soil-inserter interactions during the insertion process. In contrast, the Hertz-Mindlin no-slip contact model was selected for the contacts between the inserter and soil, the clove and the inserter, and the clove and soil, as it is effective for modeling contact behavior between solid bodies.

2.2. Discrete element modeling

After modeling the inserter in SolidWorks, it was imported into EDEM to generate a geometric model. The dimension of the soil slot of the simulation model was 450 mm × 300 mm × 200 mm. The soil particle parameters were set according to the related literature and adjusted according to the actual situation. The radii of the soil particles were 0.5 mm, 1.5 mm, and 2.5 mm, and the sizes of the particle sizes were randomly distributed between 0.9 and 1.1 times the particle size, in which the percentage of each type of particle was 15%, 75%, and 10%, respectively. The soil was divided into six layers in order to facilitate observation and analysis during post-processing. A schematic of the simulation model is shown in Fig. 2.

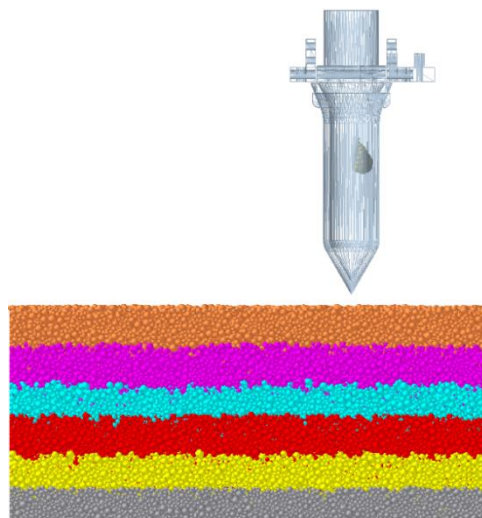


Fig. 2 - Discrete element models

The discrete element simulation parameters have a crucial influence on the simulation results. Through relevant experiments and literature review (Zhao *et al.*, 2025; Li *et al.*, 2020), the final simulation parameters were determined, as shown in Table 1.

Table 1

Discrete element simulation parameters	
Parameter	Value
Size and proportion of soil particles (radius)	0.5 mm (15%); 1.5 mm (75%); 2.5 mm (10%)
Density of soil particles / (kg/m ³)	1750
Shear modulus of soil / Pa	6.0×10 ⁷
Poisson's ratio of soil	0.3
Coefficient of restitution (soil-soil)	0.6
Static friction coefficient (soil-soil)	0.53
Dynamic friction coefficient (soil-soil)	0.16
Surface energy between soil particles / J/m ²	0.2~10
Coefficient of restitution (clove-soil)	0.4
Static friction coefficient (clove-soil)	0.3
Rolling friction coefficient (clove-soil)	0.1
Coefficient of restitution (clove-inserter)	0.4
Static friction coefficient (clove-inserter)	0.4
Rolling friction coefficient (clove-inserter)	0.2
Coefficient of restitution (inserter-soil)	0.3
Static friction coefficient (inserter-soil)	0.4
Rolling friction coefficient (inserter-soil)	0.2

2.3. Design of the simulation

Clove seeding can be classified into two types: intermittent seeding and continuous seeding. Intermittent seeding refers to a process in which the seeding mechanism moves vertically up and down, and the seeding port opens to release the clove. During this process, the seeder does not move horizontally, so it is also referred to as in-situ seeding. Continuous seeding, in contrast, involves the inserter moving not only vertically but also horizontally during the seeding process.

Based on the results of previous experimental trials, it was determined that in the intermittent insertion method, the primary factors influencing the variability of clove uprightness and planting depth are the insertion depth and the moment at which the inserter's duckbill begins to open. The opening moment of the duckbill can be represented by the distance between the duckbill tip and the maximum insertion depth at the time of opening; therefore, in the following sections, the lifting height (HL) is used to characterize the duckbill opening moment of the planter. In the intermittent seeding simulations, five insertion depths were selected: 40 mm, 50 mm, 60 mm, 70 mm, and 80 mm. For each insertion depth, five lifting heights were set: 0 mm, 7.5 mm, 15 mm, 22.5 mm, and 30 mm. A total of 25 simulation groups were conducted, with 10 garlic cloves simulated in each group.

Theoretical analysis and pre-tests revealed that the speed ratio of the planter and soil moisture content in the continuous insertion method are the main factors affecting the uprightness of garlic insertion and the volatility of planting depth. In order to explore the influence of each factor on the performance of upright insertion, the following simulation experiment design was carried out: (1) eight types of insertion speed ratios were selected for the simulation experiment when the surface energy was set to 0.2 J/m², which were 0.5, 1, 1.5, 2, 2.5, 3.0, 3.5 and 4.0; (2) four types of surface energy were selected for the simulation experiment when the insertion speed ratio was set to 2.0, which were 0.2 J/m², 0.5 J/m², 2 J/m² and 10 J/m², respectively. 10 garlic cloves were simulated for each set of tests.

3. Design of test device

3.1. Structure and principle of the test device

To verify the validity of the simulation results, a dedicated test device was designed to drive the inserter and reproduce all motion conditions used in the simulation. The detailed structure of the test setup is shown in Fig. 3.

The working principle of the test device is as follows: by controlling the motion parameters of the actuating components, the device enables precise control of the insertion speed, displacement, and duckbill opening angle in both the horizontal and vertical directions. Specifically, the horizontal motion of the duckbill is achieved by controlling the rotation speed and rotation angle of the stepper motor (7). Vertical motion is realized through the electric actuator (5). The opening angle and opening moment of the duckbill are controlled by the servo motor (9).

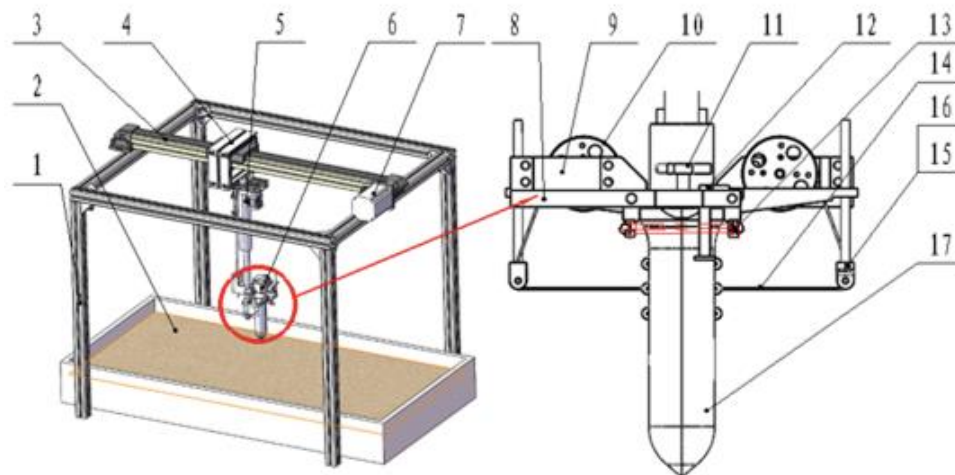


Fig. 3 - Mechanical structure of the test device

1. Frame; 2. Soil tank; 3. Slide track; 4. Slide seat; 5. Electric actuator; 6. Directional insertion mechanism; 7. Stepper motor; 8. Mounting bracket; 9. Servo motor; 10. Winch; 11. Photoelectric switch sensor; 12. Insertion-depth control lever; 13. Return spring; 14. Steel wire; 15. Bearing housing; 16. Bearing; 17. Duckbill inserter

3.2. Control system of the test device

The control system of the test device is primarily composed of an industrial computer, a data acquisition card, an electric-actuator stepper-motor driver, a slide-table stepper-motor driver, Servo 1, Servo 2, a photoelectric switch sensor, and other auxiliary components.

The industrial controller uses an NI PXIe-8840 Quad-Core processor, with LabVIEW 2018 as the development and control software. The built-in data acquisition board is an NI PXIe-6356. The servos used are SPT543LV-270 models, and the photoelectric switch sensor is an FFU670-CR1, PNP type.

According to the functional requirements of the test setup, the control system is divided into four functional modules: the insertion-depth signal acquisition module, the slide stepper-motor pulse signal generation module, the pusher stepper-motor pulse signal generation module, and the servo pulse duty-cycle adjustment module. The control system was developed using the LabVIEW platform, and the four modules run in parallel within a While loop. The program block diagram is shown in Fig. 4.

The function of the seeding-depth signal acquisition module is to detect the depth to which the duckbill inserter penetrates the soil and to provide feedback for depth control of the test bench. When the duckbill reaches the specified insertion depth, the soil pushes the insertion-depth control lever upward. At this moment, the photoelectric switch sensor detects the change and sends a signal to the industrial computer through the data acquisition card. Based on the control algorithm implemented in LabVIEW, the industrial computer outputs a control signal to rotate the servo motor by a specified angle. The servo then drives the pulley, which in turn pulls the steel wire. As the steel wire is tensioned, the two duckbills open outward, thereby achieving active control of the seeding depth. When the steel wire is tensioned, the two duckbills open outward, enabling active control of the insertion depth. The slide stepper-motor pulse signal generation module and the actuator stepper-motor pulse signal generation module control the movement speed and direction of the slide base and the electric actuator, respectively, thereby regulating the insertion speed ratio. The primary function of the servo pulse duty-cycle adjustment module is to control the rotation angle and direction of the two servos, enabling the opening and closing of the duckbill inserter as well as adjusting the magnitude of the duckbill opening angle.

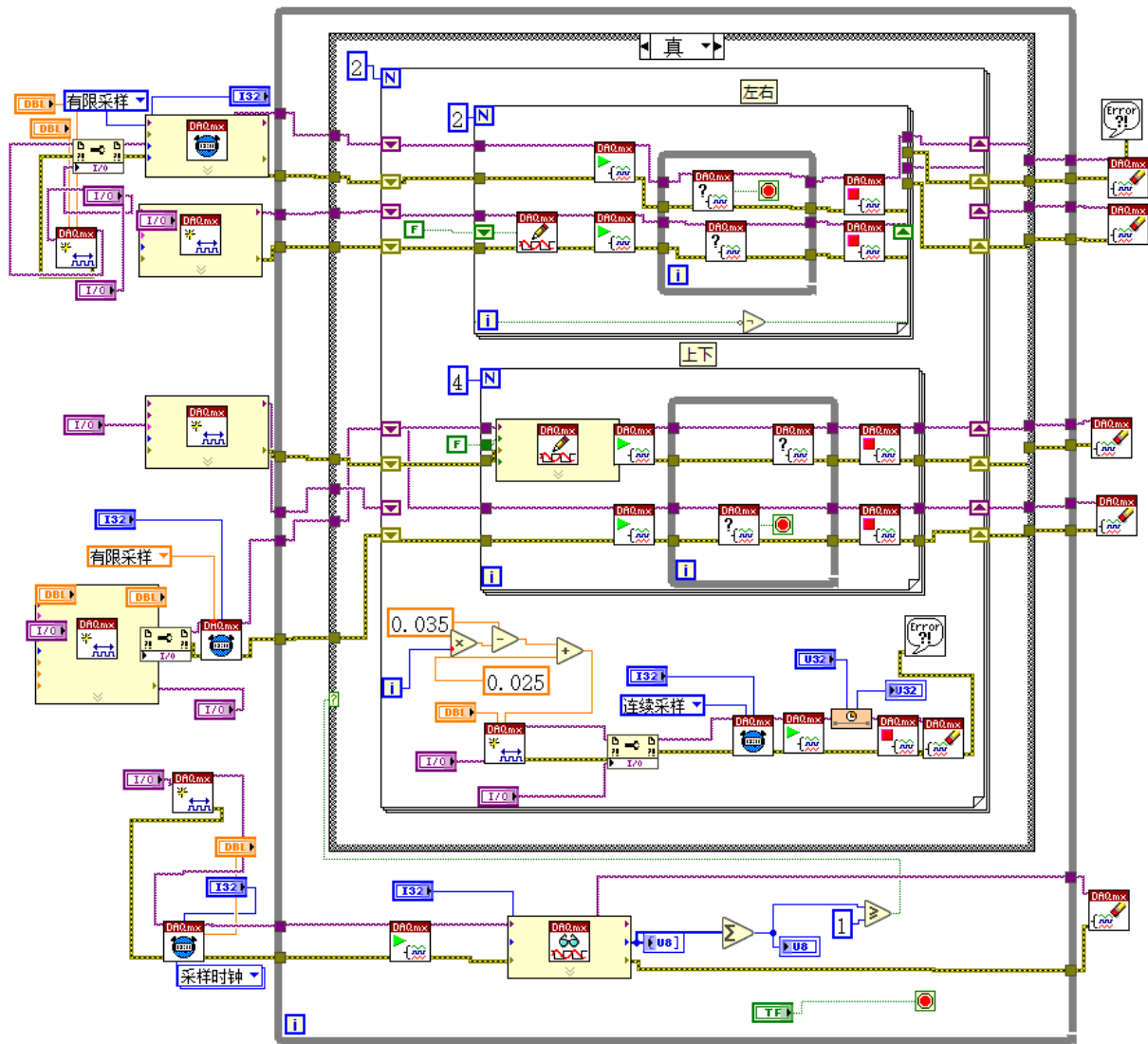


Fig. 4 - Block diagram of the control program for the test device

RESULTS AND DISCUSSION

1. Evaluation indicators

Uprightness reflects the degree to which the garlic clove bud end points upward and remains vertical relative to the ground. It is expressed as the angle between the bud axis and the ground plane, as shown in Fig. 5. The maximum uprightness is 90°, and a larger value indicates better upright orientation. The uprightness fluctuation value refers to the deviation of uprightness from its average value and is calculated using Eq. (5). A smaller uprightness fluctuation value indicates greater stability and better planting consistency.

$$\delta_{\phi} = \phi_v - \bar{\phi}_v \quad (5)$$

where: δ_{ϕ} is the uprightness fluctuation value, °; $\bar{\phi}_v$ is the mean uprightness value, °.

The planting depth is defined as the distance from the soil surface to the bottom of the garlic clove and is denoted by the symbol d . A smaller planting-depth fluctuation value indicates more consistent planting depth, which in turn leads to more uniform seedling emergence time.

The fluctuation value of planting depth represents the deviation of each measured depth from its mean value and is calculated as:

$$\delta_d = d_h - \bar{d}_h \quad (6)$$

where:

δ_d is measured planting depth, mm; $\bar{d}_h$ is mean planting depth, mm.

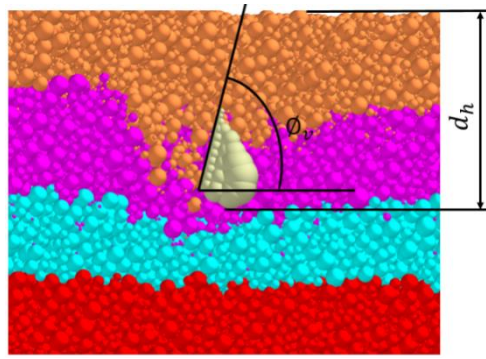


Fig. 5 - Diagram of the definition of uprightness and depth parameters

2. Simulation analysis and discussion

Seeding uprightness and depth consistency are two important performance index parameters of the garlic precision planter. To improve the performance parameters of the garlic precision planter, discrete element analysis of the garlic upright seeding process is carried out with the variable factors of seeding depth, lifting height, seeding speed ratio, and soil particle surface energy. This study explores the main factors affecting the uprightness and planting depth consistency of garlic seedlings, and a specific simulation analysis was conducted to provide theoretical support for the development of a precision garlic seeding machine.

(1) Effect of insertion depth on uprightness

Simulation tests were conducted to explore the impact of insertion depth on uprightness. The relationship between insertion depth and uprightness was investigated at five different lifting heights. There were 25 sets of simulation trials, with each set consisting of 10 different cloves. The impact of insertion depth on uprightness is illustrated in Figure 6. The experiments demonstrated a significant correlation between the depth of insertion and the degree of uprightness. The average uprightness ranged from 42° to 70° at various insertion depths. Furthermore, uprightness increased within a specific range as the insertion depth increased. However, this trend gradually diminished as the insertion depth approached 70 mm.

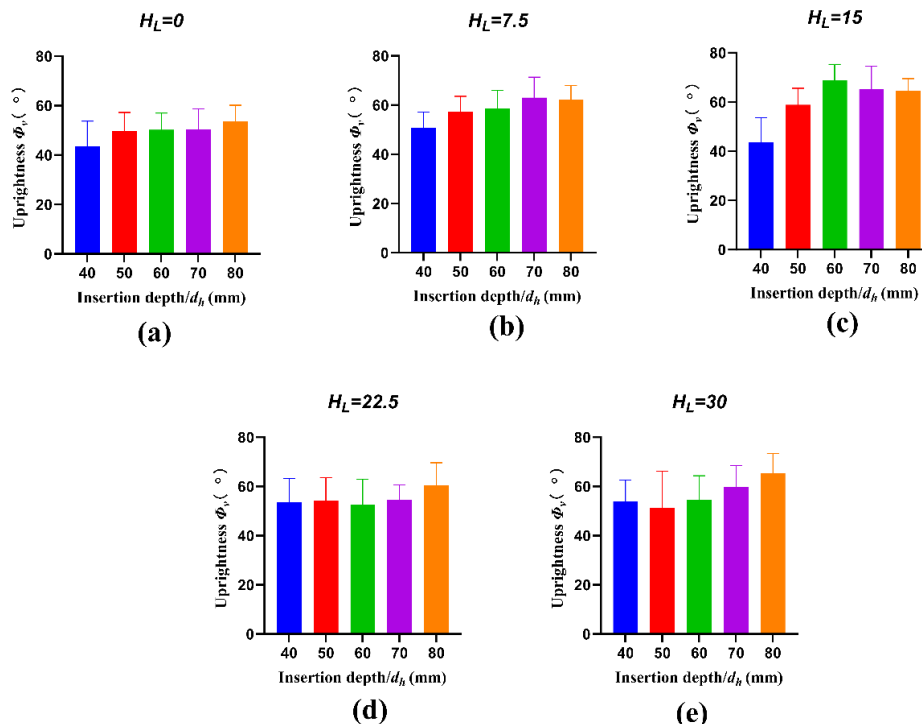


Fig. 6 - Effect of insertion depth on uprightness

Increasing the insertion depth within a specific range offers multiple advantages for enhancing the degree of uprightness in garlic planting. Firstly, as the insertion depth increases, the soil particles at the top of the seed hole flow back more rapidly to the bottom when the insertion duckbill opens. This rapid flow of soil particles ensures better encapsulation of the garlic, effectively maintaining its upright posture and thereby improving its degree of uprightness.

Additionally, assuming a constant opening angle of the insertion duckbill, a greater insertion depth results in a narrower taper of the seed hole. This increased taper enhances the constriction of the seed hole, which in turn increases the likelihood of the garlic remaining upright upon release from the inserter. As illustrated in Fig.7, the insertion depth has a significant impact on both soil disturbance and the flow rate of soil particles. In summary, increasing the insertion depth within a defined range can markedly improve the verticality of garlic planting.

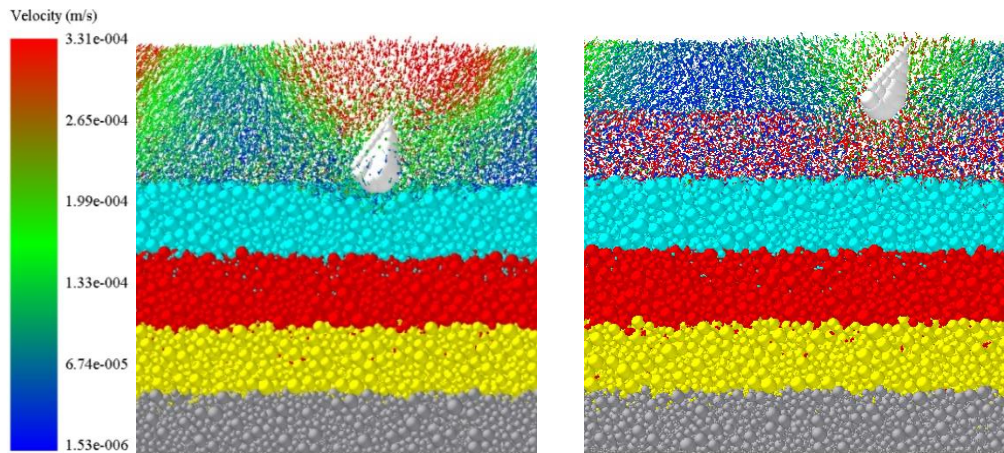


Fig. 7 - Different insertion depths corresponding to insertion soil velocity vector diagram

(2) Effect of Lifting Height on Uprightness

To investigate how lifting height influences garlic uprightness, numerical simulations were conducted to systematically analyze the relationship between lifting height and uprightness under five different planting-depth conditions. A total of 25 simulation groups were performed, with each group simulating 10 garlic cloves exhibiting natural morphological variation. The results are shown in Fig. 8. The findings indicate that lifting height is a key factor affecting uprightness. Under fixed planting-depth conditions, the average uprightness initially increases as the lifting height increases and then stabilizes. Once the lifting height reaches a critical threshold, further increases have little effect on uprightness. Notably, under shallow planting conditions, excessively large lifting heights can cause a substantial decrease in uprightness. This may be related to insufficient anchoring resistance in shallow soil layers, and the underlying mechanism requires further investigation.

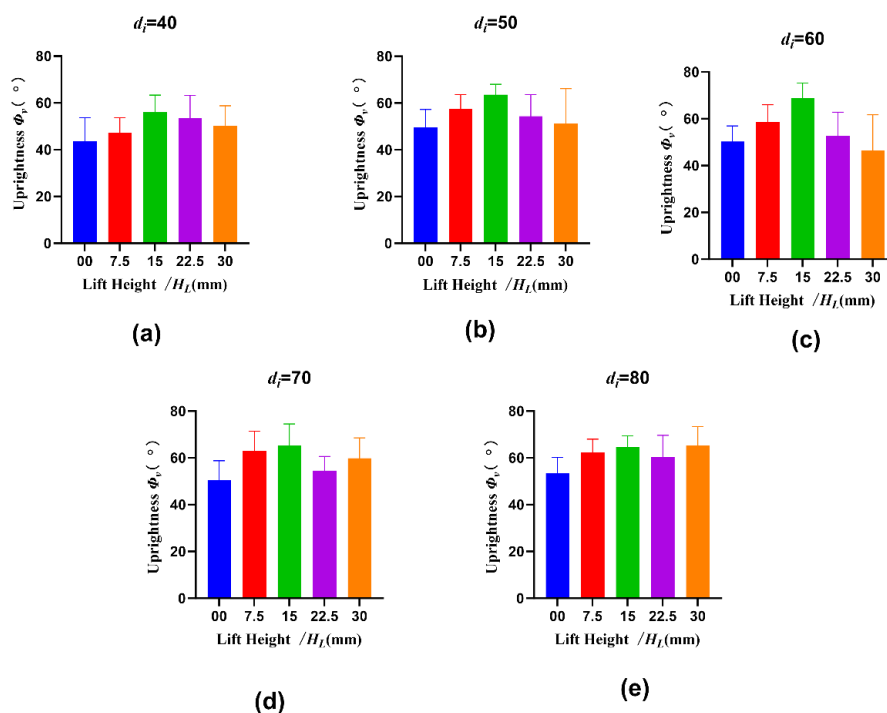


Fig. 8 - Effect of lifting height on uprightness

Figure 9 illustrates the mechanism of the lifting height during the planting process. The study reveals that a moderate increase in lifting height is beneficial for improving uprightness, primarily due to the formation of conical seed holes and the characteristics of soil backfilling. When the planter reaches its lowest point, its conical tip creates an initial conical hole in the soil. As the planter is lifted, although some soil particles backfill, the basic shape of the conical hole is maintained. Once the planter is raised to the set height, the duckbill opens, allowing the garlic seed to fall into the conical hole under gravity. Simultaneously, the disturbed soil particles quickly backfill around the seed. Under the combined effect of the conical hole wall and the backfilled soil, the garlic seed maintains an optimal upright posture. However, when the lifting height exceeds a critical value, the uprightness tends to decline. This is mainly attributed to two factors: first, an excessive lifting height causes more soil particles to fall into the conical hole, reducing its depth; second, at a fixed planting depth, an excessive lifting height decreases the distance between the garlic seed and the ground surface when the duckbill opens, reducing the amount of effectively backfilled soil particles.

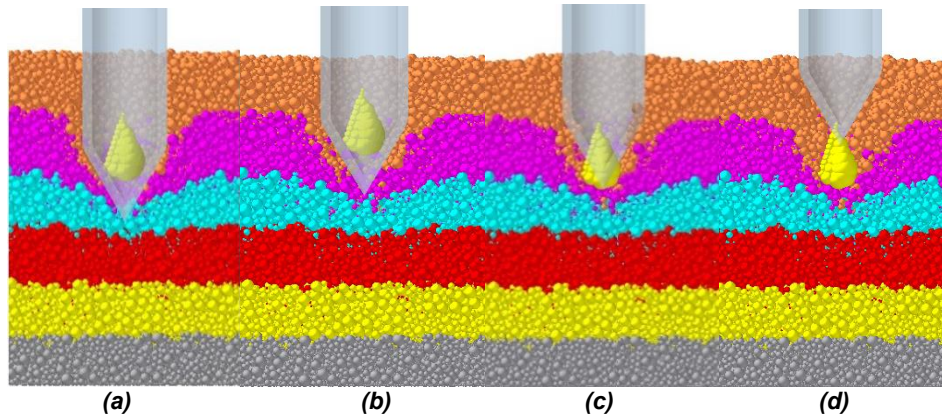


Fig. 9 - Schematic diagram illustrating the insertion process influenced by lifting height

(3) Effect of insertion speed ratio on uprightness

In the process of continuous dibbling operations, the composite motion of the dibbler in both vertical and horizontal directions plays a decisive role in the formation of seed hole morphology. Among these, the ratio of vertical to horizontal motion speed (i.e., the dibbling speed ratio) is a critical parameter. In this study, the surface energy of soil particles was set at 0.2 J/m^2 , and the influence of the dibbling speed ratio on the quality of dibbling was investigated through experiments. Fig 10 illustrates the effect of the dibbling speed ratio on seed uprightness. The results indicate that a higher average seed uprightness can be achieved when the dibbling speed ratio falls within a reasonable range. However, when the speed ratio is either too small or too large, it leads to a significant decline in seed uprightness. Further analysis of the impact of the dibbling speed ratio on the stability of uprightness reveals that there is considerable fluctuation in seed uprightness during continuous dibbling operations, primarily due to the combined effects of various random factors during the process. Notably, selecting an appropriate dibbling speed ratio has a significant effect on reducing the range of uprightness fluctuations, providing an important basis for improving the stability of dibbling operations.

The mechanism by which an appropriate dibbling speed ratio improves seed uprightness and reduces its variability is primarily reflected in the following aspects: the dibbling speed ratio influences seed uprightness by determining the geometric morphology of the seed hole. When the dibbling speed ratio is small, the formed seed hole exhibits an elongated shape, which leads to two adverse effects: first, the garlic seed has a larger range of positional and orientational changes during the implantation process; second, the horizontal movement of the dibbling duckbill during its opening process exerts a dragging effect on the garlic seed through friction, thereby reducing uprightness. As the dibbling speed ratio increases, the morphology of the seed hole gradually becomes smoother, resulting in two positive effects: first, the range of positional and orientational changes of the garlic seed during implantation is significantly reduced; second, the horizontal displacement of the dibbling duckbill after opening decreases, which not only avoids posture changes caused by dragging but also promotes rapid soil backfilling, thereby improving uprightness. However, when the dibbling speed ratio exceeds a critical value, the horizontal dimension of the seed hole becomes smaller than its lateral dimension. At this point, further increasing the speed ratio produces negative effects. On one hand, the spatial constraints prevent further improvement in uprightness. On the other hand, excessively small horizontal movement inhibits soil backfilling, leading to a decline in uprightness.

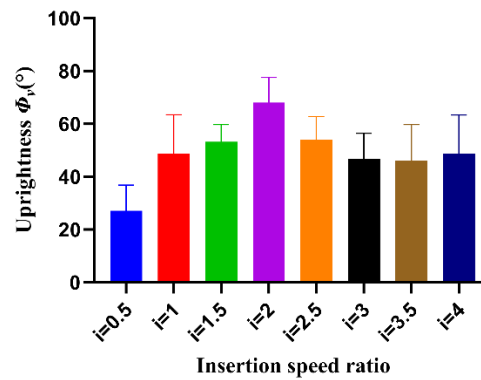


Fig. 10 - Effect of insertion speed ratio on uprightness

3. Field Experimentation and Validation

To systematically verify the consistency between the discrete element method (DEM) simulation model and actual field performance, field validation experiments were conducted using a self-developed garlic planter (Fig. 11). A comparative analysis of four representative operating conditions (Fig. 12) showed strong agreement between the simulation results and the field-measured data. The average relative errors for both seeding uprightness and planting depth—two key performance indicators—were less than 10%. These findings confirm the reliability of using the discrete element method to investigate the interaction mechanisms within the garlic-planter-soil system. Moreover, this study provides an effective numerical simulation approach for optimizing planting operational parameters to enhance seeding uprightness and planting-depth consistency.



Fig. 11 - Garlic planter

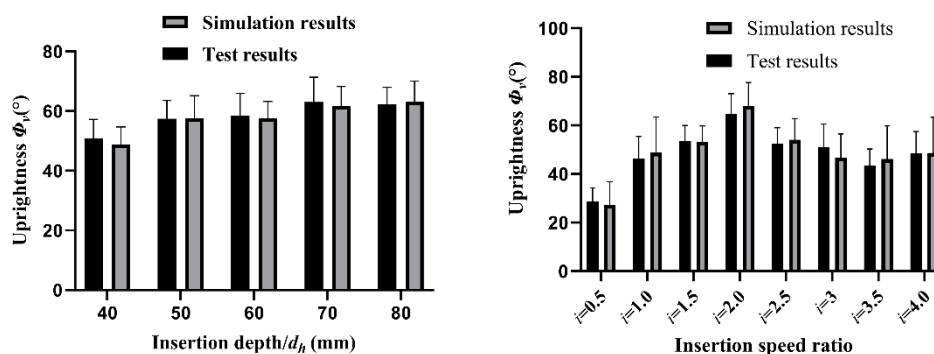


Fig. 12 - Comparison of simulation and experimental results

CONCLUSIONS

This study systematically analyzed the interactions between the dibber, soil, and garlic during the directional seeding process using the Discrete Element Method (DEM). The key factors influencing garlic uprightness and planting-depth consistency, as well as their underlying mechanisms, were identified. The main conclusions are as follows:

(1) Effect of Dibbling Depth on Uprightness:

Within a certain range, increasing the dibbling depth significantly improves uprightness. However, when the dibbling depth exceeds a critical value (70 mm), the improvement gradually diminishes. Greater dibbling depth promotes faster soil backfilling and stabilizes the garlic posture, but excessive depth may increase variability in uprightness.

(3) Effect of Lifting Height on Uprightness:

Lifting height is an important factor affecting garlic uprightness. Within a reasonable range, increasing the lifting height effectively enhances uprightness. However, once the lifting height exceeds a critical threshold (15 mm), uprightness decreases. Optimizing the lifting height helps form a stable conical seed hole, promotes soil backfilling, and improves the upright orientation of the garlic clove.

(4) Effect of Dibbling Speed Ratio on Uprightness:

The dibbling speed ratio (vertical-to-horizontal speed ratio) has a significant impact on uprightness. Both excessively low and excessively high speed ratios reduce uprightness. When the soil-particle surface energy is set to 0.2 J/m², a speed ratio of 2 yields the best uprightness performance. An appropriate dibbling speed ratio enhances uprightness and reduces variability by influencing seed-hole geometry and soil backfilling behavior.

Overall, this study provides a theoretical foundation and numerical simulation methodology for optimizing directional garlic seeding technology, offering valuable guidance for improving uprightness and planting-depth consistency. Future research may further explore the effects of different soil types, structural optimization of the dibber, and the synergistic effects of multiple factors on garlic planting quality.

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