DESIGN AND EXPERIMENT OF PROGRESSIVE SEED-CLEANING MECHANISM FOR AIR-PRESSURE MAIZE PRECISION SEED-METERING DEVICE
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气压式玉米精量排种器递进性清种装置设计与试验

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ABSTRACT

In order to improve the sowing performance of air-pressure maize dense planting high-speed precision seed-metering device and reduce the occurrence of multiple and missed seeds phenomenon, a seed-cleaning mechanism with progressive seed scraper was designed. The structure and working principle of the seed-metering device and seed-cleaning mechanism are described, the mechanical model before and after the excess seed enters the seed cleaning area is established, and the design parameters of the key components of the seed-cleaning mechanism are determined through the method of theoretical analysis. The experiments of single-factor and multi-factor are conducted with seed clearing angle, operating speed, positive pressure value of blower as influencing factors, and with qualified index, miss index, multiple index as the experimental indexes. The results show that the optimal seed-clearing performance parameter combination of the seed-cleaning mechanism is seed-clearing angle of 0.024°, operating speed of 10 km/h, positive pressure value of 6.0 kPa, verification test of the parameter combination of the qualified index of 98.11%, multiple index of 1.44%, miss index of 0.45%. In the comparative experiment, the qualified index of the device with seed-cleaning mechanism increased by about 2.3% compared to the device without seed-cleaning mechanism, and the multiple index decreased by about 2.2%. The seed-cleaning mechanism is reasonably designed to meet the seed clearing operation requirements of air-pressure maize dense planting high-speed precision seed-metering device.

摘要

为提高气压式玉米密植高速精量排种器的播种作业性能，减少漏播、重播现象的发生，设计了一种带有递进性刮种刀的清种装置。阐述了排种器、清种装置的结构与工作原理，建立了多余种子进入清种区前后的力学模型，得到了风机正压值与作业速度是影响清种装置清种性能的主要因素，通过理论分析的方法确定了清种装置关键部件的设计参数。以清种角度、作业速度、风机正压值为影响因素，以粒距合格指数、重播指数、漏播指数为试验指标进行了单因素试验，确定了合理的因素变化范围进行了多因素试验，得到了清种装置的最佳清种性能参数组合并对其进行了试验验证以及对比试验。结果表明，清种装置最优清种性能参数组合为清种角度 0.024°、作业速度 10km/h、风机正压值 6.0kPa，验证试验该参数组合的合格指数为 98.11%、重播指数 1.44%、漏播指数 0.45%，对比试验中带有清种装置的排种器较无清种装置的排种器合格指数提高了 2.3%左右，重播指数降低了 2.2%左右，清种装置设计合理可满足气压式高速密植精量排种器对清种装置的清种作业要求。

INTRODUCTION

Maize is one of the most widely grown crops in the world, with multiple attributes such as feed, food, medicine and economy *(Huma et al., 2019)*. Considering the whole production chain of maize, the quality of sowing directly affects the yield and quality of maize *(Testa et al., 2016)*.

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Precision planting technology is an important means of improving the quality of maize sowing *(Nardon et al., 2022)*, which is based on the agronomic requirements of maize planting seeds according to a certain plant spacing, row spacing, sowing depth into the seed bed, which can ensure a reasonable growth space for the plant. Corn precision seed-metering device is the core working part to realize the precision planting technology *(Zhang et al., 2023; Van et al., 2020)*, air-pressure seed-metering device, as a kind of pneumatic precision seed-metering device, has the advantages of good adaptability to seeds, does not hurt the seeds, and is suitable for high-speed sowing, etc., but the internal structure is more complicated. As an important part of seed-metering device, seed-cleaning mechanism is a key component to avoid the phenomenon of multiple seeds, and its reasonable design has an important impact on the operational performance of seed-metering device *(Younis et al., 2020; Ramesh et al., 2015; Li et al., 2021)*.

In the whole working process of seed-metering device, seed cleaning is an important link to reduce the index of the multiple and miss, and current scholars have carried out in-depth research on the seed cleaning process of seed-metering device *(Li et al.,2023; Liquan et al.,2021; Zhang et al.,2023)*. Qi Bing designed a circumferential seed-cleaning device for the problem of serious reseeding in the low-speed operation of set-row maize precision seed-metering device *(Qi et al.,2015)*. Aiming at the problems of high reseeding index of air-suction maize seed-metering device and the difficulty of ensuring the rationality of the design of seed clearing mechanism, Ding Li optimized the design of seed clearing mechanism of seed-metering device, which is well adapted to different varieties of maize seeds *(Ding et al., 2019)*. In addition to maize, Hu designed a double-sided seed clearing mechanism consisting of seed clearing scraper and disturbing air nozzle for the problem that the seed clearing performance of internal cotton air-suction seed-metering device is poor *(Hu et al., 2022)*. He designed a positive pressure airflow seed clearing device for improving the qualified index of coated hybrid rice pneumatic seed-metering device *(He et al., 2022)*. However, current scholars have less research on the seed clearing device of air-pressure maize dense planting high-speed precision seed-metering device.

Aiming at the problem that the high multiple index of air-pressure maize dense planting high-speed precision seed-metering device leads to the decline of its performance, this study designs a seed-cleaning mechanism with a progressive seed scraper, which can be adjusted by a single-degree-of-freedom rod-slider mechanism to adapt to the seed clearing requirements for different sizes and shapes of maize seeds, and provides design references for the research of seed clearing device of pneumatic high-speed dense planting precision seed-metering device.

MATERIALS AND METHODS

MATERIAL

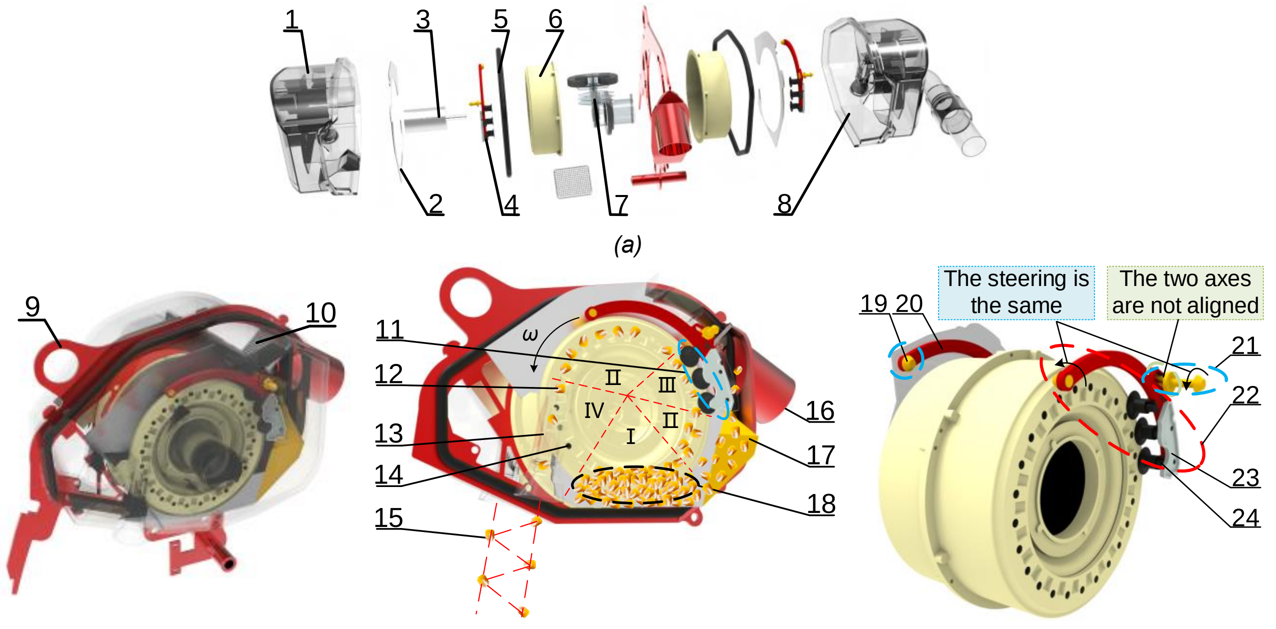
Structure and working principle of seed-metering device

The schematic diagram of the air-pressure seed-metering device is shown in Fig. 1 (a) and (b), which mainly consists of seeding plates, seed-cleaning mechanism, shell, seed blocking net, seed blocking plate, connecting plate, motor, pressure relief wheel, and its connecting frame. When seed-metering device is in operation, the blower delivers airflow to the device chamber, forming a positive pressure chamber. The internal chamber of seeding plates is connected to the outside world, creating a pressure difference between the inside and outside of the shape hole, ensuring stable pressure attachment of maize seeds to the shape hole. The two chambers on the left and right are symmetrically arranged as independent seeding units, and the two seeding plates are fixed and installed at a certain angle to achieve differential time interlaced seeding two rows of one device.

The entire working process of the device can be divided into four stages: filling, cleaning, carrying, and feeding. The working principle is shown in Fig. 1 (c). Maize seeds are divided into two symmetrical seeding chambers through the guide plate on the shell through the air inlet, and are disturbed by the air flow and the grooves of the seeding plates in the waiting seed filling area. The motor drives the seeding plates to rotate, and maize seeds are continuously pressed onto the shape holes by the airflow to rotate at a uniform speed. When the seeds are transferred to the seed cleaning area, the seed-cleaning mechanism removes excess seeds from the shape hole, keeping only single seed. When the single seed is transported to the unloading point, the pressure relief wheel will block the inner side of the hole at the unloading point, and the pressure difference received by the seed will disappear. With the assistance of gravity and air flow, it will be thrown away from the device through the seed discharge pipe, and one seeding operation cycle will be completed.

Structure and working principle of seed-cleaning mechanism

There are significant differences in the shape and size of maize seeds, and when they are pressed onto the surface of shape hole by the airflow, they may not fully cover the surface of the hole. When airflow passes through the uncovered area of the hole, it will carry other seeds and press them onto the surface of the hole again, causing multiple seeds in one hole, seriously affecting the seeding performance of the device *(Xu et al., 2023)*. The seed-cleaning mechanism with progressive seed scraper is mainly composed of an adjustment mechanism and executing mechanism, as shown in Fig. 1 (d). The adjustment mechanism is a single degree of freedom rod slider mechanism consisting of three rotating pairs and one moving pair; the executing mechanism mainly consists of base, arc-shaped frame, scraper blade, and scraper blade fixing frame. One end is fixed on the positioning hole of the shell, and the other end slides on the sliding groove of the shell to adjust the cleaning angle of the scraper blade to meet the cleaning requirements of seeds of different sizes and shapes. The seed-cleaning mechanism is symmetrically arranged on both sides of seeding plates. When shape hole carrying multiple seeds passes through the cleaning area, three Suona shaped scraper blades are used to perform a progressive seed cleaning operation on the excess seeds, gradually reducing the proportion of excess seeds occupying the hole area and ensuring only a single seed that is pressed into the hole.



(a)

(b) *(c)* *(d)*

Fig. 1 - Structure and working principles diagram of seed-metering device and seed-cleaning mechanism

1. shell 1; 2. seed blocking plate; 3. motor; 4. seed-cleaning mechanism; 5. seals; 6. seeding plate; 7. pressure relief wheel and its connecting frame; 8. shell 2; 9. connecting plate; 10. seed blocking net; 11. progressive seed scraper; 12. unloading point; 13. seed discharge pipe; 14. shape hole; 15. maize; 16. air inlet; 17. guide plate; 18. waiting seed filling area; 19. positioning hole; 20. arc-shaped frame; 21. adjustment mechanism; 22. executing mechanism; 23. base; 24. scraper blade fixing frame; I. seed filling area; II. seed cleaning area; III. seed carrying area; IV. seed feeding area.

METHODS

Before excess seed enters the clearing area

In this study, the diameter d_1 of shape hole was 5.5 mm. Based on the three-axis size, thousand grain weight of the tested maize (Table 1), and previous experimental observations, the probability of three seeds appearing in a hole was relatively low.

Table 1

Information of test seed

Seed pictures	Variety name	Thousand grain weigh/g	Length / mm	Width / mm	Thickness / mm
	Demeya No.1	304.3	11.12±0.70	10.14±0.62	5.56±0.69

The analysis of the situation where two seeds are attached to the same type of hole can be divided into four situations: the inner and outer seeds are placed horizontally (Fig. 3a); the outer seeds are placed horizontally and the inner seeds are placed laterally (Fig.3b); the inner and outer seeds are placed laterally (Fig.3c); the outer seeds are placed laterally and the inner seeds are placed horizontally (Fig.3d). Considering the rationality of the internal structure layout of the device, seed-cleaning mechanism is located on the outside of seeding plates for single-sided cleaning, and the scraper applies force to the seed (excess seed) on the outside of the hole for cleaning operation. Define k_i as the ratio of the area S_i (approximated as a circle) of the excess seed covering shape hole to entire area S of the hole:

$$k_i = \frac{S_i}{S} = \frac{4S_i}{\pi d_2^2} \tag{1}$$

a) b) c) d)

Fig. 2 - Different states of compression attachment of two seeds on shape hole

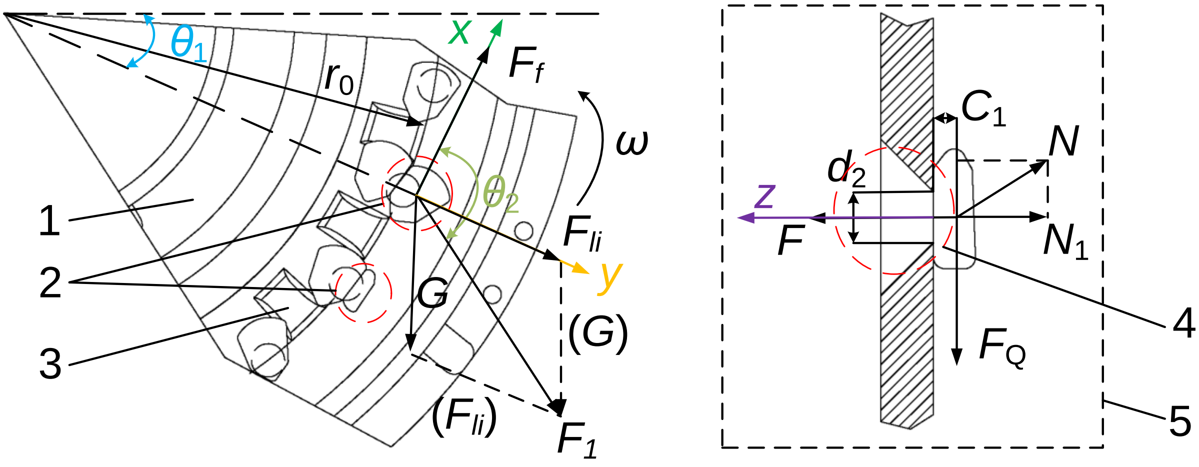


Fig. 3 - Schematic diagram of the forces on the excess seeds before enters the clearing area

1. seeding plate; 2. excess seeds; 3. groove; 4. shape hole; 5. forces of excess seed z-axis direction.

Perform force analysis on the excess seed before entering the seed cleaning area, as shown in Fig. 3. Establish *xyz* three-dimensional coordinate system with the seed center of gravity as the coordinate origin. The *x*-axis direction is the tangential direction of seeding plate, the *y*-axis direction is the radial direction of the plate, and the *z*-axis is the axis of shape hole. Excess seed will be subjected to centrifugal force F_{li}, air resistance F_Z (negligible), airflow pressure force F, gravity G, as well as frictional force F_f and support force N_1 caused by the force *N* from shape hole before entering the seed cleaning area. F_Q is the combined force on the seed in the *xy* plane, and a mechanical equation is established based on the D'Alembert's principle:

$$\begin{cases} F\dfrac{\sqrt{k_i}d_2}{2} = C_1 F_Q \\ F = \Delta P S_i \\ F_1 = \sqrt{G^2 + {F_{li}}^2 + 2F_{li}G\sin\theta_1} \\ F_Q = \sqrt{{F_f}^2 + {F_1}^2 + 2F_f F_1 \cos\theta_2} \end{cases} \tag{2}$$

where:

θ_1 is the angle between the radial and horizontal directions where the seed is located, (°); θ_2 is the angle between F_f and F_1, (°); C_1 is the distance from the seed centroid to the hole of seeding plate, (m); ΔP is the pressure difference inside and outside the mold hole, (Pa).

Equations 1~2 can be organized as follows:

$$\sqrt{k_i^3} = \frac{8K_1K_2C_1}{\Delta P\pi d^3}\sqrt{F_{li}^2 + G^2 + F_f^2 + 2\,GF_{li}\sin\theta_1 + 2F_f\sqrt{F_{li}^2 + G^2 + 2GF_{li}\sin\theta_1}\cos\theta_2} \tag{3}$$

which:

$$\begin{cases} F_{li} = m\omega^2 r \\ G = mg \end{cases} \tag{4}$$

where: m is seed quality, (kg); ω is the angular velocity of seeding plate, (rad/s); r is the distance from the seed centroid to the center of seeding plate, (m).

From equation (3), it can be seen that, under the condition that the structure of the device is determined, the ratio k_i is positively correlated with the distance C_1 and the angular velocity ω and negatively correlated with the pressure difference ΔP. When the outer seed is in a lateral position, the distance C_1 from the seed centroid to the hole is larger, making it easier to clear the seed. Angular velocity ω of the plate and the pressure difference ΔP has a significant impact on the seed cleaning process, and will be used as influencing factor to explore its impact on the seed cleaning performance of seed-cleaning mechanism in the following text.

After excess seed enters the clearing area

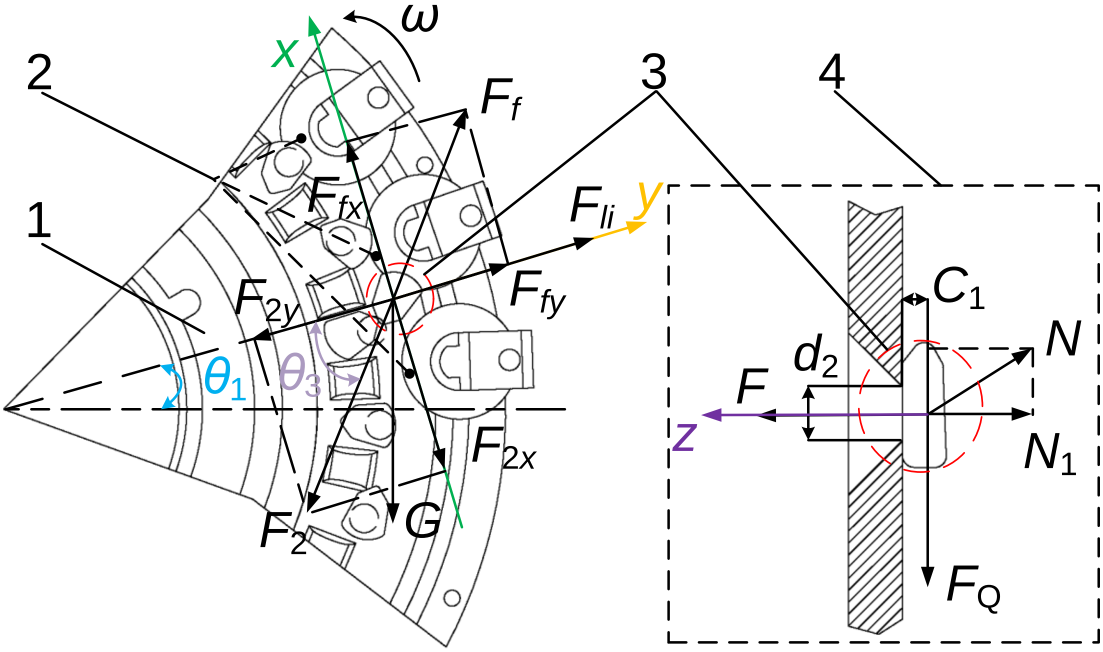


Fig. 4 - Schematic diagram of the forces on the excess seeds after entering the clearing area

1. seeding plate; 2. seed scraper; 3. excess seed; 4. forces of excess seed z-axis direction.

After the excess seed enter the seed cleaning area (Fig. 4), it will be subjected to centrifugal force F_{li}, air flow pressure force F, gravity G, as well as forces N from shape hole and F_2 from scraper. The force N exerted by the hole on the seed can be decomposed into frictional force F_f and supporting force N_1. The force F_2 exerted by the seed scraper on the seeds can be decomposed into F_{2x} and F_{2y} on the x-axis and y-axis, respectively.

Establish the mechanical equilibrium equation:

$$\begin{cases} \sum F_x = 0 \Rightarrow F_{fx} = G\cos\theta_1 + F_2\sin\theta_3 \\ \sum F_y = 0 \Rightarrow F_{fy} = G\sin\theta_1 + F_2\cos\theta_3 - F_{li} \\ \sum F_z = 0 \Rightarrow F = N_1 \end{cases} \tag{5}$$

which:

$$\begin{cases} F_f = \mu N_1 \\ F_f = \sqrt{F_{fx}^2 + F_{fy}^2} \end{cases} \tag{6}$$

where:

θ_3 is the angle between the radial position of the seed and F_2, (°); F_{fx} is the component of F_f in the x-axis direction, (N); F_{fy} is the component of F_f in the y-axis direction, (N); μ is the friction coefficient between the seed and seeding plate.

Equations 1 and Equations 5~6 can be organized as follows:

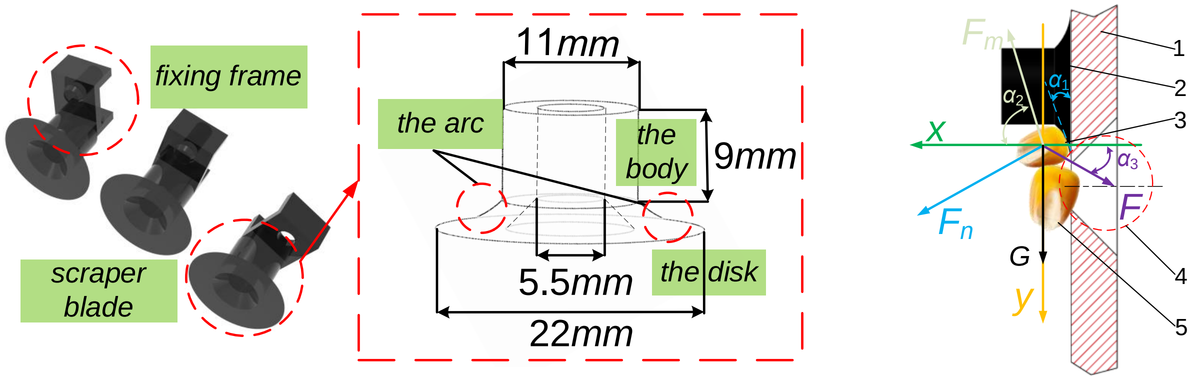
$$k_i = \frac{4}{\mu \Delta P \pi d^3}\sqrt{(G\cos\theta_1 + F_1\sin\theta_2)^2 + (G\sin\theta_1 + F_1\cos\theta_2 - F_{li})^2} \tag{7}$$

From equation (7), when the structural dimensions and working conditions of the device are determined, the required ratio k_i is positively correlated with the force F_1 of the scraper on the seeds. As the scraper increases its force F_1 on the seeds, the k_i will decrease until excess seeds are removed and the cleaning is completed, and so that the design of the seed-cleaning mechanism should meet the principle of gradually reducing the proportion k_i of the excess seed to the hole area.

Parametric design of key components

As a key component of seed-cleaning mechanism, the rationality of the structure and parameter design of the scraper directly affects the effectiveness of the seed cleaning operation of the device. The main structural parameters of the seed scraper include the disk diameter of the scraper blade, the number of scraper blades, the distance between the center of each scraper blade and the center of seeding plate at the starting cleaning position, respectively, the center angle between adjacent scraper blades, and the adjustable seed-clearing angle range.

To cushion the collision between the seeds and the seed scraper, and avoid damaging the seeds, the shape of the scraper blade is designed to be similar to the Suona shape, and the material is nitrile rubber. Due to the fact that seed cleaning is not effective when the number of seed scrapers is low. When the number is large, the seed scrapers that first come into contact with the seeds have already removed excess seeds from the hole, making the seed scrapers that come into contact with the seeds ineffective in clearing the seeds afterwards. Therefore, it is advisable to design three seed scrapers. In the preliminary experiment, it was observed that when the disk diameter of the scraper blade was large, there was a phenomenon of "over-clearing", which caused the single seed on the hole to be removed and missed seeding occurred. When the diameter was small, the clearing effect was not obvious and led to multiple seeding. Considering the limitations of the structure size of the device chamber, the disk diameter d_2 was designed to be 22 mm, and the diameter of blade body was taken as half of the base diameter to be 11 mm. The blade length was 9 mm. An arc with inclination angle from 0° to 90° was designed between the body and the disk. The scraper blade is equipped with a through-hole with a diameter of 5.5 mm, which is installed on the fixing frame by matching with countersunk screws, as shown in Fig. 5 (a).



(a) (b)

Fig. 5 - Schematic diagram of the structure of the scraper blade and the forces on the excess seed

1. seeding plate; 2. seed scraper; 3. seed B; 4. shape hole; 5. seed A.

Perform force analysis on the excess seeds on the arc as shown in the Fig. 5 (b), and establish the dynamic equation as follows:

$$\begin{cases} ma_x = F_n\cos\alpha_1 + F_m\cos\alpha_2 - F\cos\alpha_3 \\ ma_y = F_n\sin\alpha_1 - F_m\sin\alpha_2 + F\sin\alpha_3 + G \end{cases} \tag{8}$$

where: a_x is the acceleration of excess seeds in the positive x-axis direction, (m·s^{-2}); a_y is the acceleration of excess seeds in the positive y-axis direction, (m·s^{-2}); α_1 is the angle between F_n and the positive x-axis, (°); α_2 is the angle between F_m and the positive x-axis, (°); α_3 is the angle between F and the negative x-axis, (°);

F_n is the force exerted by the scraper on excess seeds, (N); F_m is the force exerted by seed *A* on seed *B*, (N).

The conditions for excess seed to fall are:

$$\begin{cases} a_x > 0 \\ a_y > 0 \end{cases} \tag{9}$$

When the working speed of the device is constant with the pressure inside the chamber, excess seeds enter the seed cleaning area, and with the rotation of seeding plate, the arc angle α_1 where the excess seeds are located will gradually increase, causing the force F_n to gradually increase, increasing the probability of excess seeds falling off.

To reduce the proportion of excess seeds occupying the hole area k_i, the distance between the center of each scraper blade and the center of seeding plate gradually decreases. At the same time, to prevent the cleaned seeds from colliding with the pressed seeds during the process of falling back into the waiting seed filling area, the starting cleaning position of the scraper blade I is designed on the *x*-axis. Referring to the Agricultural Machinery Design Manual (*Agricultural Machinery Design Manual: The First Volume.*, *2007*), the adjustment range Δ*d* of the scraper blade I is -2~8 mm (overlapping with the center of the hole is 0, negative inward, positive outward). Establish a Cartesian coordinate system with the center of the seeding plate as the coordinate origin, the horizontal direction as the *x*-axis, and the vertical direction as the *y*-axis, as shown in Fig. 6.

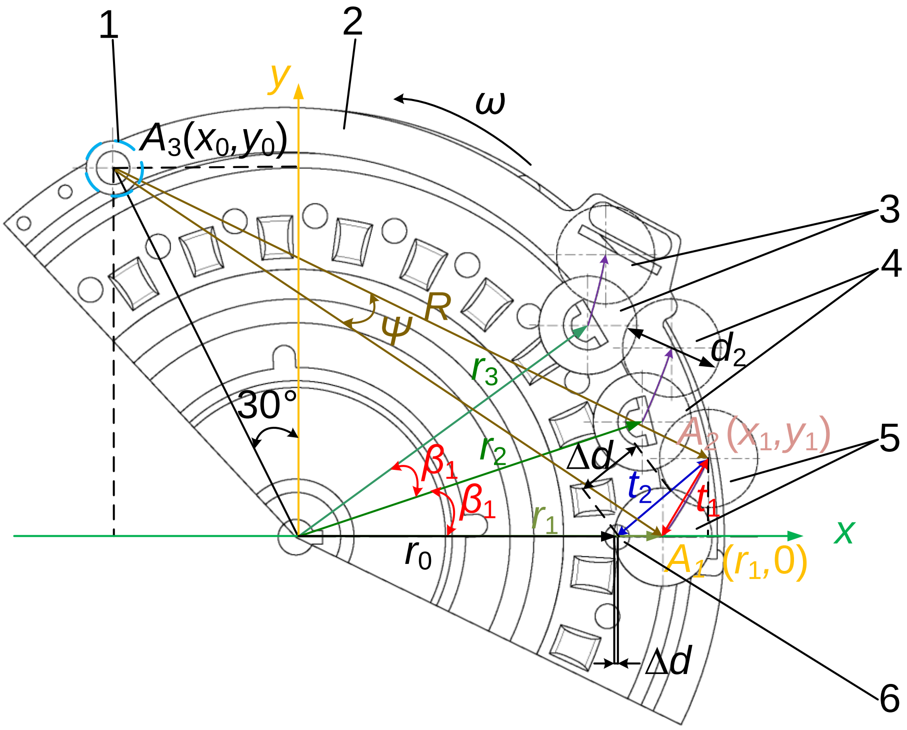


Fig. 6 - Schematic analysis of the key parameters of the seed scraper

1. positioning hole; 2. arc-shaped frame; 3. scraper blade III*; 4. scraper blade* II*; 5. scraper blade* I*; 6. hole* I.

When the hole I rotates to the *x*-axis, the distance between the disk of the scraper blade I and the center of the hole is -2 mm, and the distance r_0 between the center of the hole and the center of seeding plate is 72 mm.

The equation for the starting position of the seed scraper for seed cleaning is established as follows:

$$\begin{cases} r_1 = r_0 + \dfrac{d_2}{2} - 2 \\ r_2 = r_1 - \Delta r \\ r_3 = r_2 - \Delta r \end{cases} \tag{10}$$

where:

r_1 is the distance between the center of scraper blade I and the center of seeding plate, (m); r_2 is the distance between the center of scraper blade II and the center of seeding plate, (m); r_3 is the distance between the center of scraper blade III and the center of seeding plate, (m); Δr is the decreasing distance from the scraper blade to the center of seeding plate, value 1 mm.

After calculation, the distances from the center of the scraper blades I, II, and III to the center of seeding plate are 81 mm, 80 mm, and 79 mm, respectively. To prevent interference between the scraper blades, the center angle β_1 of adjacent scraper blades should meet the following requirements:

$$\frac{\pi}{180^\circ} \times \beta_1 \left(\frac{d_2}{2} + r_0 + \Delta d \right) > d_2 \tag{11}$$

After calculation, the center angle β_1 not less than 15.56°. After meeting the condition of no interference between the scraper blades, the smaller the center angle, the closer the connection between the scraper and the longer the continuous clearing time. Considering the convenience of processing, Center angle β_1 takes a value of 16°.

The seed scraper can adjust and rotate around the positioning hole based on the rod slider mechanism within a certain angle range, and the location of the positioning hole should minimize the distance from the center of seeding plate without affecting the normal operation of the plate, so as to reduce the chamber volume and reduce the fan loss. Considering the convenience of processing, the coordinates A_3 (x_0, y_0) of the positioning hole are determined to be (-45, $45\sqrt{3}$). Points A_1 and A_2 are the center of the disk where the adjustable angle of scraper blade I starts and ends, respectively. The scraper blade I rotates around the positioning hole with R as the radius and the adjustable angle is ψ.

The position relation equation of the seed scraper is established as:

$$\begin{cases} \cos\psi = \dfrac{2R^2 - t_1^2}{2R} \\ t_1 = \sqrt{(x_1 - r_1)^2 + y_1^2} \\ x_1 - r_0 = \sqrt{t_2^2 - y_1^2} \\ t_2 = \dfrac{d_2}{2} + \Delta d \\ R^2 = (x_1 - x_0)^2 + (y_1 - y_0)^2 \end{cases} \tag{12}$$

where: t_1 is the distance between point A_1 and point A_2, (m); A_2 (x_1, y_2) are coordinates of the endpoint where scraper blade I can be adjusted.

According to triangular geometry:

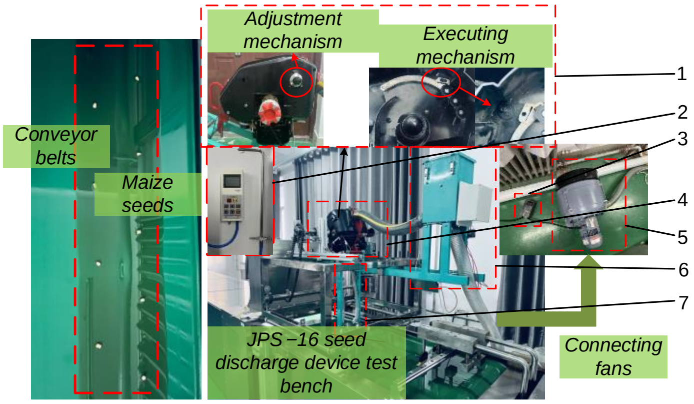
$$R^2 = (r_1 - x_0)^2 + y_0^2 \tag{13}$$

By combining equations 12~13, it can be determined that the adjustable seed-clearing angle range ψ of the seed scraper is 0~5°.

RESULTS AND DISCUSSIONS

Experimental condition

In order to investigate the optimal seed clearing performance of seed-cleaning mechanism of the device, the bench performance test was carried out in the high-speed precision seeding laboratory of Heilongjiang Bayi Agricultural University. The test conditions and seeding effect are shown in Fig. 7.



Seeding effect *Experimental conditions*

Fig. 7 - Experimental conditions and effects

1. seed-cleaning mechanism; 2. DP2000 intelligent pressure and wind velocity air volume meter; 3. frequency converter; 4. air-pressure precision seed-metering device; 5. HTB-multi-stage blower; 6. seed-supply device; 7. seed guide tube.

The main test equipment includes air-pressure precision seed-metering device, seed-cleaning mechanism, HTB-multi-stage blower, JPS−16 seed discharge device test bench, seed guide tube, seed-supply device, frequency converter and DP2000 intelligent pressure and wind velocity air volume meter. The maize seed variety used in the experiment is "Demeya No. 1", and the material parameters were shown in Table 1.

Experimental factors and Indexes

In order to explore the effect of seed clearing operation of seed-cleaning mechanism, the seed-clearing angle ψ, the operating speed V, and the positive pressure of blower P were taken as the influencing factors, and the qualified index W_1, multiple index W_2, and miss index W_3 were taken as the test indexes. The average value of each horizontal test was repeated three times as the test results. The formula of qualified index W_1, multiple index W_2 and miss index W_3 is as follows:

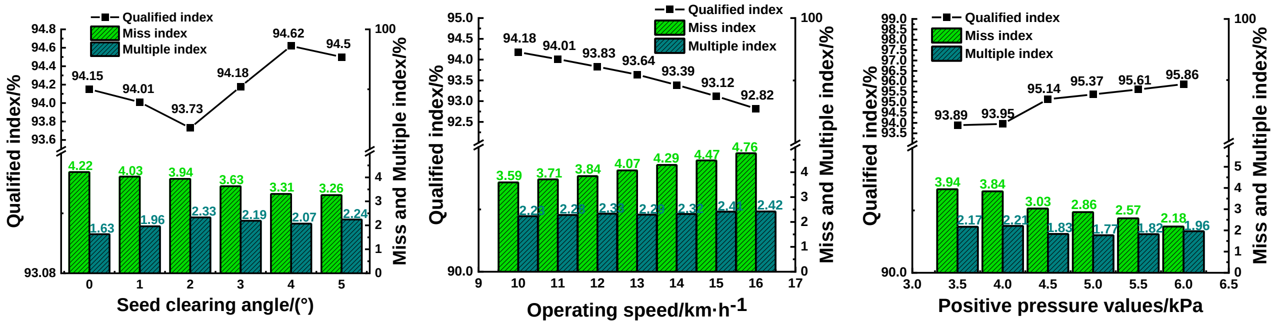
$$\begin{cases} W_1 = \dfrac{n_1}{N'} \times 100\% \\ W_2 = \dfrac{n_2}{N'} \times 100\% \\ W_3 = \dfrac{n_3}{N'} \times 100\% \end{cases} \tag{14}$$

where: n_1 is the number of passes; n_2 is the number of duplicates; n_3 is the number of leaks; N' is the total number of zones.

Set the theoretical plant spacing as L_r, the actual distance between neighboring seeds discharged by the device as L_s, L_s<0.5L_r for duplicates, L_s>1.5L_r for leaks, and 0.5L_r <L_s<1.5 L_r for passes.

Experiments of single-factor

Considering the actual working conditions, the seed clearing angle ψ is 0~5°, the operating speed V is 10~16 km/h, and the positive pressure P is 3.5~6.0 kPa as the factor range.



(a) V=12km/h *P*=4.0kPa *(b) ψ*=2° *P*=4.0kPa *(c) ψ*=2° *V*=12km/h

Fig. 8 - Influence of single-factor on test index

(1) Effect of seed clearing angle on the test index

Set the operating speed of 12 km/h, the positive pressure value is 4.0 kPa, and select the seed clearing angle of 0~5° every 1° as a level value for the single-factor test, and get the effect of the seed clearing angle on the experimental index as shown in Fig. 8 (a). As can be seen from the figure, with the increase of the seed clearing angle, miss index is a decreasing trend. The lowest miss index is 3.26% when the seed clearing angle is 5°. With the increase of the seed clearing angle, multiple index first increased and then stabilized. The lowest multiple index is 1.63% when the seed clearing angle is 0°. Qualified index is greater than 93%.

(2) Effect of operating speed on the test index

The seed clearing angle was set to 2°, the positive pressure value was set to 4.0 kPa, and the operating speed of 10 ~16 km/h was selected as a horizontal value for every 1 km/h to set the test bench. The influence of operating speed on the experimental index was shown in Fig. 8 (b). As can be seen from the figure, with the increase of operating speed, miss index generally shows an upward trend, and the highest miss index is 4.76% when the operating speed is 16 km/h. Multiple index fluctuates around 2.3%, and the lowest multiple index is 2.23% when the operating speed is 10 km/h. Qualified index gradually decreases, reaching a minimum of 92.82% at the operating speed of 16 km/h. It can be seen from the results that qualified index gradually decreases when the operating speed of the seed feeder is 10~16 km/h, while multiple index tends to be stable after the gradual increase. It is said that seed-cleaning mechanism reduces the degree to which multiple index is affected by the operating speed, while an increase in operating speed will relatively reduce the filling time of the seeder, leading to an increase in the miss index.

(3) Effect of the positive pressure on the test index

Set seed clearing angle to 2 ° and the operating speed to 12 km/h. Select the positive pressure value from 3.5 to 6.0 kPa every 0.5 kPa as one horizontal value for the experiment. The impact of the positive pressure value on the experimental index is shown in Fig. 8 (c). As shown in the figure, with the increase of positive pressure, the overall miss index shows a decreasing trend. At a positive pressure of 6.0 kPa, miss index reaches its lowest point of 2.18%; multiple index first increases and then fluctuates within the range of 1.77% to 1.96%. When the positive pressure value is 4.0 kPa, multiple index reaches the highest of 2.21%; qualified index gradually increases, reaching a maximum of 95.86% when the positive pressure value is 6.0kPa. From the results, it can be seen that when the positive pressure value is between 3.5 and 4.0 kPa, the increase in pressure of blower increases the possibility of multiple seeds in a hole. However, at 4.5 and 6.0 kPa, multiple index is all less than 2%, indicating that seed-cleaning mechanism reduces the degree to which multiple index is affected by the positive pressure value.

Experiments of multi-factor

Based on the results of the single-factor test, the range of seed clearing angle was determined to be 0~4°, the range of operating speed to be 10~12 km/h, and the range of positive pressure values to be 4.0~6.0 kPa, and a three-factor, five-level Central Composite experimental design was conducted. The coding of the test factors is shown in Table 2, where *x*1, *x*2, and *x*3 are the coded values of the seed clearing angle, operating speed, and positive pressure value, respectively.

Table 2

Experimental factor code table

Coded values	**Factor**		
	***x*1 / (°)**	***x*2 / km·h^{-1}**	***x*3 / kPa**
-1.682	0	10	4.0
-1	1	10.4	4.4
0	2	11	5.0
1	3	11.6	5.6
1.682	4	12	6.0

The experimental program and results are shown in Table 3.

Table 3

Experimental design and results

Number	***x*1**	***x*2**	***x*3**	**W_1/%**	**W_2/%**	**W_3/%**
1	-1	-1	-1	94.39	2.47	3.14
2	1	-1	-1	94.41	2.86	2.73
3	-1	1	-1	93.94	2.28	3.78
4	1	1	-1	93.84	2.65	3.51
5	-1	-1	1	96.94	1.19	1.87
6	1	-1	1	96.43	2.01	1.56
7	-1	1	1	96.63	1.14	2.23
8	1	1	1	96.23	1.91	1.86
9	-1.682	0	0	94.82	1.31	3.87
10	1.682	0	0	95.77	2.09	2.14
11	0	-1.682	0	96.35	2.01	1.64
12	0	1.682	0	95.47	1.82	2.71
13	0	0	-1.682	93.67	2.42	3.91
14	0	0	1.682	97.48	1.66	0.86
15	0	0	0	95.38	1.05	3.57
16	0	0	0	95.96	2.03	2.01
17	0	0	0	94.83	1.76	3.41
18	0	0	0	95.12	1.99	2.89
19	0	0	0	95.09	1.37	3.54
20	0	0	0	94.96	1.76	3.28
21	0	0	0	95.61	1.61	2.78
22	0	0	0	95.02	1.37	3.61
23	0	0	0	95.22	1.04	3.74

The data in the Table 3 was processed using Design Expert 12 software to obtain the quadratic equation analysis of variance for the qualified index W_1, multiple index W_2, and miss index W_3, as shown in Table 4.

In the table, the *P*-value of the regression models for the qualified index, multiple index, and miss index are all less than 0.01, indicating that the regression model is extremely significant. The *P*-value of the lack of fit are all greater than 0.05, indicating that the regression model has good fitting. In the analysis of variance of the qualified index, operating speed $x2$, and the positive pressure value $x3$ show significant effects. In the analysis of variance of the multiple index, seed clearing angle $x1$, the positive pressure value $x3$, and the quadratic term $x3^2$ are all significant; In the analysis of variance of the miss index, seed clearing angle $x1$, operating speed $x2$, the positive pressure value $x3$, the quadratic terms $x2^2$, and $x3^2$ are all significant. The other factors are not significant.

Excluding insignificant factors, the regression equations for qualified index W_1, multiple index W_2, and miss index W_3 are obtained:

$$\begin{cases} W_1 = 151.37 - 11.63x2 + 1.98x3 + 0.51x2^2 \\ W_2 = 18.88 + 0.23x1 - 6.4x3 + 0.57x3^2 \\ W_3 = -130.71 - 0.26x1 + 21.73x2 + 6.23x3 - 0.97x2^2 - 0.76x3^2 \end{cases} \tag{15}$$

Table 4

The quadratic equation analysis of variance

Source	Qualified index		Multiple index		Miss index	
	Sum of squares	*p*-value	Sum of squares	*p*-value	Sum of squares	*p*-value
Model	20.29	< 0.0001**	4.36	0.0083**	14.01	0.0012**
$x1$	0.027	0.667	0.98	0.01*	1.33	0.0325*
$x2$	0.66	0.0483*	0.0554	0.49	1.10	0.0487*
$x3$	18.88	< 0.0001**	2.05	0.0009**	8.49	< 0.0001**
$x1\ x2$	0.00	0.99	0.0006	0.94	0.0008	0.95
$x1\ x3$	0.086	0.45	0.086	0.39	1.8e-15	1.00
$x2\ x3$	0.033	0.64	0.0078	0.79	0.0722	0.59
$x1^2$	0.021	0.70	0.11	0.33	0.0372	0.70
$x2^2$	0.52	0.0755	0.41	0.076	1.86	0.01*
$x3^2$	0.062	0.52	0.67	0.0287*	1.14	0.046*
Residual	1.82		1.44		3.03	
Lack of Fit	0.81	0.36	0.34	0.77	0.5790	0.85
Pure Error	1.01		1.09		2.45	
Cor Total	22.11		5.79		17.04	

Note: * indicates a significant impact; ** indicates a highly significant impact.

To explore the impact trend of interaction terms on multiple and miss indices, a contour map is drawn as shown in Fig. 9. Fig. 9a, 9b, 9c, 9d, 9e, and 9f respectively showing the effects of the other two factors on multiple and miss index, explored at seed clearing angle of 2°, operating speed of 11 km/h, and positive pressure value of 5 kPa.

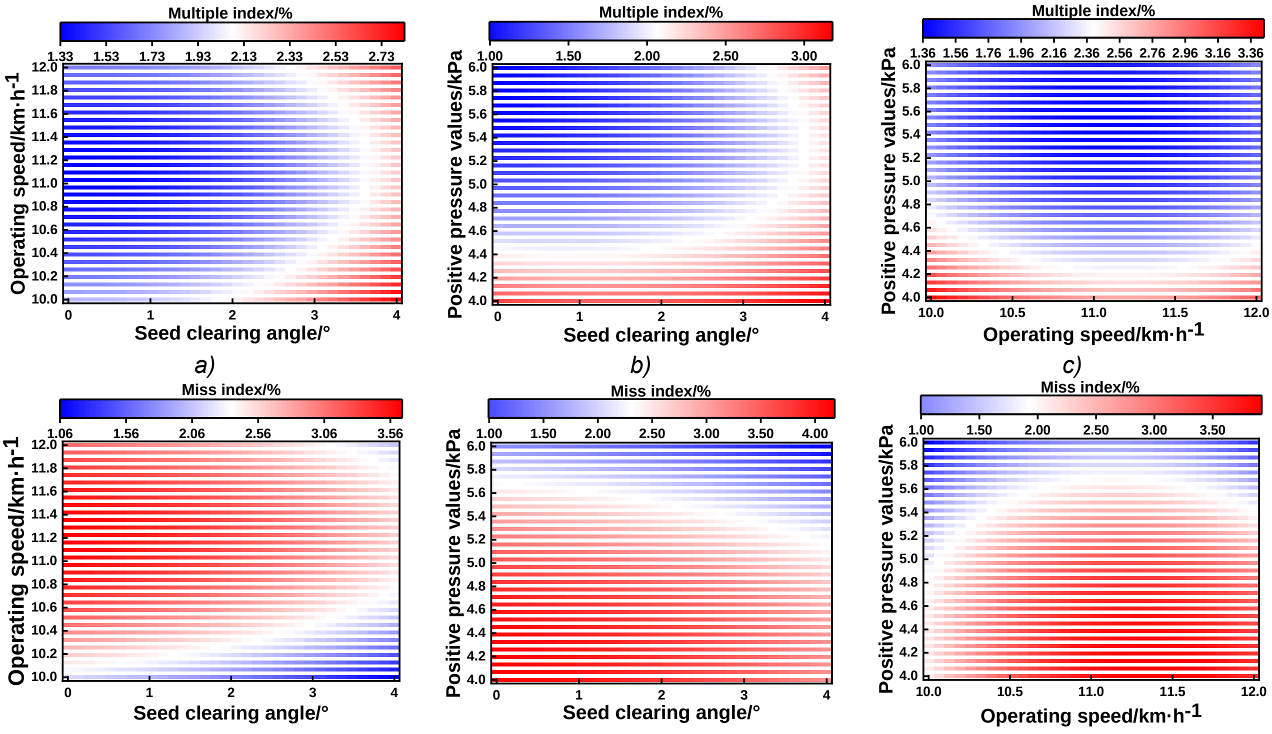
In Fig.9a, when operating speed is constant, multiple index gradually increases with the increase of seed clearing angle. However, when seed clearing angle is constant, multiple index does not change significantly with operating speed, indicating that the influence of operating speed on seed clearing angle is not significant, which is consistent with the results of the analysis of variance. In Fig. 9b, when seed clearing angle is between 0~3.6° and positive pressure value is between 4.5~6.0 kPa, multiple index is lower.

In Fig. 9c, when operating speed is constant, multiple index gradually decreases with the increase of the positive pressure value. However, when the positive pressure value is constant, multiple index does not change much with operating speed.

For miss index, in Fig.9d, when operating speed is less than 10.8 km/h, miss index decreases as seed clearing angle increases. However, when operating speed is greater than 10.8 km/h, miss index is relatively high, indicating that seed-cleaning mechanism has a better cleaning effect under sub-high-speed operation.

In Fig.9e, when seed clearing angle is constant, miss index decreases with the increase of the positive pressure value. When the positive pressure value is below 5 kPa, seed-cleaning mechanism's effect is not obvious. The reason is that low chamber pressure is not conducive to seed filling, and the seeds attached to shape hole are unstable during the seeding process. When the positive pressure value is higher than 5 kPa, the lowest value of miss index is 1%, indicating that the cleaning effect of seed-cleaning mechanism is better when the positive pressure value of the blower is higher.

In Fig. 9f, when operating speed is constant, miss index gradually decreases with the increase of the positive pressure value. However, when the positive pressure value is constant, miss index increases with the increase of operating speed, indicating that operating speed and positive pressure value have a significant impact on miss index, which is consistent with the results of the variance analysis.



a) *b)* *c)*

d) *e)* *f)*

Fig. 9 - Effect of interactivity on test index

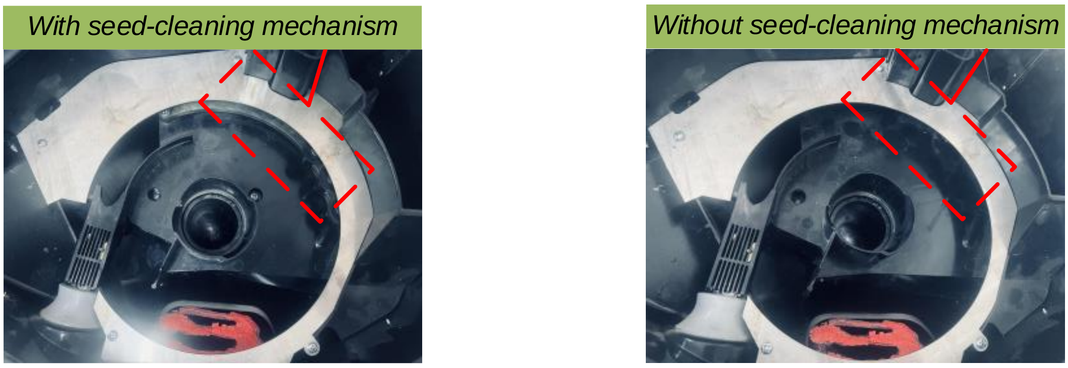
In order to obtain the optimal seed cleaning performance of seed-cleaning mechanism and improve the operation performance of the device, the highest qualified index and the lowest miss and multiple index were found within the range of factors, and the optimization equation was established:

$$\begin{cases} maxW_1 \\ minW_2 \\ minW_3 \\ s.t.\begin{cases} 0° \geq x1 \geq 4° \\ 10\text{km/h} \geq x2 \geq 12\text{km/h} \\ 4.0\text{kPa} \geq x3 \geq 6.0\text{kPa} \\ 1 \geq W_1(x1,x2,x3) \geq 0 \\ 1 \geq W_2(x1,x2,x3) \geq 0 \\ 1 \geq W_3(x1,x2,x3) \geq 0 \end{cases} \end{cases} \tag{16}$$

The optimal seed cleaning performance parameter combination of the device was obtained as follows: seed clearing angle 0.024°, operating speed 10 km/h, and positive pressure value 6.0 kPa. Under this parameter combination, qualified index is 98.218%, multiple index is 1.426%, and miss index is 0.356%. In order to verify the optimization results of parameters, verification tests were carried out on JPS−16 seed discharge device test bench. Combined with the actual test conditions, test parameters were set according to seed clearing angle of 0°, operating speed of 10 km/h, and the positive pressure value of 6.0 kPa. The qualified index is 98.11%, multiple index is 1.44%, and miss index is 0.45%. The deviation between the actual result and the parameter optimization is less than 0.2%. The optimized parameter combination can make the seed clearing device achieve better seed clearing performance.

Comparative experiment

In order to investigate the improvement of seed-cleaning mechanism of the device designed under the optimal combination of seed cleaning parameters, the device installed (Fig. 10a) and the device not installed (Fig. 10b) were used for comparison test.



a) b)

Fig. 10 - Comparison with and without seed-cleaning mechanism

The test conditions of the device without installation were set according to the operating speed of 10 km/h and the positive pressure value of 6.0 kPa. The test was repeated for five groups and the data obtained were shown in Table 5. In the table, the qualified index of the device with seed-cleaning mechanism increased by about 2.3% compared with the device without seed-cleaning mechanism, multiple index decreased by about 2.2%, and miss index changed little and were all less than 1%. The results showed that the seed filling effect was better and the phenomenon of missing sowing was less under the optimal combination of seed cleaning parameters. The miss index of the device with seed-cleaning mechanism was lower than that of the device without installation. The phenomenon of "over-clearing" did not occur in the device.

Table 5

Comparative test results

Test number	Seed-cleaning device installed or not	Qualified index /%	Multiple index /%	Miss index /%	Difference in qualified index /%
1	Installed	97.96	1.56	0.48	2.27
	No	95.69	3.78	0.53	
2	Installed	98.05	1.48	0.47	2.24
	No	95.81	3.68	0.51	
3	Installed	98.12	1.47	0.41	2.28
	No	95.84	3.72	0.44	
4	Installed	98.12	1.42	0.46	2.36
	No	95.76	3.77	0.47	
5	Installed	98.06	1.49	0.45	2.28
	No	95.78	3.69	0.53	

In conclusion, seed-cleaning mechanism with progressive seed scraper is reasonable in design, which reduces multiple index of the device, avoids the occurrence of "over-clearing" phenomenon, and improves the operation performance of the device.

CONCLUSIONS

In this study, the main factors affecting the seed clearing performance of the seed-cleaning mechanism were determined to be the pressure of blower and the operating speed. Based on single-factor results, the range of seed-clearing angle is determined to be 0~4°, the range of operating speed is 10~12 km/h, and the range of positive pressure of blower is 4.0~6.0 kPa. The optimal combination of cleaning performance parameters for seed-metering device was obtained, which included a cleaning angle of 0.024°, an operating speed of 10 km/h, and a positive pressure value of 6.0 kPa. Under this parameter combination, the qualified index is 98.218%, the multiple index was 1.426%, and the miss index was 0.356%. According to the actual test conditions, the test parameters were set in accordance with the cleaning angle of 0°, the operating speed of 10 km/h, and the positive pressure value of 6.0 kPa. The qualified index under the verification test is 98.11%, the multiple index is 1.44%, and the miss index is 0.45%. In the comparative experiment, the qualified index of seed-metering device with seed-cleaning mechanism increased by about 2.3% compared to without seed-cleaning mechanism, the multiple index decreased by about 2.2%, and the miss index was all less than 1%. This indicates that the reasonable design of the seed-cleaning mechanism can meet the cleaning operation requirements of the seed-metering device.

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