DESIGN AND EXPERIMENT OF AIR-SUCTION GARLIC SEEDING UNIT
/
气吸式蒜苗单体的设计与实验

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ABSTRACT
Based on the requirements for hybrid garlic seed sowing, the overall structure of an air-suction garlic seeding unit was designed, and its working principle was described. The adsorption pressure required for the seed metering device was determined to be -5 kPa. One hopper was selected for the bud reversing device, with an angle of 24.5°, and the perimeter of the insertion device measured 600 mm. The optimal combination of parameters for sowing involved a negative pressure of -5 kPa and a forward speed of 1 km/h at the third level. Under these conditions, the qualified rate of individual sowing reached 84.26%, while the missed sowing rate was 7.12%, meeting the agronomic requirements for garlic seed sowing. Field experiments validated the theoretical analysis and bench tests, providing a solid foundation for the future production and promotion of garlic sowing units.

摘要
根据杂交大蒜种子的播种要求，设计了吸气式大蒜播种单体的整体结构，并描述了其工作原理。确定种子计量装置所需的吸附压力为-5 KPa。为磷芽交换装置选择了一个料斗，角度为24.5°，插入装置的周长为600 mm。播种的最佳参数组合为负压-5 KPa，前进速度为1 km/h，设定在三级档位。在此条件下，单粒播种的合格率达到了 84.26%，漏播率为 7.12%，满足了大蒜种子播种的农艺要求。田间试验验证了理论分析和台架试验的准确性，为大蒜播种单体的未来生产和推广奠定了基础。

INTRODUCTION
Garlic can be consumed as both garlic head and garlic sprouts and can also be used as a seasoning. Garlic has the effects of disinfection, swelling relieving, insecticidal, and dysentery stopping *(Jia-feng et al., 2021)*. Garlic polysaccharides extracted from garlic have a specific lipid-lowering effect, which can improve human intestinal microbiota, reduce liver burden, and may reduce the risk of metabolic syndrome *(Chan-yuan et al., 2020)*. In 2020, the global garlic planting area was 1.68 million hectares, with a garlic production of 32 million tons. Its planting area, production, and foreign trade export volume ranked first globally *(Xiang-yuan et al., 2017; Bin-bin et al., 2019)*. At present, the cultivation of garlic in China is still mainly artificial *(Jia-lin et al., 2018)*. However, due to the high planting cost and long planting cycle, the mechanization of garlic planting should be strengthened. At present, *Minghao Lu* from Anhui Agricultural University, one of the article’s author, has designed an anti-seed tooth assisted air suction garlic seeder. *Chun-ling Zhang et al., (2021),* designed an electric hydraulic mixed regulation garlic seeder. *Xiang et al., (2023),* from Nanjing Vocational and Technical University of Technology have designed a self-propelled garlic sowing and fertilization integrated machine. Internationally, Türkiye DEMSAN Company has designed a traction garlic planter *(Zhao-guo et al., 2021)*. Italian company SPAPPERI has also designed a mechanical garlic seeder that can sow a single seed, avoiding situations where there is multiple or no garlic seeds at once *(Shuang-xi et al., 2015)*. French company ERME has designed three different series of garlic seeders *(Dong et al., 2020)*.

Garlic seeders on the market still mainly use mechanical seed picking and metering. People used metering components similar to the spoon chain type *(Ai-jun et al., 2018)*, which cannot adapt well to different garlic sizes and may cause congestion. At the same time, there will be significant vibration when sowing in the field, making the efficiency of the mechanical seeder low *(Yu-xiang et al., 2022)*. The pneumatic type relies on the negative pressure provided by the fan to tightly adsorb garlic onto the seed tray, meeting the requirements of garlic seeds of different sizes and ensuring the stability of single seed picking *(Xin-peng et al., 2022; Han et al., 2023)*.

Zaidi et al., (2019), invented a pneumatic planter for peas planting. However, current research is still limited to seeders, and it is necessary to study a garlic seeding unit to solve the seeding problem *(Yu-dao and Xue-zhen, 2020)*.

To increase the single seed rate of garlic seeding, a kind of air-suction garlic seeding unit was designed in this paper. It mainly includes an air-suction garlic seeder, an upright planting mechanism, a pneumatic system, and a profiling mechanism. It can achieve the functions of single seed picking and upright planting of garlic seeds, meeting the agronomic requirements of garlic planting.

MATERIALS AND METHODS

The air-suction garlic sowing unit mainly consists of components such as an air-suction garlic seeder, a bracket, a profiling rod, a ground wheel, a seed guide device, a bud reversing device, and an upright insertion device, as shown in Figure 1. The unit body adopts a traction type and is connected to the tractor through a three-point suspension. The bracket mainly consists of square, tubular, and fixed brackets. The front end of the tubular support is fixedly connected with a three-point suspension hanger, the upper part of the tubular support is fixedly connected with a negative pressure fan, and the tubular support is fixedly connected with fixed support. The two sides of the fixed support are connected with four profiling rods through shaft hinges, and the other end of the four profiling rods is hinged with the square frame through another pair of shafts. The rear end of the negative pressure fan is fixedly connected to the belt pulley on the PTO （Power Take-Off） device through a belt, forming a mechanical structure with belt transmission. The belt pulley serves as the driving wheel, and the shaft at the rear end of the fan serves as the driven shaft. Through a hose, the fan is connected to the negative pressure pipe of the suction garlic seeder to form a closed channel, and the fan provides stable negative pressure for the air chamber of the seeder.

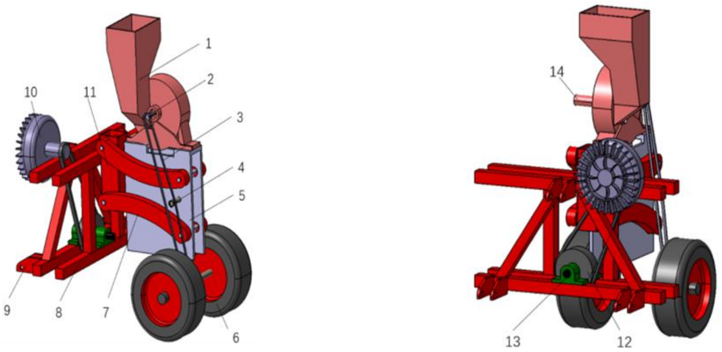


Fig. 1 - Schematic Diagram of the Air-Suction Garlic Sowing Unit Structure

(1) Air suction garlic seeder; (2) Seeding shaft; (3) Chain; (4) Tensioning wheel; (5) Square bracket; (6) Ground wheel; (7) Profiling rod; (8) Pipe bracket; (9) Three-point suspension hanger; (10) Negative pressure fan; (11) Fixed bracket; (12) Belt pulley; (13) PTO device; (14) Negative pressure pipe

Inside the square bracket, a seed guide device is fixedly connected below the seed discharge port of the air-suction garlic seed metering device. A bud reversing device is fixedly connected below the seed guide device. A vertical insertion device is fixedly connected below the bulb-reversing device. A tensioning wheel is fixedly connected to the outer surface of the square bracket and meshes with the chain to help adjust its tension. A ground wheel is fixedly connected to the rear of the vertical insertion device below the square bracket.

The suction-type garlic sowing unit provides negative pressure adsorption of garlic seeds on the seeding tray through a negative pressure fan and rotates regularly with the seeding tray. Subsequently, the hybrid garlic seeds are discharged from the seed discharge port of the seeder and then enter the bulb-reversing device. Finally, they enter the vertical insertion device in an upright posture. With the insertion device standing upright, they are planted in the soil, and the air-suction garlic sowing unit achieves a single seed sowing operation.

Structure of the bud-reversing device

Below the seed guide device is a bud reversing device, mainly composed of a conical hopper, connecting rod, gear, and other components, as shown in Figure 2. The apex of the conical hopper faces downwards. When the garlic seed falls into the conical hopper, it leans against the side wall. After the garlic seed stabilizes in the hopper, the hopper opens from the top of the cone, it leans against the side wall.

After the garlic seed stabilizes in the hopper, the hopper opens from the height of the cone, and the garlic seed that tends to be upright at this time falls out in this posture. The movement process of the hopper is shown in Figure 3. In this upright state, the hybrid garlic seeds enter the insertion device to achieve the goal of upright sowing.

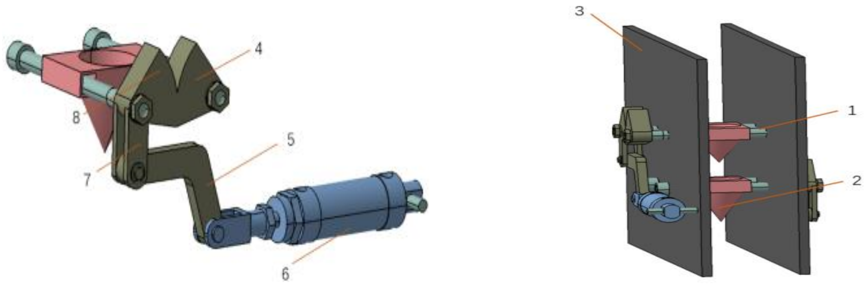


Fig. 2 - Schematic diagram of the structure of the bud-reversing device:
(1) Rotary shaft; (2) Conical hopper; (3) Square frame; (4) Right gear; (5) Obtuse angle connecting rod; (6) Cylinder; (7) Straight connecting rod (8) Left gear

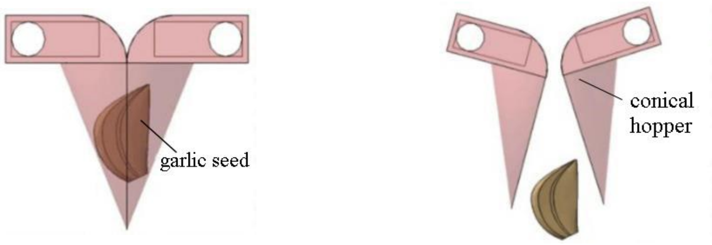


Fig. 3 - Working process of conical hopper

For the opening and closing of the conical hopper, the principle is controlled by the motion of the connecting rod mechanism. A pair of rotating shafts with gears connected to the surface are symmetrically fixed near the conical top surface of the hopper. The two gears mesh together, and a straight connecting rod is fixedly connected below the left gear. Its lower hinge is hinged with an obtuse angle connecting rod, and a small cylinder is hinged with it below this obtuse angle connecting rod. The small cylinder relies on an electromagnetic valve to control the extension of the piston, which causes the left gear to rotate clockwise, driving the right gear and its corresponding rotating shaft to rotate, making the hopper open and close. After some time, the piston rod retracts, and similarly, the hopper becomes tightly closed.

For the design of a conical hopper size, the following conditions must be met, as shown in the formula (1) (*Rong-jiang et al., 2022*).

$$\begin{cases} D_Z > h_{\max} \\ D_1 > t_{\max} \\ D_1 > w_{\max} \\ H_Z > h_{avg} \end{cases} \tag{1}$$

$$k = \frac{D_1}{2H_Z} \tag{2}$$

where:

D_Z is the top diameter of the seed dropping and D_1 is the stabilizing zones of the conical hopper, [mm]; H_Z is the height of the stabilizing zone, [mm]; h_{max} is the maximum length of the hybrid garlic seed, 34.1 mm; $t_{\max}$ is its maximum thickness, 19.8 mm; $w_{\max}$ is the maximum width of the hybrid garlic seed, 21.8 mm; h_{avg} is the average length of the hybrid garlic seed, 29.6 mm. k is the slope of the generatrix of the conical hopper.

Therefore, the seed falling area of the conical hopper is designed to be 40 mm, the diameter of the stable area is not less than 21.8 mm, and the height of the stable area is not less than 29.6 mm. According to formula (2), the slope of the hopper generatrix can be obtained.

Support and profiling mechanism

In the design of the air suction garlic sowing unit, a square bracket is set up with a U-shaped side view. Above, it is used to place an air-suction garlic seeder, and a groove is opened for the seeder to drop seeds at the seed discharge port. Two profiling rods are hinged on the square frame's outer side. During the movement of the air suction seeding unit, the relative position of the fixed bracket remains unchanged and is only affected by the traction of the tractor. The components behind the fixed bracket will fluctuate with the fluctuation of the ground.

For the contour line of the profiling rod, a certain degree of curvature is used to ensure that the rod can withstand internal and external pressure during stationary and moving processes. One side of the four rods is hinged on a fixed bracket, and the other is hinged on a square bracket (*Safari et al., 2019; Patel and Prajapati, 2018*).

In order to carry the garlic seeder with a bottom length of 405 mm and a width of 88.5 mm, accommodate the bud reversing device, and reduce weight, volume, and cost; its length is designed as 410 mm, and its width is designed as 120 mm. For the design of the profiling rod, the parallelogram profiling mechanism, known for its parallelogram movement characteristics, is widely used in corn seeders to ensure consistent sowing depth during operation and enhance the overall stability of the machine (*Patel and Prajapati, 2018*).

The profiling rod is in contact with the square bracket, so the lateral width of the profiling rod is designed to be 120 mm, the length is designed to be 250 mm, and the profiling rod is designed to be parallel to the profiling rod, as shown in Figure 4.

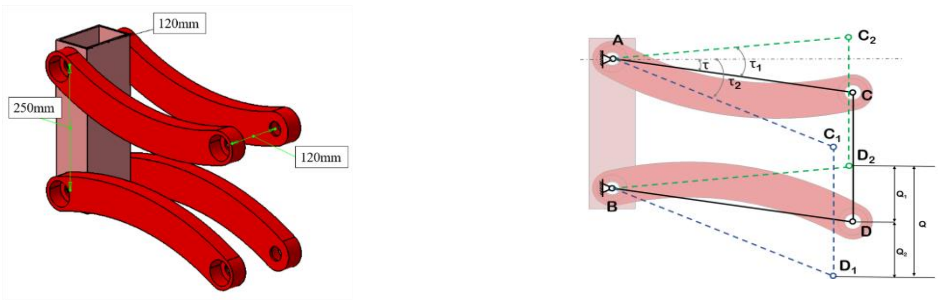


Fig. 4 - Schematic Diagram and Dimensional Drawing of the Profiling Rod

The calculation formula for the upper and lower profiling quantities (*Shu-hong et al., 2013*) is shown below.

$$Q = L\left[\sin(\tau + \tau_2) + \sin(\tau_2 - \tau)\right] \tag{3}$$

$$L = \frac{Q_2}{\sin\tau + \sin\left(\tau_2 - \tau\right)} \tag{4}$$

$$Q_1 = L\left[\left(\tau + \tau_1\right) - \sin\tau\right] \tag{5}$$

where:

Q is the total profiling displacement, [mm]; Q_1 is the upper profiling displacement, [mm]; Q_2 is the lower profiling displacement, [mm]; L is the length of the line connecting the hinge points on both sides of the profiling rod, [mm]; τ is the traction angle, [◦]; τ_1 is the upper profiling angle, [◦]; and τ_2 is the lower profiling angle, [◦].

According to the formula, when the upper and lower profiling quantities are the same, the shorter the profiling rod L, the greater the variation of τ. Therefore, it is necessary to reduce the variation range of τ appropriately while ensuring that the machine's overall size and center of gravity are reasonable. Referring to the work *Ji-guo et al., (2022*), substituting formula (6) yields L_{AC} = 413.4 mm, taken as L_{AC} = 410 mm, and substituting formula (5) yields Q_2=99.2 mm, satisfying the condition.

Performance analysis of air-suction garlic sowing unit operation

The angle of the conical hopper is set to the intermediate value of 24.5 °, and simulation experiments are conducted on 1, 2, and 3 hoppers, as shown in Figure 5. The statistical test results show the effect of the number of conical hoppers on the rate of bulb erection. Set each hopper's opening and closing times to 10 times, and each particle factory drops seeds ten times. After repeating the experiment at three levels five times, statistically analyze the number of garlic seeds with upright scales and record the upright rate of scales, as shown in Table 1. The maximum upright rate of scale buds is 92.09%, the minimum is 90.83%, and the difference is 1.26%. Therefore, the number of conical hoppers has little effect on whether the scale buds of hybrid garlic seeds can stand upright. Therefore, one is selected as a component of the bud-reversing device in selecting the number of conical hoppers.

(a) (b)

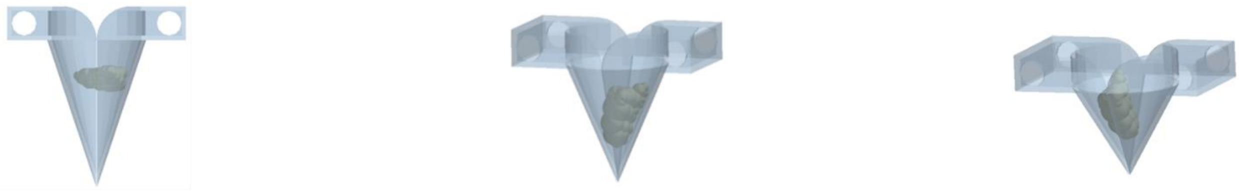
Fig. 5 - Simulation process diagram of the effect of the number of hoppers on the upright scale of hybrid garlic seeds

(a) 2-stage conical hopper (b) 3-stage conical hopper

Analysis of the influence of conical hopper angle

When the number of conical hoppers is 1, a single-factor experiment is conducted on the angle of the conical hopper to analyze the influence of its angle on the vertical rate of the scales.

Seven levels, 18.5°, 20.5°, 22.5 °, 24.5°, 26.5°, 28.5°, and 30°, were set as hopper angles. Each hopper's opening and closing times were set to 10 times, and each particle factory dropped ten times. After repeating the experiment five times at the three levels, the vertical rate of the experimental evaluation index was statistically analyzed. The specific experimental plan and results are shown in Table 2.



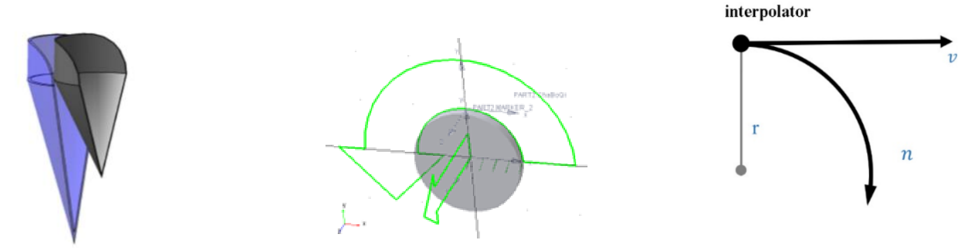
(a) (b) (c)

Fig. 6 - Simulation process diagram of the effect of hopper angle on the upright scale of hybrid garlic seeds

(a) 18.5 ° conical hopper (b) 24.5 ° conical hopper (c) 30 ° conical hopper

Analysis of Vertical Insertion Performance

As the final step in the sowing process of hybrid garlic seeds, the performance of the vertical sowing device directly affects the sowing results. In the previous section, the angle of the conical hopper was determined to be 24.5 °. In order to make the seeding depth meet the requirements, a cone with the same top diameter and a height of 50 mm is designed on the external surface of the inserter, as shown in Figure 7(a).



(a) (b) (c)

Fig. 7 - Schematic diagram of the structure and motion principle of the insertion device

The movement of the planting mechanism is composed of the horizontal movement of the air-suction garlic planting unit and the planting motion of the planting device. Using the Adams virtual prototype analysis software, a dynamic simulation analysis of the planting mechanism was conducted. The planting device model was simplified to a circular cam, and the planting mechanism was simplified to a marked point on the edge of the cam. In the simulation software, it was assumed that there is no gravity, as shown in Figure 7 (b).

Conduct dynamic analysis on the insertion device, where the insertion device is located at the highest position relative to the ground, the initial position of movement, and moves in a circular direction while also moving horizontally with the tractor, as shown in Figure 7 (c).

Set the distance between the marked point and the axis of the circular convex block as r, and as time passes, the coordinates (x, y) of the marked point will continuously change, as shown in the following equation.

$$x = vt + r\cos 2\pi nt \tag{6}$$

$$y = 2r - \sin 2\pi nt \tag{7}$$

where: x is the horizontal displacement component of the seeding unit, [m]; y is the vertical displacement component of the seeding unit, [m]; v is the forward speed of the machine unit, [m/s]; n is the rotational speed of the seeding unit, [r/s]; r is the radius of the seeding unit, [m].

In general, during actual sowing operations, the forward speed of the unit is 0.5~1.5 km/h, and the spacing of garlic seeds is 10 cm. Therefore, when the insertion device rotates around the axis to the next insertion device and comes into contact with the ground, the arc length is 10 cm. The relationship between the perimeter of the insertion device, the number of insertion devices installed on the insertion mechanism, and the rotation speed of the insertion device is shown below.

$$C = 0.1u \tag{8}$$

$$C = 2\pi r \tag{9}$$

$$n = \frac{v}{C} \tag{10}$$

where: C is the circumference of the seeding unit, [m]; u is the number of seeding unit; v is the forward speed of the machine unit, [m/s].

From the above equation, it can be concluded that the circumference of the insertion device is only related to the number of insertion devices. Once the circumference is determined, the size of the rotational speed can be determined.

Field trials

This article tests the sowing performance of air-suction garlic seeders by GB/T 6973-2005 "Test Methods for Single Grain (Precision) Planters". A field experiment was conducted in the Agricultural Cuiyuan of Anhui Agricultural University in April 2023, with a temperature of 15-22℃. Before sowing, rotary tillage was performed on the soil.

(a) **(b)**

Fig. 9 - Field Experiment

As shown in Figures 9(a) and 9(b), the sowing unit includes a frame, profiling rod, seed guide, scale bud reversing device, vertical planting device, pneumatic system, and transmission system. The tractor powers the fan to supply negative pressure for the air-suction metering device, allowing stable discharge of garlic seeds. Hybrid garlic seeds, separated from low-quality seeds, served as the experimental material, with an average length, width, thickness, and sphericity of 29.6 mm, 16.9 mm, 15.1 mm, and 66.3%, respectively.

The seeds were spot-sown at 100 mm intervals, with a 30-40 mm depth and 45-52 plants/hm² density. The air-suction seeder operated under a -5 kPa pressure and at forward speeds of 0.5, 1, and 1.5 km/h.

After each sowing, record the number of holes without garlic seeds as the missed seeding count, and record the number of holes with a single garlic seed as the qualified seeding count. The formulas for calculating the missed seeding rate and qualified seeding rate are as follows:

$$A = \frac{a}{S} \times 100\% \tag{11}$$

$$B = \frac{b}{S} \times 100\% \tag{12}$$

where: A is the missed seeding rate, [%]; a is the number of holes without garlic seeds; S is the total number of hybrid garlic seeds counted; B is the qualified seeding rate, [%]; b is the number of holes with a single garlic seed.

RESULTS

The effect of the number of conical hoppers on the rate of bulb erection

After repeating the experiment at three levels five times, statistically analyze the number of garlic seeds with upright scales and record the upright rate of scales, as shown in Table 1. The maximum upright rate of scale buds is 92.09%, the minimum is 90.83%, and the difference is 1.26%. Therefore, the number of conical hoppers has little effect on whether the scale buds of hybrid garlic seeds can stand upright. Therefore, one is selected as a component of the bud-reversing device in selecting the number of conical hoppers.

Table 1

The effect of the number of hoppers (1, 2, 3) on the uprightness rate of garlic seeds, including the standard deviation and coefficient of variation of the experimental results

Number of conical hoppers X_1 (piece)	Scale bud upright rate (%)	Average (%)	Standard deviation (%)	Coefficient of variation (%)
1	91.62 92.09 91.76 91.31 90.94	91.54	0.39	0.43
2	90.98 90.83 91.37 91.21 91.89	91.26	0.37	0.40
3	91.38 91.95 91.53 91.21 91.88	91.60	0.28	0.31

The influence of single-factor hopper angles on the upright scale of hybrid garlic seeds

After repeating the experiment five times at the three levels, the vertical rate of the experimental evaluation index was statistically analyzed. The specific experimental plan and results are shown in Table 2.

The simulation process diagram shows the influence of single-factor hopper angles on the upright scale of hybrid garlic seeds. Seven angle levels were set in the experiment, and the diagram only displays three different conical hopper designs.

Table 2

Results of single factor test on the effect of hopper angle on hybrid garlic seed upright rate

Hopper angle (°)	Upright rate of hybrid garlic seeds (%)				
	1	2	3	4	5
18.5	84.31	84.87	85.09	85.01	84.62
20.5	87.56	86.57	87.43	86.96	87.02
22.5	90.03	90.14	89.94	91.24	90.53
24.5	91.98	92.65	91.44	91.88	91.32
26.5	90.26	89.42	89.57	88.79	89.36
28.5	86.01	85.71	86.47	85.71	86.39
30.0	84.12	85.21	84.01	84.98	85.62

Note: *In the single-factor experiment, the number of hoppers was set to 1.*

By analyzing the trend of changes in the upright rate of the bulb, it can be concluded that when the number of conical hoppers is 1, the upright performance of the bulb reversing device first increases and then decreases with the increase of hopper angle. When the angle of the conical hopper is 24.5°, the upright effect of the bulb is the best. The upright rate of hybrid garlic seeds is 91.854%, which can meet the requirements for the upright rate of garlic seeds.

The influence of the insertion device perimeter on the trajectory of the inserter

Draw a trajectory map of the inserter with a 400-900 mm circumference, as shown in Figure 8. Observe the trend of changes in the trajectories of each graph. The point corresponding to the end of the vertical axis is the lowest point of the inserter. Moving 50 mm above the vertical axis is the trajectory of the inserter entering and exiting the soil.

As the inserter's perimeter increases, the inserter's trajectory entering the soil tends towards a vertical line. However, considering the position relationship of the insertion device and the size of the individual machine, 600 mm is selected as the perimeter of the insertion device, which means there are six insertion devices, and the rotation speed of the insertion device is 0.463 rad/s.

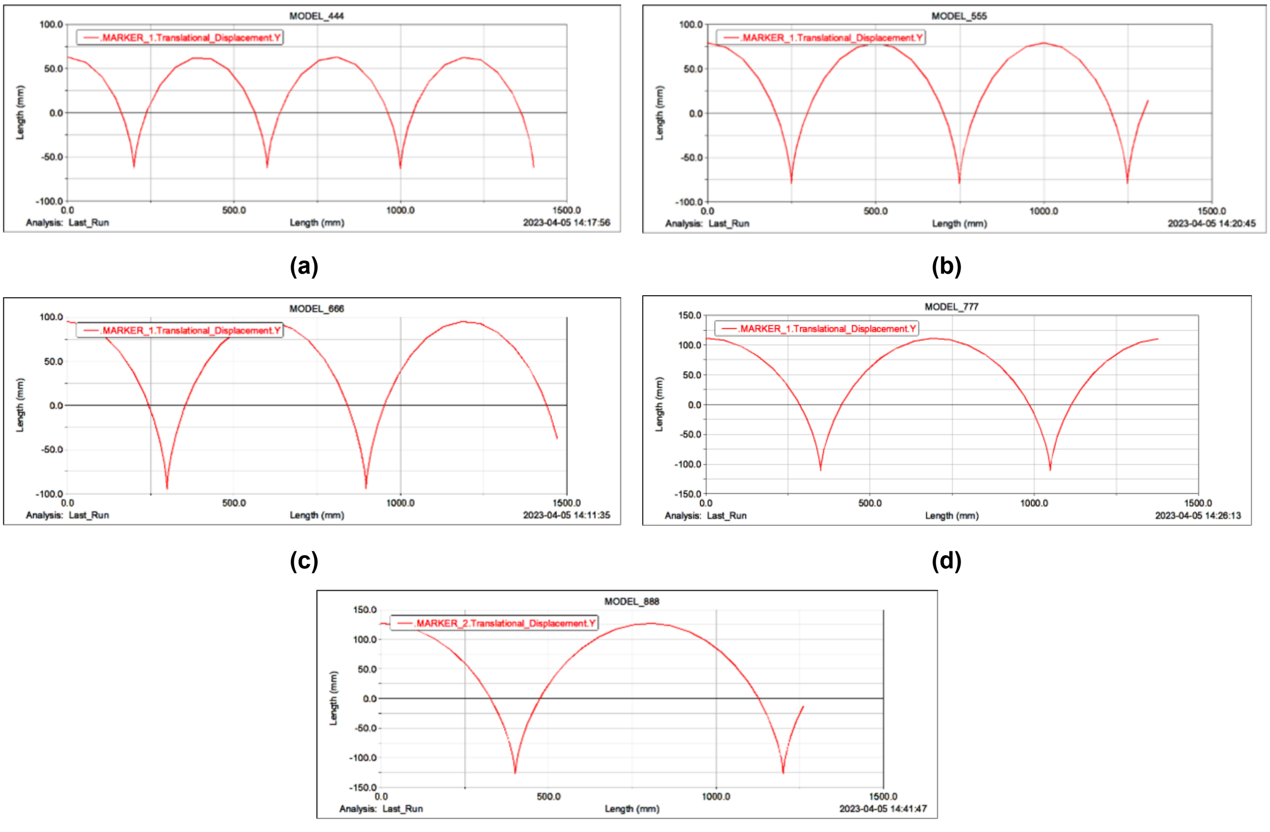


Fig. 8 - Spooler trajectory diagram

(a)400 mm perimeter trajectory; (b) 500 mm perimeter trajectory; (c) 600 mm perimeter trajectory; (d) 700 mm perimeter trajectory; (e) 800 mm perimeter trajectory

Field trials results

The experiments were conducted under the specified conditions, and the following results were obtained. Statistical analysis revealed the effect of the unit's forward speed on the seeding qualification rate and missed seeding rate. Each experiment was repeated three times, with the average values calculated and presented in Table 3.

Table 3

Impact of three-level unit forward speed on garlic seeding qualification and missed seeding rates

Level	Forward speed of the unit (km/h)	Seeding qualification rate (%)	Missed seeding rate (%)
1	0.5	81.12	11.33
2	1	84.26	7.12
3	1.5	79.29	9.54

Table 3 shows that when the negative pressure remains constant, and the unit advances at a speed of 1 km/h, it is the level with the highest qualified seeding rate and the lowest missed seeding rate among the three levels.

The forward speed of the unit is set to 1 km/h, and three levels of negative pressure (-4, -5, and -6 kPa) were applied to regulate the metering devices in the seeding unit. Each experiment is repeated three times. Calculate the average of the test results and record the results as shown in Table 4.

Table 4

Impact of three-level negative pressure on garlic seeding qualification and missed seeding rates

Level	Negative pressure (kPa)	Seeding qualification rate (%)	Missed seeding rate (%)
1	-4	80.39	9.33
2	-5	84.26	7.12
3	-6	82.86	7.83

When the negative pressure is -5kPa, the qualified rate of sowing reaches the highest among the three levels, and the missed rate reaches the lowest among the three levels.

CONCLUSIONS

This study proposes an air-suction garlic seeding unit. This unit allows the garlic to be stably planted upright in the soil. The unit adsorbs garlic seeds onto the seeding tray through negative pressure and delivers the seeds to the seed guide device at zero speed. Finally, it enters the vertical planting device upright and is planted in the soil. Therefore, it meets the agronomic requirements of garlic seeds to achieve single-seed sowing and erect scales during the mechanical sowing process.

According to the requirements of hybrid garlic seed sowing, the overall structure of the air-suction garlic sowing unit is designed, and its working principle is explained. For the principle analysis and theoretical calculation of the critical components of the seeding unit, the adsorption pressure required for the seed metering device is -5kPa, the number of hoppers used for the bulb seed changing device is selected as 1, the angle is selected as 24.5 °, and the perimeter of the insertion device is selected as 600 mm. These data provide support for subsequent field experiments.

When conducting a three-level field experiment, the optimal parameter combination for sowing results is negative pressure of -5kPa and a forward speed of 1 km/h at the three-level. The qualified rate of individual sowing can reach 84.26%, and the missed sowing rate is 7.12%, which meets the agronomic requirements for garlic seed sowing. Field experiments have verified the accuracy of theoretical analysis and bench tests, laying the foundation for the future production and promotion of garlic sowing units.

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