MATERIAL CHARACTERISTICS OF VEGETABLE SEEDS WITH SMALL GRAIN SIZE AND DESIGN OF SEED METERING DEVICE
/
小粒径蔬菜种子物料特性研究与排种器的设计

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ABSTRACT
In order to solve the problems of poor universality and complex structure of the current air-suction precision seed metering device for small vegetable seeds, an air-suction precision seed metering device based on the physical characteristics of small vegetable seeds was developed. The physical characteristics of several typical small vegetable seeds were measured to provide a theoretical basis for the design of air-suction precision seed metering device. Analyzed the force on the seed during seed metering, and used discrete element method to analyze the overall state of the seed at different times in combination with the basic structure. The experiment was designed with the pass rate, replay rate and miss rate as experimental indicators. The regression model was established to obtain the reasonable range of each parameter. The experimental results showed that when the rotary table speed was 28.65 r/min and the working negative pressure was 4.40 kPa, the seeding pass rate of the seed meter was 91.07%, the replay rate was 4.70%, and the missed rate was 4.23%.

摘要
针对目前小粒径蔬菜种子气吸式精密排种器存在的通用性差、结构复杂等问题，设计了一种基于小粒径蔬菜种子物理特性的气吸式精密排种器。测定多种典型小粒径蔬菜种子的物理特性，为排种器的设计提供理论基础，分析排种过程中种子受力情况，结合基本结构运用离散元方法对种子不同时间的整体状态进行分析。以合格率、重播率、漏播率为实验指标，通过正交试验分析得出排种时各参数的合理区间。实验结果表明：当转盘转速为28.65r/min，工作负压为4.40kPa时，排种器排种合格率为91.07%，重播率为4.70%，漏播率为4.23%。

INTRODUCTION
In recent years, with the increase of global vegetable consumption demand, vegetables have become the second largest crop after grains, among which cabbage, rape and other small seed vegetables have the most promotion value, the most extensive planting area and large demand. At present, vegetable planting in most areas of China is mainly based on traditional manual sowing, and the mechanization of vegetable sowing has been at a low level and degree (*Yu et al., 2011; Xia et al., 2008*). Therefore, it is of great significance to study the precision seed metering device for small diameter vegetables for promoting the mechanized production of sowing.

The performance of precision seed metering device directly affects the sowing quality. The air-suction seeder has become the research direction of precision seeder due to its advantages of no seed damage and high operating speed (*Liu et al., 2017; Ding et al.,2018*). *Hensh et al., (2022*), used the electronic metering device to monitor and feed back the seed metering process of the precision seed metering device in real time, reducing missed seeding and improving the precision of seeding quality. *Wang et al., (2022*), have designed a vacuum central cylinder seed metering device, which can realize the replacement of devices with different diameters such as suction holes and stirring, and achieve the effect of high seed suction qualification rate. *Gautam et al., (2019)* based seed metering mechanism provides good seeding uniformity for sowing of

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different seeds like okra, cowpea, groundnut etc. at low cost and without creating any environmental hazards. *Karayel et al., (2004),* determined the vacuum negative pressure requirements when sowing different vegetable seeds by exploring a variety of vegetable seeds.

Although the above research has improved the seed metering quality and precision, it has not yet achieved the sowing of multiple-grain size seeds. Based on the research on the physical characteristics of several common small vegetable seeds, this paper designed an air-suction precision seed metering device for small diameter vegetable seeds with adjustable holes to realize the sowing of different diameter seeds; The seed stacking and seed disturbing performance of seed seeder were analyzed in discrete element simulation; Finally, the best operation parameters of seed metering device were obtained through bench test. The seed metering device overcomes the disadvantage that the traditional seed metering device can only sow seeds with the same grain size, greatly improves the universality of the seed metering device, and realizes the sowing of seeds with multiple-grain size.

MATERIALS AND METHODS

Determination of physical parameters of small vegetable seeds

The whole frame

The research objects selected in this paper are six typical small grain vegetable seeds, namely Suzhou Qing, Shanghai Qing, Fast vegetable, pak choi, Chinese cabbage, and Chinese little greens. Through electronic balance, measuring cylinder, vernier caliper, angle of repose tester and other instruments, a thousand seeds weight, density, particle size distribution, angle of repose, and sliding friction angle of six typical small vegetable seeds are measured and analyzed, and the physical characteristics of small grain seeds are fully studied, It can provide guidance and reference for the design of key parameters such as the structure design of seed metering device, the size and distribution of shaped holes (*Zhang et al., 2015;Su et al., 2022*). The six typical small grain vegetable seeds selected are shown in Fig.1.

a) Suzhou Qing b) Shanghai Qing c) Fast vegetable d) pakchoi e) Chinese cabbage f) Chinese little greens

Fig. 1 - The six typical small vegetable seeds

Determination of physical characteristic parameters

Determination of a thousand seeds weight

The study of a thousand seeds weight is helpful to determine the negative pressure value of seed suction, and the electronic balance with an accuracy of 0.001 g is used to measure small vegetable seeds. The determination was carried out in 1000 clean vegetable seeds randomly for weighing and repeated twice. If the weight difference between the two times is more than 5% of the total weight of the sample, weigh the third sample, and select the sample with the smallest difference between the two times to calculate the average value. Take the average value as a thousand seeds weight test value.

Determination of angle of repose of seeds

The angle of repose of seeds can reflect the scattering characteristics and internal friction characteristics of seed materials. The selected measuring instrument is BT-1001 intelligent powder characteristic tester. The experimental instrument and measuring principle diagram are shown in Fig. 2.

a) Angle of repose tester b) measuring principle

Fig. 2 - The intelligent powder characteristic tester and measuring principle

During the measurement, the seeds are stacked on the plane as a cone, and the important parameters for measuring the angle of repose are obtained: the horizontal bottom radius of the material cone, the height of the cone from which the seeds are stacked. The angle of repose is calculated using Eq.(1):

$$\theta' = \arctan \frac{H}{R} \qquad (1)$$

where:

θ' is angle of repose, [°]; H is the height of the species cone, [mm]; R is the horizontal bottom circle radius of the material cone, [mm].

Determination of sliding friction angle of seeds

The sliding friction angle of the seed is of great significance to the design of the seed box and the shape design of the seed metering device. During the measurement, 30 groups of 6 types of small vegetable seeds were randomly selected from each type, and 100 seeds were taken from each group and placed on the tester. Slowly shake the handle of the tester to make it more inclined. When the number of seeds to be measured on the tester reaches more than 95%, the inclination angle of the tester was measured, and the data were measured and recorded for many times. Finally, the average value of the measured data was selected.

Determination of seed size

The particle size of the seed has a great influence on the design of the pore size in the later stage. The seeds of the above six typical vegetables are spherical. In this experiment, a vernier caliper with an accuracy of 0.02mm is used to measure the particle size of the seed. Five plump and uniform seeds are selected from each type of seed. The final particle size of the seed is determined by measuring the selected seeds five times and calculating the average value.

Determination of seed density

Seed density is an important factor affecting the suspension characteristics of materials, which is of great significance to the subsequent seed metering structure design and simulation analysis. Put a certain mass of material in the liquid, determine the actual volume of the measured material, and then calculate the volume and mass of the material to calculate the density. The seed density is calculated using Eq.(2):

$$\rho = \frac{m}{v} \qquad (2)$$

where: P is the seed density, [g/cm^3]; m is the mass, [g]; v is the volume, [cm^3].

Repeat the test three times for each type of seed, and take the average value as the test value of this density measurement.

The basic parameters of 6 common vegetable seeds obtained from the test are shown in Table 1.

Table 1

Seed test data

Name	Suzhou Qing	Shanghai Qing	Fast vegetable	pakchoi	Chinese cabbage	Chinese little greens
A thousand seeds weight (g)	3.211	2.317	2.089	1.991	3.082	2.749
Angle of repose (°)	26.07	25.65	23.57	24.92	24.39	23.92
Sliding friction angle (°)	21.3	20.5	20.7	21.4	20.6	20.1
Average seed size (mm)	1.71	1.46	1.44	1.41	1.51	1.23
Seed density (g/cm^3)	1.053	0.891	0.880	0.873	0.988	0.927

The overall structure and kinematic analysis of seed feeding process

The whole frame

Air - suction precision seed metering device for small vegetable seeds is shown in the figure Fig. 3. The fixed disc is provided with seed disturbing rod as shown in Fig.4, to stir the seeds close to the seed metering disc, so that the seeds continuously move and surge upward, so as to reduce the friction and adhesion between the seeds and improve the seed filling performance.

One side of the double disc is an air chamber, which is connected with the fan pipe through the air chamber shell, and the other side is a seed chamber. During the operation, the disc rotates, and the seeds leave the negative pressure area with the rotation of the disc. The shaped hole loses the adsorption force on the seeds. The seeds fall into the seed guide tube by their own weight and fall into the seed bed along the seed guide tube, and finally complete seed metering.

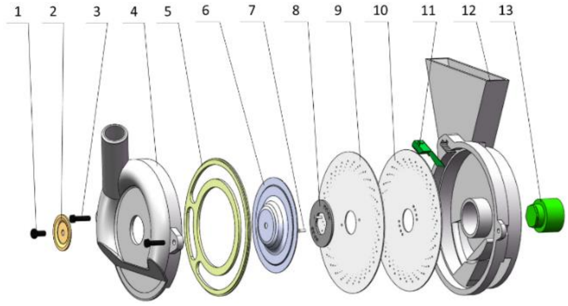


Fig. 3 - Schematic diagram of seed metering device structure

1 - Nut of cover plate; 2 - Cover plate of air chamber shell; 3 - Fix bolts; 4 - Air chamber shell; 5 - Suction pad; 6 - Air cushion pressure plate; 7 - Insert disc bolts; 8 - Fixed insert disc; 9 - Rotating disc; 10 - Fixed disc; 11 - Clearer; 12 - Back cover; 13 - Shaft

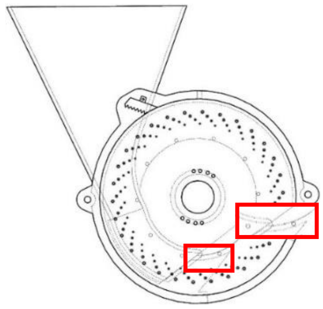
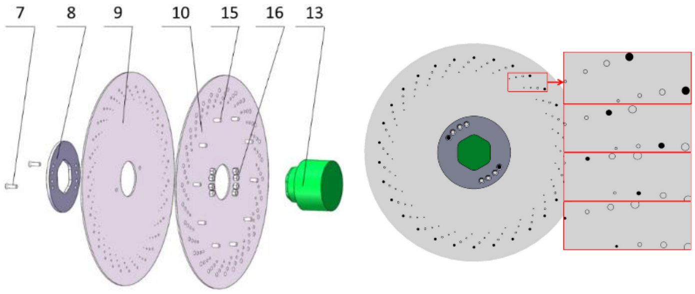


Fig. 4 - Design of the seed disturbing

Design of double discs structure with multiple-grain size

The double disc structure is shown in Fig.5a). The air-suction precision seed metering device is provided with a rotary disc and a fixed disc at the same time. The two discs are rotated axially and oppositely to make the holes with the same diameter on the two discs coincide, and seeds with different seed sizes can be sown.



a) Double disc structure *b) Diagram of hole combinations*

Fig. 5 - Schematic diagram of double disc structure

7 - Insert disc bolts; 8 - Fixed insert disk; 9 - Rotating disk; 10 - Fixed disc; 13 - Shaft; 15 - Stir bar; 16 - Hold-down nut

Through theoretical calculation and experience reference, double discs with a diameter of 240mm are selected and made of 1mm stainless steel plates. The distribution of disc shaped holes is shown in Fig.5b). Four kinds of shaped holes A, B, C and D from large to small are set on the two discs. In the four rows of shaped holes on the outside, the black shaped holes indicate that the two disc apertures are connected, while the gray shaped holes indicate that they are not. As the rotating disc rotates clockwise, the corresponding holes are connected in the order of type A holes - type C holes - type B holes - type D holes. In the fixed plug-in disc, the black fixed round hole indicates the fixed position of the plug-in disc bolt.

Kinematic analysis of seed metering process

The seeding process of the seed metering device determines the seeding accuracy of the seed metering device. Ignoring the vibration of the seeder during the seeding process, the seed is approximately regarded as a sphere, and the three-axis Cartesian coordinate system is established with the seed centroid as the origin.

The direction of friction force on the seed is the positive X axis, the direction of centrifugal force is the positive Y axis, and the direction of negative pressure adsorption force is the positive Z axis. Kinematics analysis of the seeding process of the double disc air suction seed metering device is carried out. The process of seed force analysis is shown in Fig.6.

In the process of seed suction, the force on the seed at the hole is balanced. The force analysis of seeds is calculated using Eq.(3):

$$F_p = \sqrt{J^2 + G^2 + F_f^{\ 2} + 2G\sqrt{J^2 + F_f^{\ 2}}\sin(\theta + \phi)} \cdot \tan\alpha \tag{3}$$

Under the actual working condition, considering factors such as the vibration and friction resistance of the whole machine that affect the seed suction process, and making up for factors such as different seed shapes and sizes and mutual collision and extrusion in the middle, the external condition coefficient K1 is 1.8~2.0 and the seed suction reliability coefficient K2 is 1.8~2.0 according to the mechanical design manual. The negative pressure value of seed at the molding hole is calculated using Eq.(4):

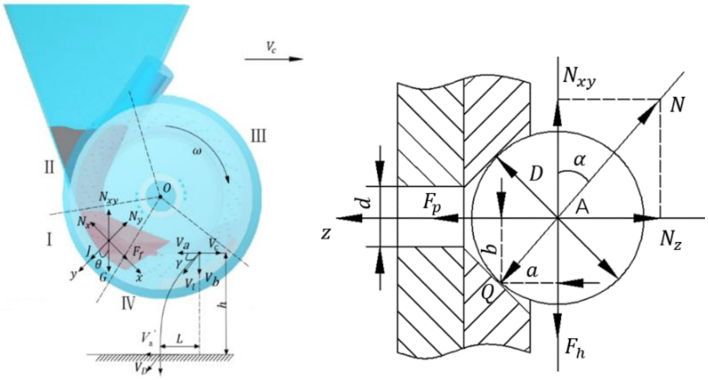
$$P = \frac{4K_1K_2\sqrt{J^2 + G^2 + F_f^{\ 2} + 2G\sqrt{J^2 + F_f^{\ 2}}\sin(\theta + \phi)} \cdot \tan\alpha}{\pi D^2 \cos^2\alpha} \tag{4}$$

The total speed of seed implantation is calculated using Eq.(5):

$$V_D = \sqrt{V_l^2 + V_c^2 + (gt)^2 + 2V_l\sqrt{(gt)^2 + \left(\frac{zk}{2\pi R}V_l\right)^2}\sin(\gamma + \psi)} \tag{5}$$

where: φ and ψ are auxiliary angles obtained by formula transformation, [°].

When the seed falls on the seed bed, the seed and seed bed will contact and collide to produce rebound, and the plant spacing cannot be guaranteed. In order to reduce the bounce and scattering during seed implantation, a seed guide tube with appropriate curve is selected to make the seed reach the outlet with a larger horizontal velocity to offset the forward speed of the seeder. In order to reduce the variation coefficient of plant spacing of the seed metering device, the rotation speed of the seed metering device can be appropriately reduced under the condition of meeting the seed sowing requirements.



a) XY plane kinematics analysis *b) Z plane kinematics analysis*

Fig. 6 - The process of seed force analysis

Note: In the Figure 6, the notations are:

a) I is seed filling area, II is seed clearing area, III is seed carrying area, and IV is seed feeding area.

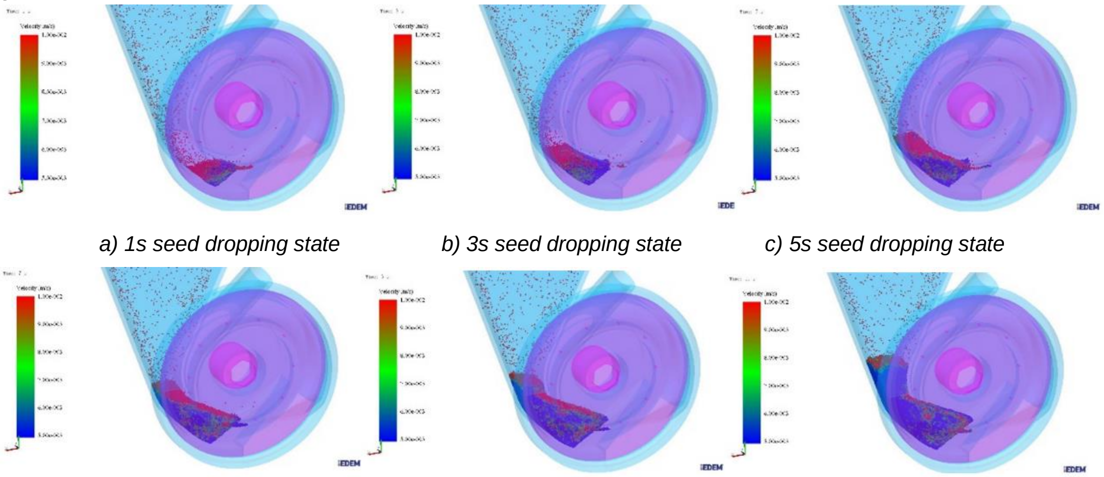
b). G is seed gravity, [N]; J - the centrifugal force exerted on the seed, [N]; F_f - the friction force on the seed, [N]; N_x and N_y are the supporting force components of x-axis and y-axis respectively, [N]; N_{xy} - the resultant force of N_x and N_y, [N]; O - the center of the disc; V_a - the horizontal partial velocity when the seed falls off, [m/s]; V_b - the vertical partial velocity when the seed falls off, [m/s]; V_C - the forward speed of the planter, [m/s]; V_l - the linear velocity when the seed falls off, [m/s]; V_D - the speed of seed implantation, [m/s]; H - the seed scattering height, [m]; L - the horizontal displacement of seed, [m]; ω - the rotation angular velocity of seed sucking disc,[rad/s]; θ - the angle between the centrifugal force and the gravity of the seed, [°]; γ - the included angle between V_l and V_a, [°].

Analysis of seed metering device based on discrete element method

Based on the discrete element method, the stacking distribution state of seeds at each time point when they enter the seed box, the movement law of seeds in the seed metering device when they are disturbed and the overall movement trend of the population are analyzed to verify the rationality of the structure design of the air-suction precision seed metering device.

Analysis of Seed Stacking Process

The seed state of the stacking process is shown in Fig.7. The seeds directly hit the seed carrier plate and the bottom of the seed box under the gravity, causing the seeds to bounce. Due to the continuous accumulation of the seeds below, the sliding slope of the upper layer seeds in the seed box keeps getting longer, the slope angle increases, the friction force on the seeds gets bigger and bigger, the speed of the seeds gradually slows down, and the missile phenomenon gradually weakens. It can be seen from the figures Fig7.a) to d) that the impact force of seed falling is relatively large 7 seconds ago. The bounced seeds fall to the seed support plate under gravity after reaching the highest point, and the seeds fall back to the bottom of the seed box under the effect of the inclined force of the seed support plate. Because the seed support plate is set reasonably, the seeds will not leave the seed support plate. The seeds are always above the seed support plate, so there will be no seed loss; After the seeds continue to fall for 9s, the upper layer seeds in the metering chamber are in a relatively stable state, and the stable state of the upper layer seeds in the seed chamber is more conducive to the adsorption of seeds in the filling stage, reducing the rate of missed seeding. In the Fig.7 f), the seed accumulation in the seed metering device reaches the saturation state, and the seed amount remains constant, and then the seed will be slowly replenished to the air-suction precision seed metering device.



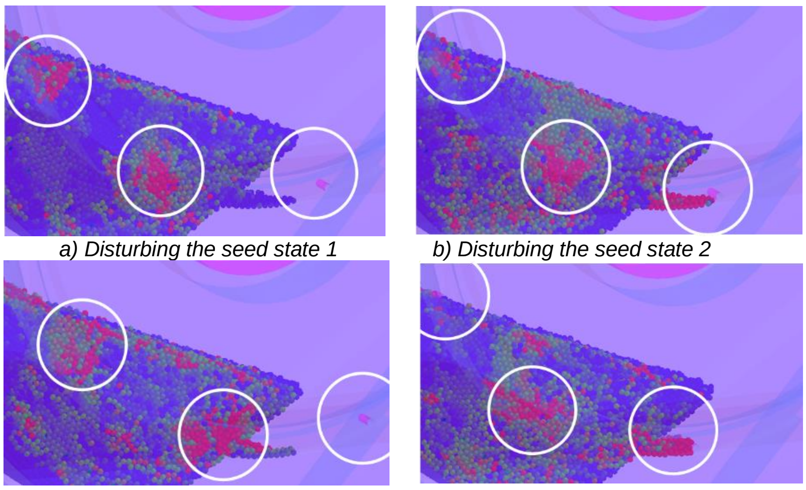
a) 1s seed dropping state *b) 3s seed dropping state* *c) 5s seed dropping state*

d) 7s seed dropping state *e) 9s seed dropping state* *f) 11s seed dropping state*

Fig. 7 - Analysis of seed state in stacking process

Analysis of disturbed seed state

When the seed flows uniformly to the seed filling area under its own gravity, a seed pile is formed in the seed filling area. It can be found in Fig.8 of the seed disturbing process that when the seed disturbing rod contacts the detained seed, the detained seed is pushed by the seed disturbing rod, and the detained seed returns to the upper part of the seed support plate under the force. As the seed disturbing rod rotates out of the seed disturbing tank, part of the seed falls into the seed disturbing tank, but it will never flow out of the seed disturbing tank, and there will be no seed scattering, And the seeds around the seed disturbing rod are obviously stressed and fast. The seed disturbing rod stirs and combs the seeds close to the seed metering disc, making the seeds continuously move upward to reduce the friction and adhesion between the seeds and improve the seed filling capacity.



a) Disturbing the seed state 1 *b) Disturbing the seed state 2*

c) Disturbing the seed state 3 *d) Disturbing the seed state 4*

Fig. 8 - Seed disturbing process

RESULTS AND DISCUSSION

Bench Test of Air-Suction Small Vegetable Seeds Metering System

Test material

After theoretical analysis and simulation analysis, in order to verify the reliability and feasibility of air-suction precision seed metering device for small vegetable seeds with multiple-grain size(Li et al., 2018; Shi et al., 2015), a seed metering performance test was conducted in the Seed Metering Performance Laboratory of Shandong Agricultural University, and the variable particle size double disc air-suction precision seed metering device was installed on the JSP-12 seed metering device performance test bench, as shown in Fig.9. The small seed size used in the bench test was Shanghai Qing, with a diameter of about 1.3 mm, 1000 seed weight of 2.317 g, and water content of 4.21%.

Fig. 9 - Seed Meter Performance Tester

1 - High-speed camera; 2 - transmission shaft; 3 - Seed metering device; 4 - Negative pressure tube; 5 - Seed tube

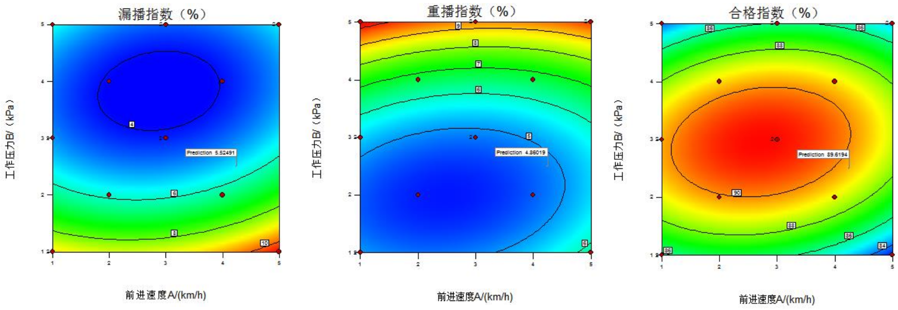
Orthogonal test analysis of velocity and pressure

In order to further explore the interaction and influence of negative pressure and rotating speed on the seed metering performance of the seed metering device, this paper conducted an orthogonal experiment on the seed metering device (*Li et al., 2020*). From previous experience, it can be concluded that when the working pressure (negative pressure) is 3.5~5kPa and the forward speed is 5~9km/h, the seed metering device has high seed metering performance. In this orthogonal experiment, speed and pressure are selected as two factors in the orthogonal experiment. There are 16 groups in total. Each group of experiments is repeated for 3 times. The average value of the data is taken. Each experiment deals with no less than 100 seeds. The experimental results are shown in Table 2.

Orthogonal test results **Table 2**

Test number	Test factors		Evaluation index		
	Forward speed A (km/h)	Work negative pressure, B（kPa）	Missed rate Y1（%）	Replay rate Y2（%）	Pass rate Y3（%）
1	8	4	6.6	3.83	89.57
2	9	3.5	10.83	6.15	83.02
3	5	3.5	9.11	4.97	85.92
4	9	5.5	5.5	9.73	84.77
5	7	4.5	4.05	3.98	91.97
6	5	4.5	5.24	6.2	88.56
7	5	4.5	5.1	6.12	88.78
8	5	3.5	9.22	5.02	85.76
9	9	5.5	5.51	10.05	84.44
10	5	5.5	5.88	10.1	84.02
11	7	5.5	4.32	10.24	85.44
12	7	4.5	4.1	3.95	91.95
13	7	5.5	4.47	10.58	84.95
14	6	5	3.8	6.89	89.31
15	8	5	4.2	6.21	89.59
16	6	4	6.5	3.52	89.98

In order to further study the influence of working pressure and forward speed on missed rate, replay rate and pass rate, the test data was further processed by Design Expert 10.0 software to obtain the response figure of interaction factors (*Gao et al., 2019*). It can be seen from Fig.10 that the interaction factors have a significant impact on the miss rate, replay rate and qualification rate (*Ding et al., 2018*). When the forward speed of the seed metering device is 6~8km/h, that is, the rotating speed is 22~30r/min, and the working pressure is within the range of 4kPa~5kPa, the missed seeding rate and replay rate of the seed metering device are at a low level, while the qualification index is at a high level.



a) missed seeding index *b) replay seeding index* *c) pass seeding index*

Fig. 10 - Response figure of interaction factors

Model optimization and verification

In combination with the boundary conditions of various factors, a parametric mathematical model is established for optimal solution. The objective function and constraint conditions are as follows Eq.(6):

$$\begin{aligned} &\max Y_3 = f_3(A,B) \\ &\min Y_1 = f_1(A,B) \\ &\min Y_2 = f_2(A,B) \\ &S.T.\begin{cases} Y_1 \le 8.0\% \\ Y_2 \le 15.0\% \\ Y_3 \ge 80.0\% \\ 6km/h \le A \le 8km/h \\ 4.0kPa \le B \le 5.0kPa \end{cases} \end{aligned} \tag{6}$$

Y_3 in the above equation, namely the qualification index, is the ultimate optimization goal. The regression model is optimized using Design Expert 10.0 to obtain the optimal optimization parameters of the seed metering device: forward speed 7.72 km/h, working pressure 4.37 kPa, at this time, the pass rate is 91.07%, the missed rate is 4.23%, and the replay rate is 4.70%.

Fig. 11 - Optimization test verification

As shown in Figure 11, the optimized theoretical results were tested on the seed metering device performance test bench. Here, the optimized data is adjusted appropriately, the forward speed of the seed metering device is set to 7.72 km/h (the corresponding speed is 28.56 r/min), the working pressure is set to 4.40kPa, and four repeated tests are carried out. The average value of the qualified seed metering index is 91.02%, the average value of the replaying index is 4.71%, and the average value of the missed seeding index is 4.27%. The bench test results are basically consistent with the theoretical analysis results, which can be used as the final optimal working speed.

CONCLUSIONS

(1) The material properties of six typical small vegetable seeds were studied and the main physical parameters of the selected vegetable seeds were determined.

(2) Based on the characteristic parameters of small vegetable size seed material, an air-suction precision metering device for multiple-grain size small vegetable seed was developed. Based on the discrete element theory, the design of seed disturbing rod, seed disturbing slot and seed box is verified and analyzed.

(3) The optimal horizontal range of the operation parameters of the seed metering device is that the rotary table speed is 22~30 r/min, and the working negative pressure is 4~5 kPa. The optimal optimization parameters of the seed metering device system are as follows: the rotational speed is 28.56 r/min, the negative pressure is 4.40 kPa, the pass rate is 91.07%, the replay rate is 4.70%, and the missed rate is 4.23%, meeting the seeding demand.

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