

Article

Analysis and Evaluation of Seed-Filling Performance of a Pneumatic Interference Precision Seeder for Small Cabbages

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Abstract: To address the current problems of poor seed-filling performance and seed leakage of the pneumatic seed filler for cabbage, we designed a pneumatic disturbing precision seed filler for cabbage based on the auxiliary disturbing seed-filling method. This seeder can completely perturb the seed population entering the bottom of the seed box casing during the seed-filling process, thereby increasing the initial velocity of the cabbage seeds, and facilitating the smooth progress of the seed-filling process. Firstly, we carried out a theoretical analysis based on the particle dynamics of the seed-filling process of the seeder and obtained the influencing factors affecting the seed-filling performance of the seeder. Secondly, through EDEM discrete element simulation, the average speed of the seed population, the disturbance frequency, and the degree of disturbance were used as the indicators to select the seed discharge disk structure with the best seed-filling performance. In the experimental aspect, a four-factor three-level orthogonal standardized test was conducted to evaluate the seed filling performance of the planter, using the seed suction qualification rate and the seed leakage rate as the evaluation indexes. The optimal structure of the seed discharge tray was selected through polarity analysis and ANOVA. The optimal combination of parameters for the seed-filling process of the planter was obtained; linear serrated disk, 40 rpm disk rotation speed, −2500 Pa negative fan pressure, and 1.2 mm aperture diameter. After comparative validation tests, the seed suction qualification rate of the seed absorber was 95.32%, and the leakage rate was 3.11%, which was in line with the agronomic planting of Chinese cabbage seeds.

Keywords: precision seeder; small cabbage; aerodynamic disturbance; seed-filling performance; EDEM simulation



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1. Introduction

Most of the vitamins and minerals needed by the human body come from vegetable species that are consumed on a daily basis. Cabbage is a widely cultivated vegetable around the world. According to the FAO statistical database, in 2021, the global cabbage cultivation was 2,450,601 hectares [1,2]. Such a huge planting demand inevitably requires high-efficiency and high-quality production methods. However, small Chinese cabbage cultivation is achieved by hand sowing [3,4]. The low level of planting will inevitably limit the yield and economic benefits of cabbage. To improve the sowing efficiency and quality of small cabbages, mechanized sowing is necessary. A pneumatic precision seeder is the core component to achieve mechanized sowing at present, and its structural parameters and working parameters will directly affect the precision and accuracy of sowing [5,6].

At present [7,8], domestic and foreign scholars have carried out extensive research on pneumatic precision planting apparatus. John Deere developed a pneumatic seeder,

which innovatively adheres the seeds to the brush seed guide belt during sowing, which enabled zero-speed seed casting with the movement of seeds with the seed guide belt with the operating speed of 15 km/h. Siemens MC [9] and others have found that, based on the mechanism of the seed's action with the soil, lowering the height of the sowing can improve the working performance of the seeder. Lei Xiaolong et al. [10] designed an airflow collector seeder, setting a staggered conical perforated wheel seed supply device on the seed discharging disk. Through the bench test, it was concluded that when the inclination angle of the perforated wheel is 20° , the seed supply performance of the seeder reaches the optimum, which can allow the optimum seed supply of oilseed rape and wheat. Yan Bingxin et al. [11] designed a disc chamber synchronized rotary air suction corn precision seeder, the grain spacing qualification rate of the seeder was 91.6%, and the leakage index was less than 5.2%, and the reseeding index was less than 5.4% at the optimal condition. Ding Yang et al. [12] designed and developed a pepper seed supply mechanism combining spiral seed supply and air-fed seed supply for the irregular and lightweight characteristics of pepper seeds and merged the mechanism with the suction roller to form a new type of air-absorbing pepper precision seeder. Tests have proved that the average value of the qualification rate of the seeder is 91.32%, the average value of the re-seeding index is 4.51%, and the average value of the leakage index is 4.17%. It can thus complete the sowing of pepper seeds well. Based on a pneumatic precision seeder, Lin Pian et al. [13] proposed the sowing of rapeseed and sesame seeds by replacing the seed disks, which enhanced the adaptability of the seeder to different seeds. Dandan Han et al. [14] studied the effect of four different seed discharge disk hole structures on corn seeds' filling volume. He obtained that when the seed discharge disk has open square holes in the radial inner direction, both the trailing force of the airflow on the seeds and the filling volume of the seeds reach the optimal effect, and the seeding of corn seeds can be well performed.

Comprehensive domestic and international research on pneumatic planting apparatus has found that pneumatic planting apparatus are generally applied to large-grain crops such as rice, cereals, and maize, while their application to microparticle vegetable seeds is still in the preliminary exploration stage. Most of the current pneumatic planting apparatus do not provide enough directional perturbation to the seeds during the filling stage, which increases the leakage rate of the seeder [15,16]. To realize the mechanized precision sowing of cabbage seeds and reduce the leakage rate of pneumatic planting apparatus, this paper designs a linear serrated disk pneumatic perturbation precision seeder, introduces the structural composition and working principle of the seeder, and theoretically analyzes the seed-filling process of the seeder based on the theory of mass dynamics. On this basis, with the help of EDEM numerical simulation, 3D printing technology, and high-speed photography technology, the seed-filling performance of the seed expeller was studied experimentally, and the working parameter combinations of the pneumatic perturbation seed expeller with the best seed-filling performance were obtained.

2. Explanation of the Working Process and Perturbation Theory of the Seeder

2.1. Composition and Working Principle of Seeder Structure

The structural composition of the pneumatic perturbation type small cabbage fine seeder is shown in Figure 1, which is mainly assembled by the seed box shell, seed guide tube, drive shaft, seed discharge disk, air chamber cavity, and other components. When the pneumatic seeder works, cabbage seeds first enter the seed-filling cavity at the bottom of the seed box from the seed inlet and pile up. Driven by the drive shaft, the linear serrated disk starts to rotate. Its upper serrated structure will break the inertia of the seeds piled up in the seed-filling chamber during the rotation process and separate a small number of cabbage seeds from the seed population for the smooth progress of the seed-filling process. At this time, the negative pressure provided by the fan will generate a pressure gradient difference on both sides of the linear serrated disk hole, so that the cabbage seeds will rely on the negative pressure to be adsorbed on top of the linear serrated disk hole and follow the rotation of the seed discharge disk. When the cabbage seeds rotate to the sowing area,

the negative pressure disappears, and the cabbage seeds at the disk hole are blown down to the seed guide tube under the action of its gravity and the positive pressure-blowing force of the fan to complete a sowing operation.

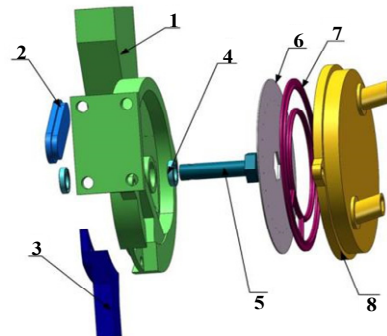


Figure 1. Structure of pneumatic seeder. 1. Seed box housing, 2. seed box cover, 3. seed guide tube 4. drive bearing, 5. drive shaft, 6. linear serrated disk, 7. air chamber sealing ring, 8. air chamber cavity.

2.2. Perturbation Theory Analysis of Seed-Filling Process

When the pneumatic seeder works, the linear serrated structure on the seed discharge disk will pass through the surface of the seed population close to the seed discharge disk. This process enables the separation and perturbation of a small number of tiny cabbage seeds that close to the seed discharge disk. In the process, the cabbage seeds start to accelerate under the effect of perturbation and then arrive at the holes to be adsorbed by the holes and rotate with the seed discharge disk at a uniform speed. The motion analysis of cabbage seeds in the seed-filling process is shown in Figure 2. Kinematic modeling of the seed-filling process is based on particle dynamics [17,18].

$$\begin{cases} Kx = 0.5mv_1^2 - 0.5mv_0^2 \\ v_1 = nR_0 \\ P = \frac{4K}{\pi d^2} \end{cases} \quad (1)$$

where:

K —pressure provided by the negative pressure gas chamber, N

x —effective distance of negative pressure adsorption of seeds in the air chamber, mm

m —mass of cabbage seeds used, kg

R_0 —radius of the seed discharge disk where the typed hole is located, mm

d —diameter of the seed discharge disk type hole, mm

v_0 —initial seed velocity, m/s

v_1 —speed of seed after being adsorbed by the typed hole, m/s

P —gas chamber vacuum size, Pa

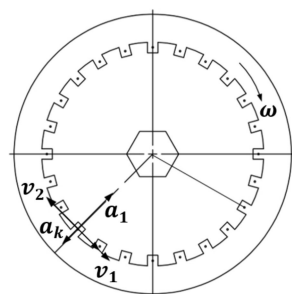


Figure 2. Kinematic analysis of the seed-filling process. Where ω is the angular velocity, v_1 is the forward speed of the planter, v_2 is the tangential velocity at disengagement, and a_k is the centripetal acceleration.

The gas chamber vacuum P required for stable adsorption of cabbage seeds at the type pore is obtained from Equation (1) as:

$$P = \frac{2m(n^2 R_0^2 - v_0^2)}{\pi x d^2} \quad (2)$$

As can be seen from Equation (2), under the condition that the rotational speed of the seed-discharging disk remains unchanged, the gas chamber vacuum P required for the stable adsorption of the cabbage seeds at the typed hole is inversely proportional to the initial speed v_0 of the cabbage seeds. When the initial speed v_0 of the cabbage seed is more incredible, the air chamber vacuum P required for the cabbage seed to be stably adsorbed at the hole in the seed-filling stage is more minor. Therefore, the addition of a serrated seed-disturbing structure on the surface of the seed discharging disk can first separate a small number of seeds from the population. It could facilitate accurate adsorption of the seeds, so the cabbage seeds can obtain a large initial velocity in the filling stage, thus reducing the value of the negative pressure that needs to be supplied by the air chamber, and reducing the power consumption of the fan.

3. Design of Essential Parts of the Seed Dispenser

3.1. Parameterization of Seed Disks

The seed-discharging disk is the core component of the pneumatic precision seeder, the performance of the seed discharging disk directly determines the seed discharging version of the seeder [19]. The structure of the seed discharge disk is shown in Figure 3. The design of the seed discharge disk mainly includes the following aspects.

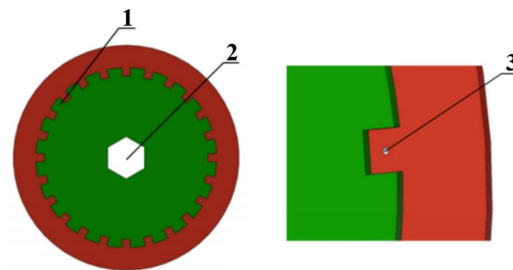


Figure 3. Three-dimensional structure of seed disk. 1. Linear serrated structure, 2. drive shaft connection holes, 3. type holes.

(1) Determination and analysis of the diameter of the seed discharge tray

The diameter of the seed-discharging disk affects the size and working performance of the whole seed-discharging device. We propose idealised assumptions to better study the diameter of the rowing disks: that the seeds are homogeneous and consistent, that there are no external disturbances, and that mechanical conditions such as wear of the disks are not taken into account. The real process may not strictly follow the theoretical model. In the seed-discharging stage, assuming that the seed-discharging time of a single hole is t_1 , it can be found according to the relationship between the speed of the seed-discharging disk and the seed-filling time,

$$\begin{cases} v_c = \frac{\pi d_c n}{60} \\ l_c = \theta \frac{d_c}{2} \\ t_1 = \frac{l_c}{v_c} \end{cases} \quad (3)$$

where:

- d_c —diameter of seed discharge disk, mm
- n —rotational speed of seed discharge disk, rpm
- v_c —line speed of seed discharge disk, m/s
- θ —seed-filling angle size, rad

l_c —arc length of the seed-filled area, mm

t_1 —seed filling time, s

From Equation (3) [20],

$$t_1 = \frac{30\theta}{\pi n} \quad (4)$$

The longer the seed discharge disk-shaped hole stays in the seed-filling area, the more favorable it is for the disturbance and adsorption of seeds, which can effectively reduce the leakage rate of the seeder. As can be seen from Equation (4), the root-filling time t_1 is only affected by the seed-filling angle and the rotational speed of the seed-discharging disk. It has no relationship with the size of the diameter of the source-discharging disk. Therefore, changing the diameter of the seeding disk does not allow the type holes to remain in the seeding area for a longer period, nor does it improve seeding performance. Therefore, the diameter of the seed discharge disk can be designed according to the overall structural parameters of the seeder. Now on the market, pneumatic seeder seed disk diameter sizes are generally within 80–260 mm [21]. To match the seeding device and the overall parameters of the seeder requirements, this paper selects the seed discharge disk diameter size of 160 mm and the disk thickness of 1 mm.

(2) Determination and analysis of the number of holes

The number of holes in the seed tray significantly impacts the seeding hole spacing [22]. According to the principal analysis of the seeding device, we can get the relationship between the centerline speed of the holes and the travel speed of the seeding device as follows:

$$\begin{cases} v_x = \frac{\pi n d_x}{60} \\ v_b = \frac{p(1-\delta)v_x l_b}{\pi d_x} \end{cases} \quad (5)$$

where:

d_x —diameter where the hole is located, mm

v_b —the speed at which the seeding device proceeds, m/s

δ —coefficient of slip of the ground wheel of the seeding device

l_b —seeding device hole spacing, m

v_x —linear velocity at the center of the typed hole on the seed discharge tray, m/s

p —number of type holes on the seed discharge disk, p

It follows from Equation (5):

$$p = \frac{60v_b}{(1-\delta)n l_b} \quad (6)$$

In the literature it can be seen [23] that for cabbage in planting, hole spacing requirements are 80–130 mm, where set hole spacing l_b is 110 mm, the slip coefficient of the ground wheel of the supporting seeding device is set at 0.8, rotational speed n is 50 rpm, and walking speed is 2 m/s. The number of holes can be obtained by putting the data into Equation (6), which is 23.72 holes, rounded to the nearest whole number $p = 23.72$, rounded up to 24 holes.

(3) Determination and analysis of borehole diameter and position

According to the agronomic planting requirements of cabbage seeds, one seed should be guaranteed in each hole. To realize the accurate adsorption of cabbage seeds, this paper determines the diameter of the typed hole based on the triaxial dimensions of tiny cabbage seeds according to Equation (7) [24].

$$d_1 = (0.64 \sim 0.66)b \quad (7)$$

where:

b —average width of cabbage seeds, mm

d_1 —diameter of the type hole, mm

The constant is a safety factor.

According to the literature [25], the average width of cabbage seeds is 1.70 mm, and the range of hole diameter is 1.09–1.12 mm according to Formula (5), with which three kinds of seed disks with hole diameters of 1.0 mm, 1.1 mm, and 1.2 mm are processed. Subsequent seed-filling performance tests determine the optimal parameters of the hole diameter.

Generally speaking, the holes of the seed discharge tray are set at 100–230 mm in diameter on the seed discharge tray, preferably 15–20 mm away from the outer edge of the seed discharge tray. However, the hole's location needs to meet the air chamber cavity to achieve accurate and stable adsorption of seeds. Combined with the structural parameters of the air chamber, seed discharge tray, and the positional requirements of the holes, the holes of the seed discharge tray are located 122 mm in diameter of the seed discharge tray.

(4) Determination of structural parameters of linear serrations

The linear serration structure affects the seed-filling and seed-discharge performance of the pneumatic seeder, and its structural parameters mainly include the length, width, and thickness of the serration, as shown in Figure 4. Cabbage seeds are spherical in shape, so the serrations are designed with a length and width of L . The serration structure during rotation will be close to the surface of the seed tray, separating a small number of seeds from the population, so the length of the serrations should be greater than the equivalent diameter of the cabbage seeds. However, if the size of the sawtooth is too large, it will get too many seeds stuck in the sawtooth structure, resulting in a severe reseeding phenomenon. Taken together, the length and width of the sawtooth design should be set to meet at least two seeds but not more than four seeds side by side, then:

$$2d \leq L \leq 4d \quad (8)$$

where:

d —measurements of the length, width, and thickness of cabbage seeds were averaged, mm

L —length and width of sawtooth structure, mm

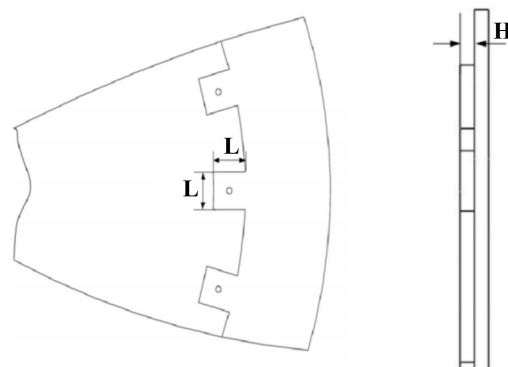


Figure 4. Parameters of the sawtooth structure of seed disk. Where L is the length and width of the sawtooth structure, mm. H is the thickness of the sawtooth structure, mm.

In conjunction with the previous description, the equivalent diameter of the cabbage seed was 1.70 mm, whereby the length and width of the serrated structure were set to 5 mm.

When designing the sawtooth structure, it is also necessary to consider the thickness of the sawtooth system H . If the thickness of the sawtooth system is too large, a small amount of seeds will be carried directly out of the seed-filling chamber during the rotation of the seed disk, resulting in serious reseeding. If the thickness of the sawtooth structure is too small, it will not be able to realize the complete separation and disturbance of cabbage

seeds. Therefore, the sawtooth thickness H should be satisfied when designing the sawtooth structure:

$$H \leq 0.5d \quad (9)$$

where:

d —cabbage seed equivalent diameter, mm

H —thickness of the sawtooth structure, mm

Combined with the equivalent diameter of cabbage seeds, the serrated structure thickness H of the maximum value of 0.85 mm to facilitate the processing and production of the seed discharge disk here makes the seed discharge disk jagged structure thickness 0.5 mm.

3.2. Parametric Design of Seed Box Housings

The seed box shell is the core component that enables the transmission of the seeder, and it is also an essential structure for storing and providing seeds. Whether the seed box shell structure design is appropriate will directly affect the seed discharge performance of the seeder [26]. When designing the seed box shell, the primary consideration is the structural parameters and volume size of the seed box shell. The seed box shell structure mainly comprises two parts, region I and region II, as shown in Figure 5.

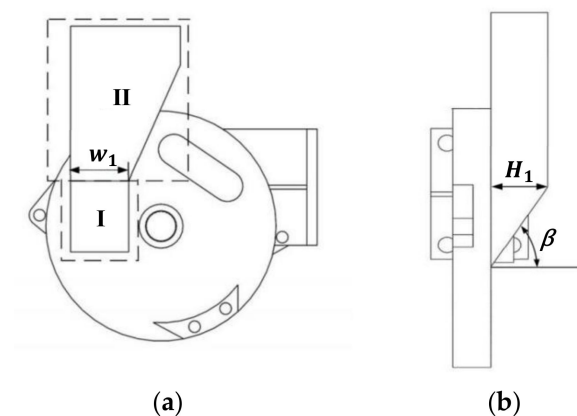


Figure 5. Structure of the seed box housing. (a) Rear view of the seed box housing, (b) Side view of seed box housing.

Small cabbage planting agronomic requirements ensure that the row spacing and plant spacing are about 110 mm. The area of each acre of land is set to 667 m², according to the Formula (10), that can be obtained to plant one acre of Chinese cabbage with the required seed box volume size.

$$N = \frac{667G_0}{\rho zh} \quad (10)$$

where:

N —seed box shell volume, m³

G_0 —mass of a single cabbage seed, g

ρ —cabbage seed density, g/L⁻¹

z —cabbage seed planting spacing, m

h —cabbage seed planting row spacing, m

In accordance with the literature [23], cabbage seeds with a single grain mass of 0.00295 g and a density of 690 g/L, by the Formula (10), can be planted in one acre with a seed box volume of 0.00024 m³, taking into consideration the comprehensive design of the seed box and the shell volume size of 0.00030 m³.

In the process of cabbage seeds entering the seed-filling chamber from the seed box shell, the seeds have strong mobility. If the seed box shell region I W_1 width is too small,

the seeds are prone to clogging and arching phenomena when the flow occurs. According to the particle flow, a Langmaid hole critical equation can be obtained [27]:

$$\begin{cases} \frac{W_{min}}{d_v} = 1.8 + 0.038 \left(\frac{\sigma_s}{\sigma_v} \right)^{1.8} \\ d_v = \frac{\sum_i 6n_i d^2}{\sum_i n_i d^3} = \frac{6}{d} \end{cases} \quad (11)$$

where:

- W_{min} —minimum width of seed box shell area I, mm
- d_v —seed specific surface area equivalent diameter, mm
- σ_s —seed surface area shape factor
- σ_v —seed volume shape factor
- n_i —number of i-th seed
- d —cabbage seed equivalent diameter, mm

Since cabbage seeds are spherical-like particles, there are $\sigma_s/\sigma_v = 6$. According to Equation (11), it can be obtained as follows: $W_{min} = 32.1$ mm. The comprehensive parameters and process requirements of the seed box shell of the whole seeder are the design of the seed box shell area I where width $W1$ is 40 mm, and the thickness $H1$ is 30 mm. To ensure that the seeds can smoothly enter the bottom of the seed box filling chamber, the angle β between the bottom plate of Area I and the horizontal direction should be greater than the sliding friction angle between the seeds, and between the seeds and the seed box. Combined with the literature [28], the angle β was determined to be 60° . The trapezoidal table structure of area II can effectively increase the volume size of the seed box shell. The top of the seed box shell area I and the bottom of area II coincide, so the volume size of area II is the difference between the volume size of the seed box shell and the volume size of area I. According to the requirements of the volume size of the seed box shell, the set area II on the bottom of the length is 40 mm, the bottom of the length is 80 mm, height is 120 mm, thickness is 30 mm, and the distance between the top of the seed box housing and the upper bottom surface of the trapezoidal platform is 30 mm.

4. Simulation of Seed Discharge Tray Perturbation

4.1. EDEM Simulation Modeling

To study the intensity of auxiliary disturbance of small cabbage seeds at the replanting stage by different row tray configurations. Three other forms of seed-rowing disks were set up. As shown in Figure 6. The figure shows no seed disturbance structure on the flat disk. The thickness of the serrated structure on the circular serrated disk and the linear serrated disk is 0.5 mm. Other structural parameters in the three seed-rowing disks are kept the same.

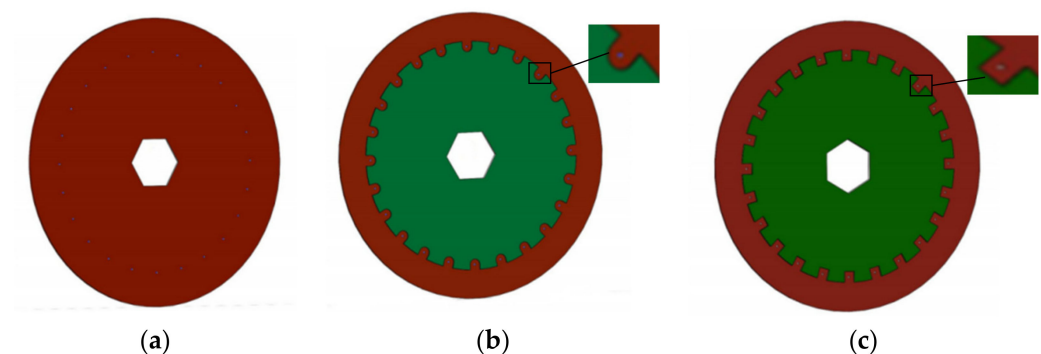


Figure 6. 3D model of seed disk used for simulation. (a) Flat disk, (b) circular serrated disk, (c) linear serrated disk.

After simplification, the overall structure of the pneumatic seeder includes three parts: the seed box shell, the seed disk, and the air chamber cavity. The details are shown in

Figure 7a. According to the literature [29], the sphericity of the cabbage seed is more than 85%, so the cabbage seed is simplified to a spherical particle model with a diameter of 1.70 mm. The simplified seed model is shown in Figure 7b.

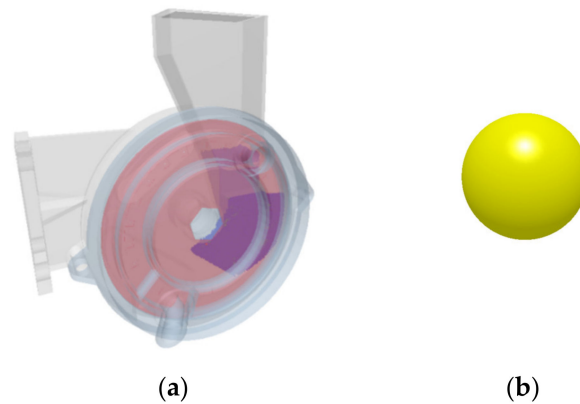


Figure 7. Model of seeder and cabbage seeds used for simulation. (a) Simplified model of seed expeller, (b) seed particle modeling.

4.2. EDEM-Related Parameter Settings

During the working process of the seeder, contact collision between the cabbage seeds and the seed box shell and the seed discharging disk will occur. So, it is necessary to set the relevant material and mechanical parameters in the simulation. The processing material of the seed box shell and air chamber cavity is ABS resin, and the processing material of the seed discharge disk is stainless steel. Combined with the findings in the literature [30], the set material and mechanical parameters in the simulation are shown in Tables 1 and 2, respectively.

Table 1. Characteristic parameters of materials used in the simulation.

Material Name	Parameter Name	Numerical Value
ABS resin	Poisson's ratio	0.4
	Shear modulus/Pa	2.7×10^{10}
	Density/kg·m ⁻³	2.7×10^3
Stainless steels	Poisson's ratio	0.3
	Shear modulus/Pa	6.1×10^{10}
	Density/kg·m ⁻³	7.85×10^3
Cabbage seed	Poisson's ratio	0.45
	Shear modulus/Pa	4.35×10^8
	Density/kg·m ⁻³	6.9×10^2

After setting the relevant material and mechanical parameters, the simplified seeder model is imported into EDEM in STL format, and the cabbage seeds and seeder are given the corresponding structural material and mechanical parameters according to the data in the table. Set up the pellet factory at the seed box shell's seed inlet. It was set to generate particles from 0 s, a total of 20,000 particles, 10,000 particles per second, all the particles were generated within 2 s, and the particle falling speed was set to 2 m/s. Then set the rotational speed of 40 rpm at the rotation center of the seed discharging tray in the counterclockwise direction, and the rotation starts from 2.5 s. The particle contact model is the Hertz-type particle contact model, which is the same as the Hertz-type particle contact model. The particle contact model was the Hertz-Mindlin model, and the gravity magnitude was set to be 9.81 m/s² in the -y direction. The Rayleigh time step in the simulation was set to 20% [31], and the total simulation time was set to 10 s. The mesh size was 2.5 times the size of the cabbage seed particles.

Table 2. Mechanical parameters of materials used for simulation.

Contact Material	Parameter Name	Numerical Value
Cabbage seed—ABS resin	coefficient of restitution	0.75
	coefficient of static friction	0.30
	coefficient of rolling friction	0.01
Cabbage seeds—stainless steel	coefficient of restitution	0.64
	coefficient of static friction	0.26
	coefficient of rolling friction	0.05
Cabbage seeds—cabbage seeds	coefficient of restitution	0.58
	coefficient of static friction	0.52
	coefficient of rolling friction	0.01

4.3. Simulation Results and Analysis

According to the previous theoretical analysis, it is known that enhancing the initial velocity of the seed population in the seed-filling stage can reduce the value of the negative pressure that needs to be provided by the air chamber under the same working conditions. It reduces the power consumption of the blower and at the same time, facilitates the accurate adsorption of the cabbage seeds by the type of holes. So here, in conjunction with the literature, the fluctuation frequency, average speed, and average kinetic energy of the seed population are chosen as indicators for evaluating the seed-disturbing performance of seed displacement trays. The fluctuation frequency and average speed reflect the overall mobility strength of the population in the seed-filling chamber, and the average kinetic energy reflects the instantaneous mobility strength of the people in the seed-filling section.

Figure 8 shows the change of the average speed of the population in 3–10 s when the rotation speed of the seed discharge disk is 40 rpm. From the figure, it can be seen that there is a big difference in the average speed change of the population under the action of different seed disk rotation structures. There is no seed disturbance structure on the plane disk, which mainly relies on the contact friction between the seed disk and the seed to realize the disturbance of the source in the working process. Thus, both the fluctuation frequency and the degree of fluctuation of the seed population under the action of the plane disk is smaller than that under the movement of the circular arc-type serrated disk and the linear-type serrated disk. From Figure 8b,c, it can be seen that the population's fluctuation frequency under the action of the linear serrated disk is more significant than that under the circular arc serrated disk. From the EDEM post-processing, it was obtained that the average velocity of the population fluctuated between 7.3×10^{-4} – 2.1×10^{-2} m/s under the action of the circular arc serrated disk and between 7.0×10^{-4} – 2.3×10^{-2} m/s under the movement of the linear serrated disk, a comparison of which showed the degree of fluctuation of the population was more intense under the action of the linear serrated disk. From Figure 9, the average speed of the people under the act of plane disk rotation was 3.89×10^{-5} m/s, the average rate of the population under the action of the circular sawtooth disk rotation was 1.19×10^{-3} m/s, and the average speed of the people under the act of linear sawtooth disk rotation was 1.26×10^{-3} m/s. From this, it can be seen that the population under the action of the linear sawtooth disk was more significant than that under the act of the plane disk and circular sawtooth disk in terms of the frequency of fluctuation, fluctuation degree, and the average speed. It is also greater than the flat disk and the arc-type seed discharge disk. It is quantitatively concluded that the linear serrated disk has the best auxiliary disturbance ability to the seed population in the seed-filling stage, and the seed expeller obtains the best seed-filling performance at this time.

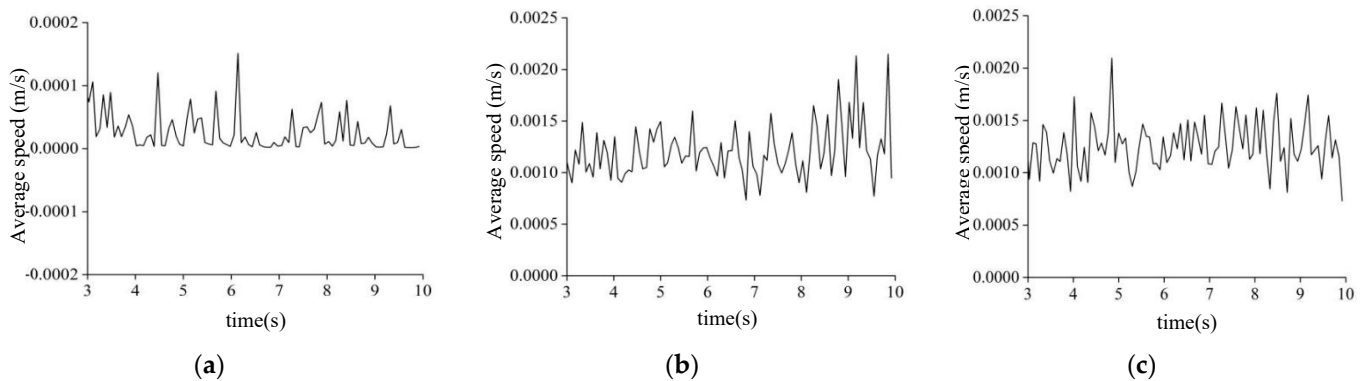


Figure 8. Distribution of changes in mean velocity of populations under different seed disks. (a) Flat disk, (b) circular–serrated disk, (c) straight–serrated disk.

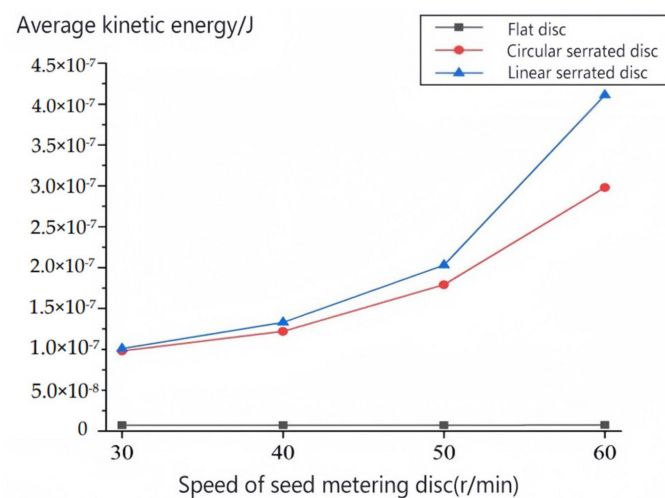


Figure 9. Changes in mean kinetic energy of populations at different speeds of seed discharging discs.

Figure 9 shows the variation of the average kinetic energy of the populations in the seed-filled chambers of the seed dispenser at different rotational speeds from 3 to 10 s. The average kinetic energy of the populations in the seed-filled chambers is shown in Figure 9. The change in the average kinetic energy of the seed population can reflect the auxiliary perturbation ability of different shapes of seed discharging discs. From the theoretical analysis part, we know that the addition of the sawtooth seed-winding structure can first separate a small number of seeds from the population, increasing the initial velocity of the seeds. The vacuum required for seed adsorption is again inversely proportional to initial velocity. As seen from the figure, the average kinetic energy of the populations under the action of the rotation of the seed disks of different structures varied greatly. As the rotational speed of the disc increases, the average kinetic energy fluctuation of the flat disc is minimal, much smaller than that of the circular and linear serrated discs. In contrast, the average kinetic energy fluctuation of the linear serrated disc is more significant than that of the circular serrated disc. It can also be seen from the figure that under the same rotational speed of the seed discharge disk, the average kinetic energy of the linear serrated disk is more significant than that of the circular arc serrated disk and the plane disk. This indicates that the instantaneous flow intensity of the seed population reaches the maximum under the action of the linear serrated disk.

As a result of the above analysis, the flow intensity of the populations in the seed filling chamber under the perturbation of the linear serrated disk is significantly better than that of the planar disk and the circular-arc serrated disk. The flow intensity of the populations reaches the maximum at this time and the vacuum required for seed adsorption

is minimised at this time. It is quantitatively concluded that the linear serrated disk has the best auxiliary perturbation ability to the seed population in the seed-filling stage, and the seeder obtains the best seed-filling performance at this time.

5. Seed Displacer Seed-Filling Performance Bench Tests

To ensure that the pneumatic seeder can effectively perturb the seed population in the seed-filling stage, this paper tests the seed-filling performance of the pneumatic seeder by building a seed-filling performance test rig.

5.1. Test Materials and Equipment

The cabbage seeds used in the experiment were “Jinzhi 30” bright green-stemmed cabbage seeds with a water content of 4.96% and a thousand-grain weight of 2.95 g. The equivalent diameter is 1.70 mm, and the sphericity is 92.80%. The cabbage seeds, purchased from Tianjin Cultivation Seed Industry Co., Ltd. (Tianjin, China), were screened before each test to remove damaged or cracked ones.

The equipment used in the test is a homemade seed-filling performance test stand, which mainly includes a digital precision pressure gauge, pneumatic precision seeder, high-speed camera, three-phase servomotor, LED flash, etc. The test stand is shown in Figure 10. The test stand is shown in Figure 10.

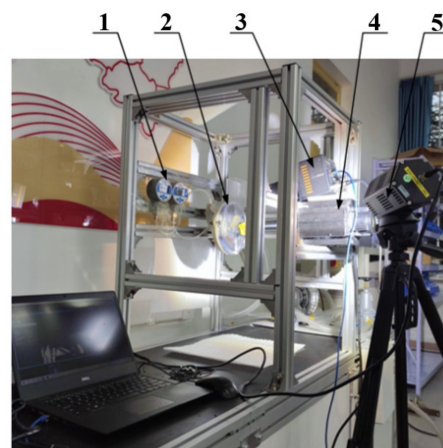


Figure 10. Seed displacement performance test rig for seeding. 1. Digital display precision pressure gauge, 2. pneumatic precision seeder, 3. high-speed camera, 4. Servo motor, 5. LED flashlight.

5.2. Test Methods and Indicators

Based on the pre-test and reference [32], four factors, namely fan negative pressure value A, seed discharge disk speed B, seed discharge disk style C, and hole diameter D, were selected to carry out four-factor, three-level orthogonal tests according to the standard orthogonal test table. For each group of tests, a high-speed camera was used to take a frontal view of the seed dispenser in the observation area of the seed box housing the seed dispenser. The first hole that entered the observation area of the seed dispenser was taken as the initial observation point. The seed adsorption images at a total of 240 holes were captured after ten rotations of the initial observation point, and the seed filling of these 240 holes was counted. The results of each group of tests can be brought into the Formula (12) to calculate the seed adsorption rate X and leakage rate L. Each group of tests was repeated five times to take the average value as the final test result. Finally, the test results were analyzed by extreme variance and ANOVA. Polar deviation analysis can get the primary and secondary relationship of the influence of each factor on the test indexes of the seeder and the best combination of working parameters, and ANOVA can grasp the significance of the impact of each element on the test indexes [33]. Table 3 shows experimental factor levels designed for the experiment.

Table 3. Seed-filling performance factor levels.

Level (of Achievement etc.)	Considerations			
	Seed Dispenser Style A	Seed Discharge Disk Speed B, rpm	Fan Negative Pressure Value C, Pa	Hole Diameter D, mm
1	A flat disk	30	−1500	1.0
2	Linear serrated disk	40	−2000	1.1
3	Circular sawtooth disk	50	−2500	1.2

The test indexes of seed-filling performance of pneumatic seeder are determined according to GB/T 6973-2005 test methods for single grain (precision) seed sower as seed suction qualification rate and leakage suction rate [34]. The calculation method of each index is as follows:

$$\begin{cases} X = \frac{n_1}{N} \times 100\% \\ L = \frac{n_2}{N} \times 100\% \end{cases} \quad (12)$$

where:

n_1 —number of type pores in a single seed, pcs

n_2 —number of type pores without seeds, pcs

N —number of all type holes in the test statistics, pcs

X —adsorption pass rate, %

L —leakage rate, %

5.3. Test Results and Analysis

Since the nine groups of four-factor, three-level orthogonal tests did not have enough degrees of freedom for multifactorial ANOVA, a tenth group of non-replicated experiments was added to allow for the analysis of the results of subsequent experimental studies. The results of the test on seed-filling performance of the seeder are shown in Table 4. The test results of each evaluation index of seed-filling performance are analyzed as follows.

Table 4. Orthogonal test results.

Test No.	Considerations				Test Indicators	
	Seed Dispenser Style A	Seed Discharge Disk Speed B, rpm	Fan Negative Pressure Value C, pa	Hole Diameter D, mm	Suction Pass Rate X, %	Leakage Rate L, %
1	1	1	1	1	87.40	6.14
2	1	2	2	2	89.89	5.79
3	1	3	3	3	90.72	5.29
4	2	1	2	3	94.16	4.32
5	2	2	3	1	95.13	3.97
6	2	3	1	2	93.20	4.77
7	3	1	3	2	91.97	2.29
8	3	2	1	3	90.95	3.14
9	3	3	2	1	91.30	1.48
10	1	2	2	1	90.02	5.34

(1) Analysis of the results of the suction seed compliance test

Through the results of extreme difference analysis in Table 5, it can be seen that the factors affecting the seed absorbing pass rate of the seed displacer are, in order of priority, seed disk style A > fan negative pressure value C > origin disk rotation speed B > hole diameter D, and the best parameter combinations are A₂B₂C₃D₃. From the F-value, it can be seen that the impact of the seed disk style A on the seed-absorbing pass rate of the seed displacer is significant, which proves that the linear serrated disk can effectively improve

the seed-filling performance of the seed displacer to improve further the origin absorbing pass rate of the seed displacer.

Table 5. Suction seed pass rate test results.

Analyze the Project	Considerations			
	Seed Dispenser Style A	Seed Discharge Disk Speed B	Fan Negative Pressure Value C	Hole Diameter D
K_1	268.01	273.53	271.55	273.83
K_2	282.49	275.97	275.35	275.06
K_3	274.22	275.22	277.82	275.83
k_1	89.34	91.18	90.52	91.28
k_2	94.16	91.99	91.78	91.69
k_3	91.41	91.72	92.61	91.94
R (extreme variance)	4.82	0.81	2.09	0.66
quadratic sum	38.89	1.00	6.88	0.87
mean value	19.45	0.50	3.44	0.44
(number of) degrees of freedom (physics)	2	2	2	2
F-value	484.46	12.51	85.66	10.84
significance	*			
order of priority		A > C > B > D		
optimal combination		A ₂ B ₂ C ₃ D ₃		

(2) Analysis of leakage rate test results

From the results of the extreme difference analysis in Table 6, it can be seen that the factors affecting the leakage rate of the seeder are, in order of precedence, seed discharging disk style A > fan negative pressure value C > seed releasing disk rotational speed B > diameter of the holes D, and the optimal parameter combinations are A₃B₃C₃D₁. From the F-value, it can be seen that the seed discharging disk style A and the negative pressure value of the fan C have a very significant effect on the leakage rate of the seeder. So, it is essential to reasonably control the negative pressure value in the chamber cavity to ensure that seeds can be accurately and steadily adsorbed at the hole in the air chamber, thus reducing the leakage rate of the seeder.

Table 6. Leakage rate test results.

Analyze the Project	Considerations			
	Seed Dispenser Style A	Seed Discharge Disk Speed B	Fan Negative Pressure Value C	Hole Diameter D
K_1	17.14	12.75	14.05	11.59
K_2	13.06	12.82	11.59	12.77
K_3	6.91	11.54	11.55	12.75
k_1	5.71	4.25	4.68	3.86
k_2	4.35	4.27	3.86	4.26
k_3	2.30	3.85	3.85	4.25
R (extreme variance)	3.41	0.42	0.84	0.40
quadratic sum	19.36	0.38	1.42	0.37
mean value	9.68	0.19	0.71	0.19
(number of) degrees of freedom (physics)	2	2	2	2
F-value	69,695.74	1380.22	5101.68	1341.90
significance	**	*	**	*
order of priority		A > C > B > D		
optimal combination		A ₃ B ₃ C ₃ D ₁		

When checking the seed-filling performance of a pneumatic seeder, ensuring the seed suction qualification rate is the first factor to be considered [20]. Combined with the results of the orthogonal test and its extreme deviation and ANOVA analysis, the optimal combination of working parameters of the seeder was selected as $A_2B_2C_3D_3$, i.e., the style of seed discharging disk is a linear serrated disk. The speed of the seed discharge disk is 40 rpm. The value of the negative pressure of the fan is -2500 Pa, and the diameter of the typed hole is 1.2 mm.

To ensure the accuracy of the best parameter combination, the best parameter combination $A_2B_2C_3D_3$ obtained was compared with the best parameter combination $A_2B_2C_3D_1$ in the orthogonal test table, and each group of tests was repeated five times. The average value was taken as the final test result of each group of tests. The test results are shown in Table 7. As can be seen from the table, the seed dispenser in the parameter combination of $A_2B_2C_3D_3$ under the working conditions was the seed dispenser where suction seed qualification rate or leakage suction rate was better when compared with the parameter combination of $A_2B_2C_3D_1$. Therefore, the best determinant for the seed dispenser is the filling performance of the best working parameter combination of $A_2B_2C_3D_3$. At this time, the seed dispenser suction seed qualification rate was 95.32%, and the leakage suction rate was 3.11%, compliant with relevant requirements [35,36]. Figure 11 shows the seed-filling performance test process at the seed tray speed of 40 rpm, fan negative pressure value of -2500 Pa, the hole diameter of 1.2 mm in the plane disk, arc-type serrated disk, and linear serrated disk. The leakage phenomenon is shown in the center of the red rectangular box.

Table 7. Seed-filling performance verification test results.

Test Number	Suction Compliance Rate		Leakage Rate	
	$A_2B_2C_3D_1$	$A_2B_2C_3D_3$	$A_2B_2C_3D_1$	$A_2B_2C_3D_3$
1	95.19	96.91	3.62	2.85
2	95.10	94.87	3.54	3.23
3	95.08	94.45	3.02	3.31
4	94.67	94.73	3.24	3.21
5	94.84	95.64	3.22	2.94
average value	94.98	95.32	3.34	3.11

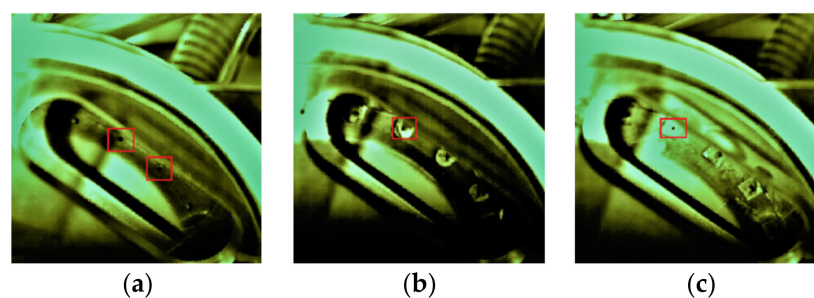


Figure 11. Seeder leakage in seed-filling performance tests. (a) Flat disk, (b) circular serrated disk, (c) linear serrated disk.

6. Conclusions

- (1) To address the problem of the pneumatic seeder having poor ability to disturb the seed population in the seed-filling stage, which leads to serious leakage of suction phenomenon, a pneumatic disturbing seeder was designed. Firstly, the important parts of the seeder were parameterized and structurally designed, and the seed-filling process of the seeder was dynamically analyzed according to the theory of mass dynamics. Secondly, the key factor affecting the seed-filling process of the seeder was obtained as the initial velocity v_0 of the seed population, and the absolute acceleration a of cabbage seed relative to the ground was inversely proportional to the initial

velocity v_0 of cabbage seeds. When the initial velocity v_0 of cabbage seeds is larger, the absolute acceleration of a cabbage seed relative to the ground obtained in the seed filling stage is smaller. Ultimately, it was found that the negative pressure adsorption force required to adsorb cabbage seeds in the air chamber was less under the same operating conditions.

- (2) The plane disk, arc-shaped serrated disk, and linear serrated disk, are three kinds of seed discharge disks. Based on EDEM simulation to carry out the simulation test of the population perturbation ability, the simulation results show that when the seed discharge disk began to rotate, whether it is the average speed of the population or the frequency of the population perturbation and the degree of concern, the linear serrated disk is better than the plane disk and arc-shaped serrated disk. It was proved that the linear serrated disk can effectively perturb the cabbage seeds sufficiently during the seed-filling process, thus reducing the leakage rate of the seeder.
- (3) Based on theoretical analysis and simulation, a four-factor, three-level orthogonal test of seed-filling performance was carried out on the pneumatically disturbed seed expeller with the qualified rate of seed suction and leakage rate as the evaluation indexes, and the style of seed expulsion disk, the rotational speed of seed expulsion disk, the value of negative pressure of the blower, and the diameter of the typed hole, as the factors. Through the analysis of polarity and ANOVA, the factors affecting the seed-filling rate were, in order of priority, seed expeller style A > fan negative pressure value C > seed expeller rotational speed B > hole diameter D, and the optimal parameter combination was $A_2B_2C_3D_3$. The factors affecting the leakage rate of seed filling were, in order of priority, seed expeller style A > fan negative pressure value C > seed expeller rotational speed B > hole diameter D, and the optimal parameter combination was $A_3B_3C_3D_1$. Careful consideration of the best performance of the seed dispensers' seed-filling performance was the combination of working parameters $A_2B_2C_3D_3$, its experimental verification of the seed dispenser at this time, with a suction seed qualification rate of 95.32%, and leakage rate of 3.11%. The test results meet the agronomic requirements of cabbage seed sowing.

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