Design and experiment of the pneumatic double disc precision seed metering device for Chinese flowering cabbage

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Abstract: Single seed metering devices for Chinese flowering cabbage planting machines have suffered such deficiencies as low efficiency, poor accuracy, and instability. To overcome these limitations, a pneumatic double disc precision seed metering device was designed. This innovative device can simultaneously plant four rows, considering the specific agricultural requirements and the geometric characteristics for Chinese flowering cabbage seeds. The precise parameters of the key component seed disc were derived through theoretical calculation. In addition, a detailed account was given for the working principle and workflow of the seed metering device. The discrete element method and EDEM software were employed to optimize the seed disc by exploring the effects of seed disc rotational speed and interleaving seed slots on seed viability. Orthogonal rotation experiments were conducted to evaluate the impact of seed disc rotational speed and negative pressure. While rates of qualified seeding, double seeding and missing seeding were adopted as test indicators. Testing results show that, at a seed disc rotational speed of 41.5 r/min and a negative pressure of 3.80 kPa, the average qualified seeding rate is 90.13%, the average missing seeding rate is 3.30%, and the average double seeding rate is 6.02%. These values satisfy the agricultural requirements for planting Chinese flowering cabbage. The findings can also provide valuable insights for the structural optimization and design of precision seed metering devices for Chinese flowering cabbage.

Keywords: Chinese flowering cabbage, precision seed metering device, double seed discs, pneumatic, experiment

DOI: 10.25165/j.ijabe.20241704.8661

Citation: Yu Y, Ge R C, Li G Y, Zhang X, Tan X Z, Yi D Z, et al. Design and experiment of the pneumatic double disc precision seed metering device for Chinese flowering cabbage. Int J Agric & Biol Eng, 2024; 17(4): 128–135.

1 Introduction

Chinese flowering cabbage, or flowering Chinese cabbage, is a member of the Brassicaceae family, belonging to the Brassica genus, Brassica oleracea species, and Brassica oleracea var. alboglabra subspecies. The cabbage is one of the main edible vegetables in southeastern China. It has a rapid growth cycle and substantial replanting index, leading to significant economic benefits[1,2]. The main planting methods involve manual planting and mechanical direct seeding. The labor-intensive nature of manual planting with its low efficiency hampers the large-scale cultivation of Chinese flowering cabbage. Despite the drawbacks of the current mechanical direct seeding method, such as excessive seed usage, high seed fragmentation rate, uneven row and plant spacing, inter-planting operation remains a requirement[3-5]. Precision direct seeding technology serves as the main method to improve the proficiency of Chinese flowering cabbage direct seeding procedure. The seed metering device is one of the key components of the seeder. Its working performance directly shapes the quality of seeding[6-8]. The current leading research direction for precision seed metering devices for small seeds revolves around pneumatic seed meters featuring high precision, a low seed damage rate, and a wide applicable seed size range[9,10].

Currently, domestic and foreign scholars have studied pneumatic precision seed meters from different aspects. Pareek et al.[11] proposed the ANN-MOPSO method to study the effects of seed suction hole shape and size, vacuum pressure, and forward working speed on seed metering performance through experiments. They established mathematical models between the parameters. Li et al.[12] designed a double-row precision seed meter for small-sized cabbage seeds with high sphericity. The researchers optimized the seed meter parameters based on experiments and variance analysis. Li et al.[10] also developed a pneumatic precision seed meter for rapeseed. They used Fluent to simulate the flow fields of various suction holes and analyzed the effects of suction hole shapes on the flow field changes in the suction chamber. Xing et al.[13] used CFD-DEM coupling simulation technology to analyze the motion details and status of rice seeds in airflow. They studied the effects of precision conveying under different parameters of a positive pressure precision seeder. Shi et al.[14] designed a seed disc with curved guide grooves that can guide seeds to move towards the holes, improving the seed filling performance of pneumatic seed meters. Li et al.[15] designed a double-row pneumatic precision seed meter with a single air duct, which realized double-row seeding for spherical seeds. In summary, pneumatic seeders are suitable for seed metering of small vegetable seeds. The seed holding capacity and seeding accuracy of seeders can be improved through structural design, simulation optimization, etc[16-19]. However, there is a lack of

Received date: 2023-11-16 **Accepted date:** 2024-07-25

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research on specialized seeders that meet the agronomic requirements for Chinese flowering cabbage seeding.

This paper aims to address the problems of insufficient seed holding capacity, low seeding efficiency and poor seeding accuracy in existing Chinese flowering cabbage seeders using single seed meters. Based on the agronomic requirements for Chinese flowering cabbage cultivation and the geometric characteristics of Chinese flowering cabbage seeds, a pneumatic double disc precision seed metering device for Chinese flowering cabbage is designed. It incorporates with dual seed discs, multi-row seed metering and stable seed suction through independent air channels. Through simulation optimization and bench testing, the optimal structure and working parameters of the seed metering device are obtained. It is hoped that this can provide references for the structural optimization and design of precision seed metering devices for Chinese flowering cabbage.

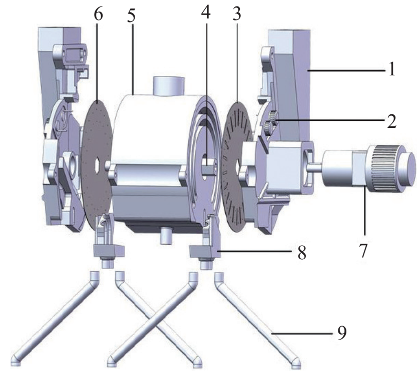
2 Overall structure and working principle

2.1 Overall structure

The pneumatic double-disc precision seed meter for Chinese flowering cabbage mainly comprises a seed box, seed discs, air chambers, seeding shafts, seed distributors, seed ducts, scrapers, etc., as shown in Figure 1. The two circles of suction holes on each seed disc correspond to the pair of negative pressure air ducts on the air chamber, which can achieve four-row seeding with one seed meter.

2.2 Working principle

The seed meter's working process includes four stages: seed filling, seed holding, seed discharging and debris blowing, corresponding to the regions on the seed disc as shown in Figure 2. During operation, both the positive and negative pressure ports are connected to the blower through air pipes. The two independent negative pressure air ducts on the air chamber correspond to the two circles of suction holes on the seed discs, providing stable negative pressure. Under the negative pressure, seeds in the seed box are attracted to the suction holes. Driven by the motor, the seed disc holding the attracted seeds rotates. The scrapers scrape off excess seeds, ensuring one seed per hole. As the seed disc continues rotating, it carries the seeds to the discharging area. Here the suction holes carrying seeds leave the negative pressure air ducts, the negative pressure disappears, and the Chinese flowering cabbage seeds fall off the suction holes under their own gravity and centrifugal forces, entering the seed ducts through the seed distributors and falling into the sowing area. Finally, the suction holes go through the positive pressure blowing holes to clear debris inside, completing the sowing process.



1. Seed box 2. Scrapers 3. Seed discs-1 4. Seeding shafts 5. Air chambers 6. Seed discs-2 7. Servo motor 8. Seed distributors 9. Seed guiding pipes

Figure 1 Pneumatic double-disc precision seed metering device for Chinese flowering cabbage

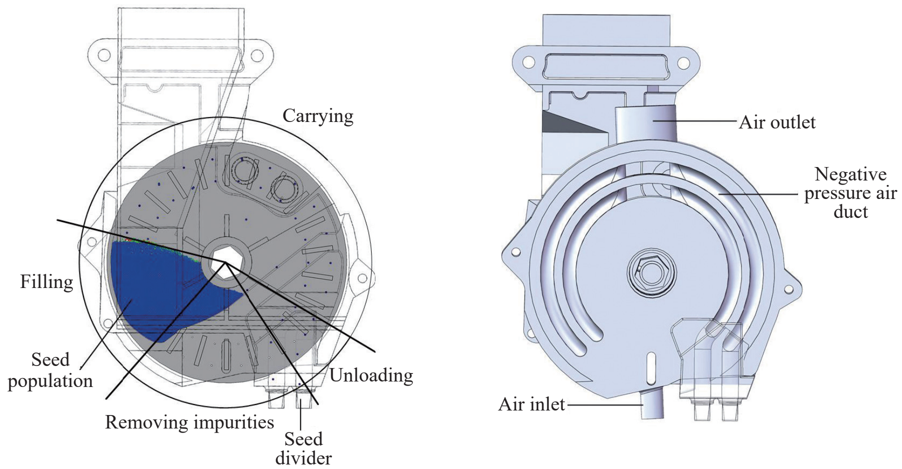


Figure 2 Working Flowchart of pneumatic double-disc precision seed metering device for Chinese flowering cabbage

3 Seed disc design

3.1 Geometric characteristics of Chinese flowering cabbage seeds

The seed disc is the key component of the seed meter. Its design is mainly based on the geometric characteristics of seeds[20]. In this study, 49-19 Chinese flowering cabbage seeds were selected as the experimental subject. 50 seeds were randomly selected and measured 5 times for the length, width and height using a vernier caliper, and the average values were taken as the three axial dimensions. The three axial dimension parameters are listed in Table 1 and the average size distribution is shown in Figure 3.

Table 1 Three-axis dimensional parameters

Parameter	Length/mm	Width/mm	Thickness/mm	Size/mm
Average value	1.8092	1.6438	1.5790	1.6833

To calculate the equivalent diameter D and sphericity φ of Chinese flowering cabbage seeds, the calculation equations are:

$$D = \sqrt[3]{LWT} \tag{1}$$

$$\varphi = \frac{D}{L} \tag{2}$$

where, D is length of Chinese flowering cabbage seed, mm; W is width of Chinese flowering cabbage seed, mm; T is thickness of Chinese flowering cabbage seed, mm; L is average length of Chinese flowering cabbage seed, mm; φ is sphericity of Chinese flowering cabbage seed, %.

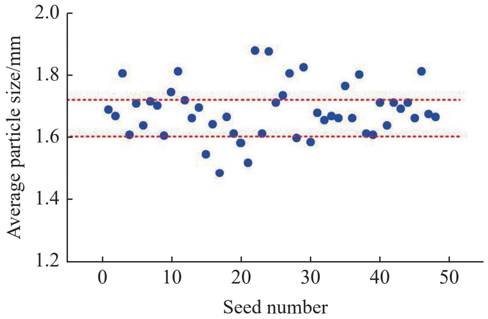


Figure 3 Distribution of the average particle size of Chinese flowering cabbage seeds

The calculated equivalent diameter D of the Chinese flowering cabbage seeds is 1.67 mm, and the sphericity φ is 92.27%. The sphericity is high, so the seeds are regular spherical. Therefore, in the following design and simulation analysis of the seed disc, the Chinese flowering cabbage seeds can be modeled as spheres for analysis.

3.2 Seed disc diameter

The seed disc is the key component to ensure precise seed metering by the pneumatic double-disc precision seed meter for Chinese flowering cabbage[21, 22]. The motion of seeds inside the seed meter is adsorption on the suction holes and rotation with the seed disc. The length of seed filling time affects the quality of seed filling. By studying the parameters of the seed disc during operation and their impact on the seed filling time, the relationship equation for the seed disc diameter is derived based on the structure and geometric relations of the seed meter:

$$\begin{cases} v = \dfrac{\pi n D}{60} \\ \omega = \dfrac{\theta_x \pi n}{360} \\ t_x = \dfrac{l_x}{v} \end{cases} \tag{3}$$

where, n is rotational speed of seed disc, r/min; D is diameter of seed disc, mm; v is peripheral velocity of seed disc, m/s; t_x is seed filling time, s; l_x is arc length of seed filling section, mm; θ_x is rotational angle of seed filling section, rad; ω is angular velocity of seed disc rotation, rad/s.

Given that the rotational angle θ_x of the seed filling section is 60°, the arc length of the filling area is approximately $\pi D/6$, substituting into Equation (3) and rearranging yields:

$$t_x = \frac{5\pi}{3\omega} \tag{4}$$

From Equation (4) we can see that the seed filling time t_x is inversely proportional to the angular velocity ω of the seed disc, i.e. inversely proportional to the rotational speed n of the seed disc. Based on the structure of the seed meter's air chamber and relevant literature, the seed disc diameter D is determined to be 220 mm. A 1 mm thick stainless steel plate is selected as the fabrication material. The strength and stiffness of the stainless steel plate both meet the requirements.

3.3 Number of seed suction holes

The suction hole parameters are important factors affecting the seed filling performance. Under fixed sowing machine operating speed and row spacing, the more suction holes, the lower seed disc rotational speed, the more beneficial for improving the seed filling performance[23]. The suction holes are located 15-20 mm away from the edge of the concentrically arranged holes, and the diameter range of the circumferential circumference where the holes are located is 100-230 mm. Since the seed disc in this study has double-row suction holes with equal numbers of holes on the inner and outer rows, increasing the hole number will lead to over-dense inner row holes and increased miss-sucking rate. Therefore, it is crucial to reasonably determine the suction hole number. The calculation equation for the suction hole number S on the seed disc is:

$$S = \frac{60 v_n}{nZ} \tag{5}$$

where, v is operating speed of sowing machine, m/s; Z is plant spacing, m.

According to the agronomic requirements for Chinese flowering cabbage planting, the operating speed of the sowing machine is 1.0-2.0 m/s. The row spacing is 0.15-0.30 m, and the seed disc rotational speed n is 20-50 r/min. From Equation (3), S ranges from 8 to 30. Considering the seed disc size and seed metering performance, the number of suction holes is selected to be 22 in this study, with the center angle between adjacent suction holes being approximately 16.4°.

3.4 Seed suction hole diameter

The suction hole diameter d is determined by the size of the Chinese flowering cabbage seeds, i.e.

$$d = (0.64 \sim 0.66)b \tag{6}$$

where, d is diameter of suction hole, mm; b is average width of seeds, mm.

The larger the suction hole diameter, the lower the suction pressure required at higher rotational speeds, but excessive size will lead to seeds clogging the suction holes and affect seed metering performance. Based on calculations using Chinese flowering cabbage seeds, the suction hole diameter on the seed disc is determined to be 1.0 mm.

4 Simulation experiments and design optimization

4.1 Design of seed disc interleaving structure based on EDEM

Through literature review and research on previous seed meters, it is found that, during operation, the seed metering performance helps to achieve the precision in sowing, and the inter-grain friction force is the most critical factor affecting the seed metering performance. During seed metering, the single seeds adhered to the seed disc need to overcome seed-to-seed friction as they move with the disc. When squeezed together under gravity, the bulk seeds form a population that generates substantial friction, thus reducing the single seed adhesion rate and negatively impact the seed metering effect. Therefore, adding agitating structures is an important measure to change this phenomenon[24-26]. In this study, a seed disc with agitating groove structures is designed, with the grooves being 28 mm long, 4 mm wide and 0.5 mm deep, evenly distributed in the spacing between adjacent suction holes, as shown in Figure 4. Compared with seed discs without agitating structures, the effect of the agitating structure on improving seed metering performance is examined using discrete element EDEM simulation. And seek the appropriate disturbance groove width through simulation experiments.

4.2 Model establishment

This section studies the agitation effect on the seed population within the cavity composed of the seed metering housing and the seed disk. So the geometric model is simplified into two parts – the single-sided seed metering housing and the seed disk, as shown in Figure 5. The materials are set as ABS engineering plastic and stainless steel. According to the size and shape of Chinese flowering cabbage seeds, the seed particles are simplified into spherical particles with a diameter of 1.6 mm, as shown in Figure 6, following a normal distribution with a standard deviation of 0.05. The Hertz-Mindlin no-slip contact model is selected, and the contact parameters are listed in Table 2.

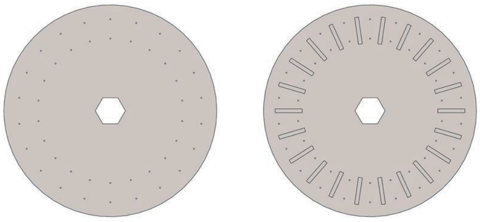


Figure 4 Seed discs of different specification

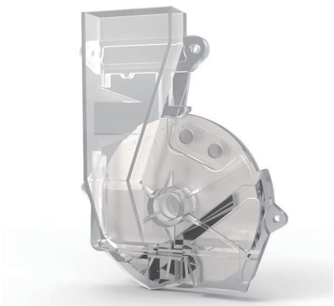


Figure 5 Simplified geometric model

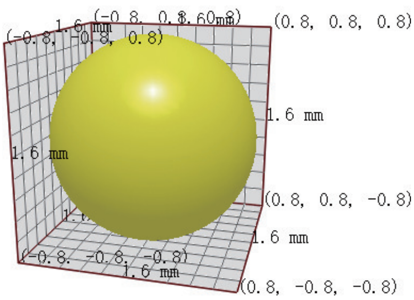


Figure 6 Chinese flowering cabbage seed particle model

4.3 Simulation results and analysis

Simulations were carried out at seed disk rotational speeds of 25 r/min, 35 r/min, and 45 r/min respectively, to observe the agitation effect on the Chinese flowering cabbage seed population, both with and without agitating grooves. 0.2 kg of Chinese flowering cabbage seeds were generated in the seed box within the first 1 s, while the seed disk rotated at a constant speed. The simulation time was 10 s. A detection box was built to cover the entire seed population within the seed metering chamber in the EDEM post-processing module, as shown in Figure 7. The simulation results, including different rotational speeds and presence of agitating structures, are shown in Figure 8. The average velocity profile of the seed particles during rotation of the two seed disks is obtained, as shown in Figure 9.

Through comprehensive analysis of the figures, it can be seen that the average velocity of the seed particles is related to the seed disk rotational speed and agitating structures, with higher speeds resulting in increased velocity. Under the same rotational speed, the seed disk with agitating grooves has a much higher agitation effect on the seed population than the seed disk without agitating structures. Therefore, to obtain better seed metering performance, it is necessary to select a seed disk with agitating groove structures.

Table 2 Mechanical properties simulation parameters

Items	Parameters	Values
Seed particles	Poisson's ratio	0.25
	Shear modulus/Pa	1.1×107
	Density/$kg \cdot m^{-3}$	1050
ABS material	Poisson's ratio	0.39
	Shear modulus/Pa	8.9×108
	Density/$kg \cdot m^{-3}$	1100
Stainless steel material	Poisson's ratio	0.30
	Shear modulus/Pa	1.1×1010
	Density/$kg \cdot m^{-3}$	7850
Particle-particle	Coefficient of restitution	0.60
	Static friction coefficient	0.50
	Dynamic friction coefficient	0.01
Particle-ABS	Coefficient of restitution	0.75
	Static friction coefficient	0.30
	Dynamic friction coefficient	0.01
Particle-stainless steel	Coefficient of restitution	0.60
	Static friction coefficient	0.30
	Dynamic friction coefficient	0.01

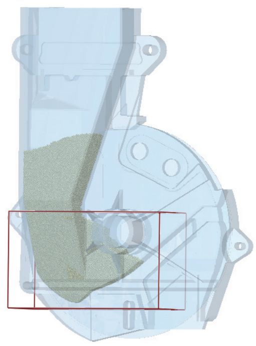


Figure 7 Filling chamber detection

Explore the effect of disturbance groove width on seeding performance by setting the seeding disc speed to 40 r/min and conducting simulations with disturbance groove widths of 1, 2, 3, 4, 5, 6, 7 and 8 mm. The simulation results for different disturbance groove widths are shown in Figure 10.

From the analysis of Figure 10, it can be seen that the particle movement speed is related to the disturbance groove width. When the disturbance groove width is set to 1-5 mm, the particle movement speed increases significantly. From 5-8 mm, the particle movement speed remains similar. Considering the manufacturing process of the seeding disc, the disturbance groove width was set as 5 mm.

5 Bench test

5.1 Test apparatus

In order to verify the seed metering performance of the pneumatic double disc precision vegetable seeder for Chinese flowering cabbage, a test rig verification experiment was carried out. The experimental setup, as shown in Figure 11, consists of a Pneumatic double disc precision seed metering device for Chinese flowering cabbage, motor drive control device, PVC transparent

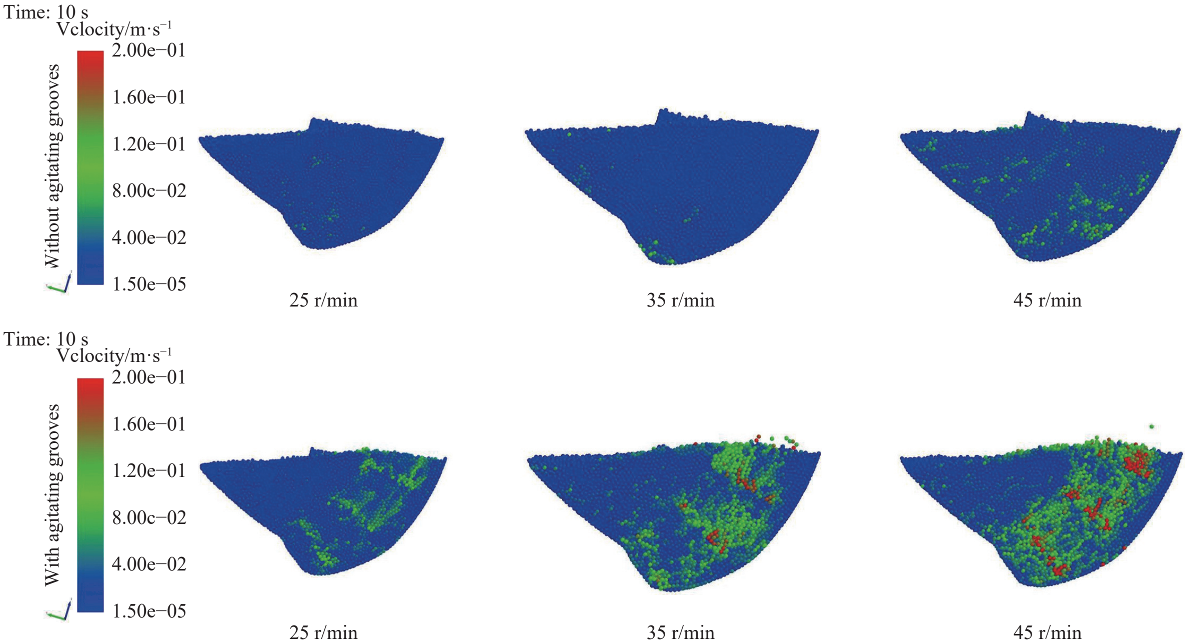


Figure 8 Agitation effect

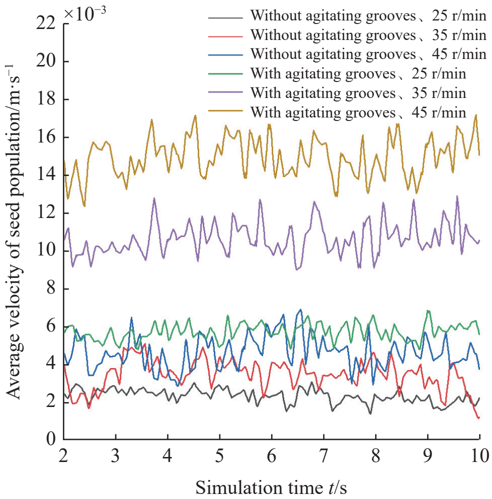


Figure 9 Average velocity of seed population

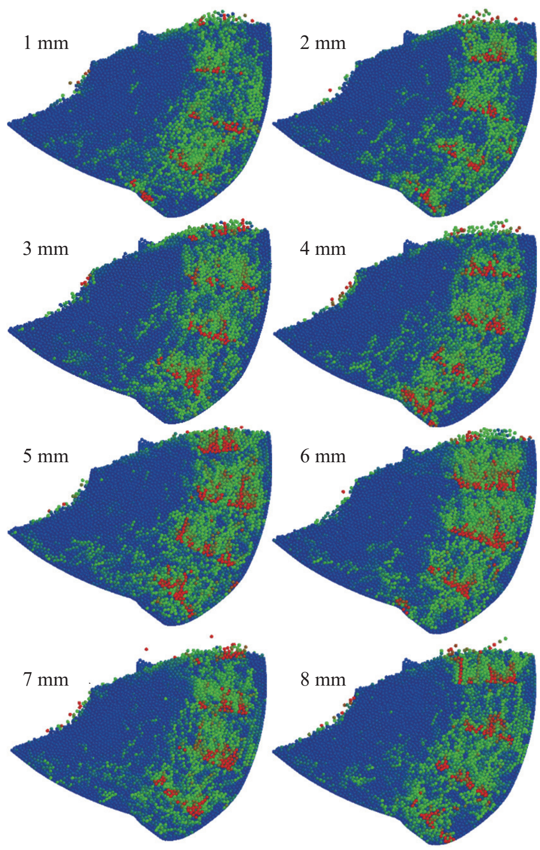


Figure 10 Effect of different disturbance groove widths

steel wire pneumatic tube, seeder performance test rig, pressure gauge, and HG220 high-pressure vortex blower.

5.2 Single-factor pre-experiment

Both the rotational speed of the seed disk and the negative pressure had a significant influence on the seed metering performance during sowing. In order to determine the reasonable ranges for seed disk rotational speed and negative pressure in the formal experiment, single factor pre-experiments were carried out. The qualified rate, missed sowing rate, and re-sowing rate are used as test indicators.

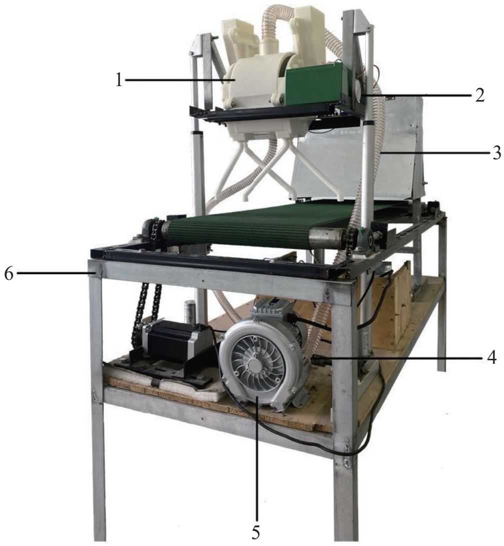
$$\text{Qualified Rate:}\ A=\frac{n_1}{N}\times 100\% \tag{7}$$

$$\text{Miss Rate:}\ D=\frac{n_2}{N}\times 100\% \tag{8}$$

$$\text{Multi}-\text{Seed Rate:}\ M=\frac{n_3}{N}\times 100\% \tag{9}$$

where, n_1 is number of qualified seeds; n_2 is number of missed sowing seeds; n_3 is number of re-sowing seeds; N is total number of experimental seeds.

The more the negative pressure, the more energy is consumed. To minimize energy consumption, the negative pressure should be reduced as much as possible while meeting the normal seed suction requirements. In the negative pressure parameter pre-experiment, the seeder performance was examined at a low seed disk rotational speed of 5 r/min and negative pressures ranging from 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 to 4.5 kPa. The results are listed in Table 3. When the negative pressure dropped to 2.5 kPa, the seeder had serious misses. As the negative pressure increased, the miss rate gradually stabilized. Therefore, the negative pressure was set between 2.5-4.5 kPa for the formal experiment.



1.Pneumatic double disc precision seed metering device for Chinese flowering cabbage 2.Motor drive control device 3. PVC transparent steel wire pneumatic tube 4. pressure gauge 5. HG220 high-pressure vortex blower. 6. seeder performance test rig

Figure 11 Test rig setup

Table 3 Pressure pre-experiment analysis results

Items	Negative pressure/kPa							
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Miss rate	16.22	15.92	13.31	10.43	9.55	8.95	8.07	8.33
Multi seed rate	3.85	4.56	5.64	6.23	7.74	8.63	9.88	11.25
Qualified rate	79.93	79.52	81.05	83.34	82.71	82.42	82.05	80.42

In the rotational speed parameter pre-experiment, the seeder's performance was evaluated, under a median negative pressure of 3.5 kPa and rotational speeds of 10, 20, 30, 40, 50, 60 r/min respectively. The results are listed in Table 4. When the rotational speed was lower than 20 r/min, the agitation was insufficient, resulting in a high miss rate. When the rotational speed exceeded 40 r/min, the high centrifugal force at high speeds led to serious misses. Therefore, the rotational speed was set between 20-50 r/min for the formal experiment.

Table 4 Analysis Results of Rotational Speed Preliminary Experiment

Items	Rotational speed r/min					
	10	20	30	40	50	60
Miss rate	10.8	7.02	6.33	5.65	7.21	13.50
Multi seed rate	12.13	10.54	6.35	7.26	8.36	6.63
Qualified Rate	77.07	82.44	87.32	87.09	84.43	79.87

5.3 Orthogonal experiment and result analysis

Based on the results of the single factor pre-experiments, rotational speed and negative pressure were taken as the key factors affecting seed metering quality. Qualified rate, miss rate, and multi-seed rate were used as evaluation indicators to explore the optimal working parameters of pressure and seed disk rotational speed. With other conditions unchanged, the rotational speed range was set to 25-55 r/min, and the pressure range was 2.5-4.5 kPa. The codes of the experimental factor levels are listed in Table 5. According to the principle of central composite test design, orthogonal rotation experiments were carried out, where A represents the rotational speed factor, and B represents the pressure factor. Each group was repeated 3 times and the average values were used for data analysis. The specific experimental design and results are listed in Table 6.

Table 5 Coded levels of experimental factors table

Codes	Factors	
	A: Rotational speed/r·min^{-1}	B: Negative pressure/kPa
−1.414	18.79	2.09
−1	25.00	2.50
0	40.00	3.50
1	55.00	4.50
1.414	61.21	4.91

Table 6 Experimental design scheme and results

Test No.	A: Rotational speed	B: Negative pressure	Evaluation indicators/%		
			A	D	M
1	−1.000	−1.000	88.74	4.55	6.71
2	1.000	−1.000	86.01	7.34	6.65
3	−1.000	1.000	88.18	4.36	7.46
4	1.000	1.000	88.69	6.18	5.13
5	−1.414	0.000	90.12	1.56	8.32
6	1.414	0.000	87.95	5.26	6.79
7	0.000	−1.414	85.32	8.79	5.89
8	0.000	1.414	88.11	6.31	5.58
9	0.000	0.000	89.95	3.35	6.70
10	0.000	0.000	90.25	3.14	6.61
11	0.000	0.000	90.67	3.41	5.92
12	0.000	0.000	89.96	3.17	6.87
13	0.000	0.000	90.36	3.62	6.02

The experimental data was imported into Design-Expert 13.0.6 software for regression fitting analysis. The response functions for qualified rate, miss rate and multi-seed rate were set as Y_1, Y_2 and Y_3. The coded influencing factors were used as independent variables to establish regression mathematical models. The regression models were derived to show the effects of various factor levels on qualified rate, miss rate and multi-seed rate were obtained:

$$Y_1 = 90.24 - 0.6611A + 0.7582B + 0.8100AB - 0.5940A^2 - 1.75B^2;$$

$$Y_2 = 3.34 + 1.23A - 0.6072B - 0.2425AB + 0.0679A^2 + 2.14B^2;$$

$$Y_3 = 6.42 - 0.5692A - 0.1511B - 0.5675AB + 0.5621A^2 - 0.3839B^2.$$

According to the analysis of variance in Table 7, the qualified rate is greatly influenced by factors A and B, regression terms AB, A^2 and B^2. The established regression model reaches a significant level (p<0.01) with F=53.19 and p<0.0001. The p value for lack of fit (0.2750) exceeds the threshold of 0.05, showing no significant difference in the model. This means non-experimental factors have little effect on the qualified rate and the model has a reliable experimental stability. The equation's reliability is demonstrated by the close fit between the predicted and actual values. The regression model for miss rate reaches a highly significant level, with a p value less than 0.01. Factors A and B and regression term B^2 have p values less than 0.01, indicating an extremely significant level, whereas regression terms AB and A^2 present p values greater than 0.05, suggesting no significant effects. The regression model for multi-seed rate shows a significant p value of 0.0019 (p<0.01). The p value for lack of fit is 0.9386 (p>0.05), indicating no significant effect. This shows the regression model fits the actual seeding situation well within a certain parameter range. Further analysis shows regression terms A, AB, A^2 and B^2 have significant effects, while regression term B has a p value exceeding 0.05, implying a lack of significant effect. After removing the insignificant regression terms, the regression models for qualified rate, miss rate and multi-seed rate can be expressed as:

$Y_1 = 90.24 - 0.6611A + 0.7582B + 0.8100AB - 0.5940A^2 - 1.75B^2$;

$Y_2 = 3.34 + 1.23A - 0.6072B + 2.14B^2$;

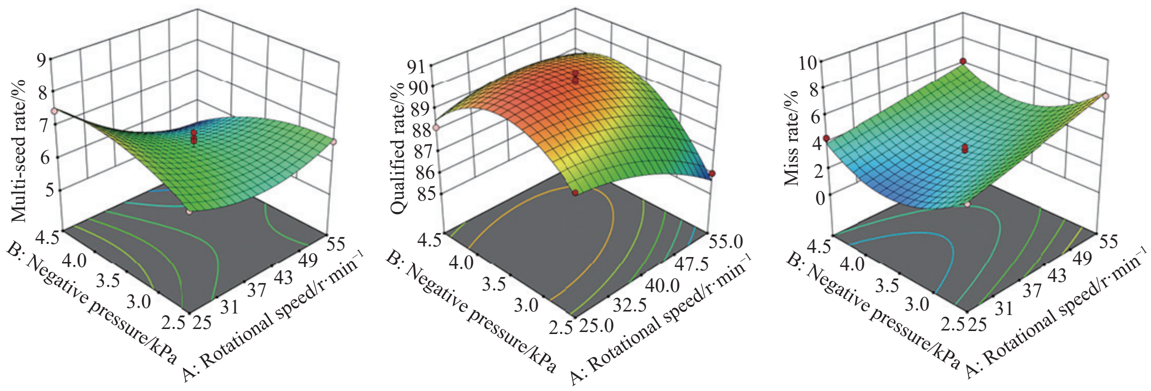
$Y_3 = 6.42 - 0.5692A - 0.5675AB + 0.5621A^2 - 0.3839B^2$.

5.4 Analysis of experimental influence effects

3D interaction plots were drawn using the software to intuitively and clearly analyze the effects of rotation speed and negative pressure on seeding's qualified rate, miss rate and multi-seed rate. As shown in Figure 12, when keeping the rotation speed constant, the qualified rate increases at first and then decreases as the negative pressure rises. The miss rate experiences an initial decline, followed by a subsequent increase as the negative pressure increases. The multi-seed rate, initially rises as the negative pressure rises, and then declines, but the overall trends are not highly pronounced. Under the constant negative pressure, an increase in rotation speed leads to a decrease in the qualified rate and a rise in the miss rate. While the multi-seed rate exhibits a pattern of first decreasing, then increasing with the change in rotation speed. Where the rotation speed ranges from 25-47.5 r/min and the negative pressure falls between 3.2-3.8 kPa. The qualified rate is at a high range, while the miss rate and multi-seed rate are at a low level.

Table 7 Experimental Design Scheme and Results

Source of variance	Qualified Rate				Miss Rate				Multi-Seed Rate			
	Sum of squares	DoF	F	p	Sum of squares	DoF	F	p	Sum of squares	DoF	F	p
A	3.50	1	28.12	0.0011**	12.11	1	104.01	< 0.0001**	2.59	1	22.78	0.0020**
B	4.60	1	36.99	0.0005**	2.95	1	25.33	0.0015**	0.1825	1	1.60	0.2459
AB	2.62	1	21.11	0.0025**	0.2352	1	2.02	0.1982	1.29	1	11.32	0.0120**
A^2	2.45	1	19.74	0.0030**	0.0320	1	0.2753	0.6160	1.93	1	16.92	0.0045**
B^2	21.40	1	172.12	<0.0001**	31.79	1	273.10	< 0.0001**	1.03	1	9.01	0.0199**
Model	33.07	5	53.19	<0.0001	47.40	5	81.43	< 0.0001**	7.44	5	13.07	0.0019**
Residual	0.8704	7			0.8150	7			0.7967	7		
Lack of fit	0.5085	3	1.87	0.2750**	0.6627	3	5.80	0.0612	0.0698	3	0.127	0.9386
Pure error	0.3619	4			0.1523	4			0.7269	4		
Total	33.94	12			48.22	12			8.23	12		



a. Multi-seed rate response surface. b. Qualified rate response surface c. Miss rate response surface

Figure 12 Influence surface of evaluation index for each factor

5.5 Analysis of experimental influence effects

To maximize qualified rate and minimize miss rate and multi-seed rate, the prediction of optimal seeding quality is conducted with rotation speed between 25-55 r/min and negative pressure between 2.5-4.5 kPa. The optimal parameters obtained are: rotation speed 41.433 r/min, negative pressure 3.839 kPa, with qualified rate 90.251%, miss rate 3.488%, and multi-seed rate 6.261%. To verify the theoretical optimal parameters, under the same other conditions, the rotation speed is set to 41.5 r/min, negative pressure is set to 3.80 kPa, and 3 repeated experiments are conducted. The average qualified rate obtained is 90.13%, average miss rate is 3.30%, and average multi-seed rate is 6.02%. The experimental results are basically consistent with the theoretical results.

6 Conclusions

1) Based on the physical properties of lettuce seeds and agronomic requirements for lettuce seeding, a pneumatic double disc precision seeder for lettuce was designed. The working principle and operating procedures were elaborated in terms of negative pressure seed picking, zero pressure seed releasing and positive pressure impurity blowing off the seeder. The key parameters including the diameter of the seeding disc, the number of suction holes and the diameter of suction holes were determined.

2) Studies were conducted to evaluate the effects of seed disc rotation speed and agitation structure on the agitation ability of seed population. Based on the discrete element method, simulation and optimization were performed using EDEM software. From the curves of the average velocity of seed population over time under different rotation speeds and with or without agitation structure, it can be seen that the vigor of seed population increases with the increase of seed disc rotation speed. The vigor of seed population with agitation groove structure is significantly higher than that without agitation structure.

3) After the single-factor pre-experiment, the parameter ranges were obtained for negative pressure and rotation speed that affects the seeding accuracy of the seeder. Rotatable orthogonal experimental design was adopted, with negative pressure and seed disc rotation speed as experimental factors, and qualified seeding

rate, miss rate and multi-seed rate as evaluation indexes. Regression analysis was performed on the experimental results to establish regression equations. The optimal parameters obtained were seed disc rotation speed of 41.5 r/min and negative pressure of 3.8 kPa. Verification experiments showed that all indicators met the national standard requirements.

Acknowledgements

This work was financially supported by Collaborative Innovation Center for Shandong's Main Crop Production Equipment and Mechanization, Qingdao Shandong 266109, China.

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