DESIGN AND EXPERIMENT OF COMBINED CAVITY-TYPE PRECISION HOLE-DROP SEED-METERING DEVICE FOR RICE

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组合腔道式水稻精量穴播排种器设计与试验

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ABSTRACT

In order to solve the problems of unstable seeding quantity and poor applicability of traditional lightweight simplification mechanical seed-metering device, a combined cavity-type rice precision hole-drop seed-metering was developed. According to the material characteristics of rice seed and the requirements of seeding quantity, the innovative metering hole structure achieves the purpose of accurate filling of rice seed. In order to adapt to the demands of different rice seeds and improve the accuracy and convenience of the adjustment of the seeding quantity, the number of cavities involved in seeding operation was simply adjusted. Bench tests are carried out on the effects of the seed-inlet width, the metering hole slope angle, and the cavity outer angle on the precision seeding performance of the seed-metering device. The test results show that when the outer and middle seed-inlets width both are 3.8 mm, the innermost seed-inlet width is 5.4 mm, and the metering hole slope angle is 35 °, and the cavity outer angle is 85 °, the performance of the three kinds of rice was better. Opening outermost seed-inlet to seeding super hybrid rice, the qualified rate is 90.67%, the miss-seeding rate is 3.77%. Opening outer and middle seed-inlets to seeding hybrid rice, the qualified rate is 90.80%, the miss-seeding rate is 3.73%. Opening all three seed-inlets to seeding conventional rice, the qualified rate is 90.67%, the miss-seeding rate is 3.53%. The field test shows the seed-metering device can also meet the requires of these kinds of rice seeding.

摘 要

为解决传统水稻轻简机械式排种器穴播量稳定性差、精确调节困难，导致品种适用性差的问题，研制了一种组合腔道式精量穴播排种器。根据稻种的物料特性及穴播量要求，创新异形量孔结构达到稻种精量充种的目的；提出通过简单调节参与排种作业的腔道个数调节排种器的穴播量，以适应不同品种水稻不同穴播量的需求，提高排种器播量调节的精确性与便捷性。先后采用单因素与全因素试验方法，研究了量孔的进种口宽度、斜面倾角、腔道外侧角对排种器穴播量的影响。明确了外层与中间腔道进种口宽度均为3.8mm、内侧腔道进种口宽度为5.4mm，量孔斜面倾角均为35°，且腔道外侧角均为85°时，排种器排种三种水稻的穴播排种性能均较优.单个进种口排种超级稻时，漏播率为3.77%，合格率为90.67%；两个进种口排种杂交稻时，漏播率为3.73%，合格率为90.80%；三个进种口排种常规稻漏播率为3.53%，合格率为90.67%。田间试验表明排种器能满足水稻精量穴直播的种植要求。

INTRODUCTION

Rice holds the status of being China's primary food crop. Its yield per area exceeds that of wheat by 22.4% and corn by 13.1% (*China Statistics Press, 2022*). Thus, the promotion of rice cultivation plays a critical role in ensuring the nutritional security of the populace in the region (*Tian et al., 2022; Jat et al., 2022*). Mechanized transplantation and direct seeding are the two primary modes of rice planting in the region.

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Among these, precision cavity direct seeding of rice through seed-metering device offers the benefits of time and labor savings, as well as accuracy and efficiency. (*Yamauchi, 2017; Zhang et al., 2018; Farooq et al., 2011*).

The critical component in the rice precision hole direct seeding technology is the seed-metering device. The component structure and working principle of rice precision hole direct seeding device were studied (*Van et al., 2020*). The seed-meter device is mainly mechanical and robust. The mechanical type is highly adaptable to seed shape and can withstand field vibration, dust, and high humidity. Its structure is simple and easy to repair. However, it requires stable gas and a gas source are prone to clogging of pores. It is a primary method to achieve lightweight simplification of rice mechanization equipment for seed-meter device (*Zhang et al., 2015; Li et al., 2021; Cheamuangphan et al., 2018*).

There are three types of rice: super hybrid, hybrid, and conventional. Their diligence capabilities have decreased in that order. Therefore, direct seeding of rice at essential points must consider the growth characteristics of each rice category (*Liu et al., 2016*). Typically, super hybrid rice, hybrid rice, and conventional rice are sown with 1-3 seeds, 2-5 seeds, and 5-10 seeds, respectively (*Xing et al., 2022; Zeng, 2013*). Due to the difference requirements of seeding quantity between the conventional and hybrid rice, the seeding quantity is difficult to be controlled accurately for the seed-metering device. Wang, Z. et al. designed a rice precision metering device with seeding quantity stepless adjusting. The precision metering device has advantages of wide adjustment range, good adaptation, simple and quick stepless adjustment show that this device is practical. Nonetheless, this device is only able to respond to the seeding demands of hybrid and conventional rice (*Wang et al., 2018*). Li Hanqing and his team have designed a rice seed-metering device that by the variable capacity roller-wheel managed to adjust the quantity of hole seeding. Because the direct seed-metering device for rice cannot continuously adjust the quantity of seeding, it has a small adjustment range and low accuracy. They designed and verified variable capacity roller-wheel. The variable capacity method achieves a stepless adjustment of the seeding quantity, and results in high accuracy (*Li et al., 2022*). Tang H and others designed the multi-grain cluster air suction type rice hole direct seed metering device. A multi grain cluster air suction type rice hole direct seed metering device was developed to solve the problem of high reseeding rates and miss-seeding rates in the rice multi-grain hole direct seeding process (*Tang et al., 2022*). Rajaiah et al. designed a precision planter for paddy rice direct seeding, its seeding plate can only hold 1-2 rice seeds in each groove and the hole seeding rate cannot be adjusted (*Rajaiah et al., 2020*). Hensh et al. designed a precision hole drop seed metering mechanism of rice, the opening time of its outlet is precisely controlled by an inductive proximity sensor. However, it is not easy for the device to adjust the seeding quantity (*Hensh et al., 2022*). Because of the lack of the light and simple mechanical direct seed-metering device that can be used for the three major types of rice, the utilization rate of precision direct seeding equipment for rice is reduced and the application of precision direct seeding technology is hindered.

In response to the issue of accurate regulation of seeding quantity stability and precision regulation of the traditional rice mechanical precision hole-drop seed-metering device, this article proposes the combined cavity-type rice precision hole-drop seed-metering device which can adjust the seeding quantity. This innovative design offers a simplified mechanical structure and allows for accurate adjustment of the measuring instrument's quantity, providing a new avenue for experimentation and advancement.

MATERIALS AND METHODS

Configuration and Working Principle

The combined cavity-type rice precision hole-drop seed-metering device is mainly composed of shells, discharge plate, as shown in Fig. 1, seeding quantity adjustment disk, seeding shafts, bolts, etc. The seeding quantity adjustment disk is embedded in the grooves installed in the discharge plate, and the two form the discharge plate. There are multiple cavities in the discharge plate, and each group of cavities consist of 3 cavities. A single cavity is composed of the metering hole part and the curve transfusion cavity. The metering hole include metering hole slope, seed-limiting plate, inner and outer side of the cavity and other side of the cavity, as shown in Fig. 3(f). The three cavities have a variety seed-inlet each, and meet at the same outlet. The seeding quantity adjustment disk can rotate relative to the discharge plate. By adjusting the relative position of the seeding quantity adjustment disk and the discharge plate, the number of opened seed-inlet is controlled. When the seeding quantity adjustment disk covers the innermost and the middle seed-inlet of the discharge plate, the seed-metering device opens the outermost seed-inlet of the discharge plate and it is used for the seeding of each hole (1-3) with the super hybrid rice.

The seeding quantity adjustment disk only covers the innermost seed-inlet, the seed-metering device opens two seed-inlets, and it is used for the seeding of each hole (2-5) with the hybrid rice.

When the seeding quantity adjustment disk does not cover the seed-inlet of the discharge plate, the seed-metering device opens all three seed-inlets and it is used for the seeding of each hole (5-10) with the conventional rice.

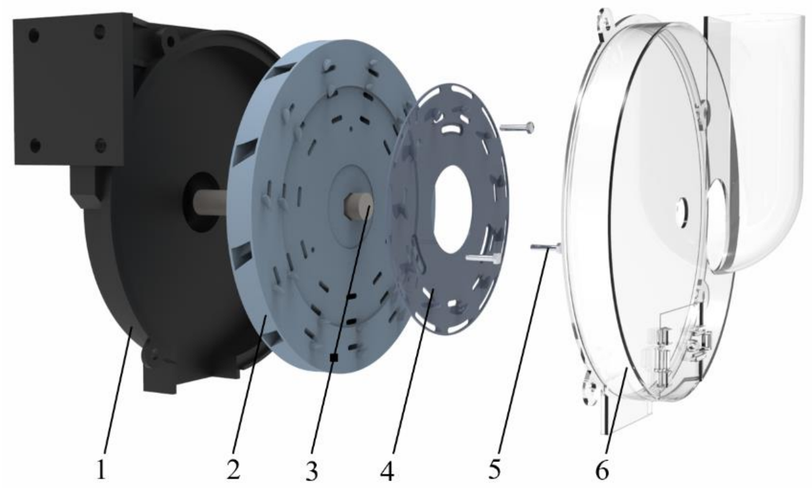

Fig. 1 - Display diagram of the seed-metering device

1. Left shell; 2. The discharge plate; 3. Shaft; 4. The seeding quantity adjustment disk; 5. Bolts; 6. Right shell.

The seeding process of the seeder is mainly formed by the three links of filling, carrying, and dropping, as shown in Fig. 2.

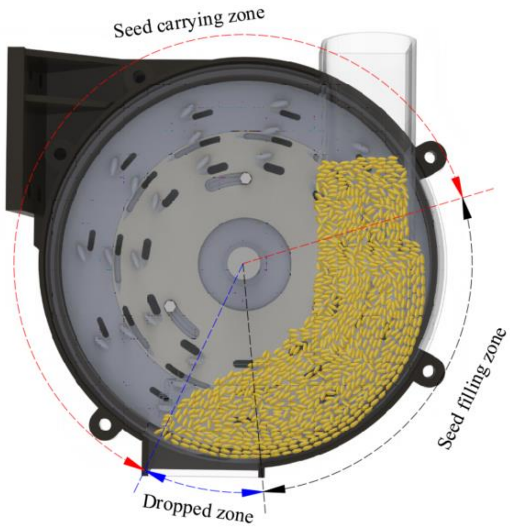

Fig. 2 - The diagram of working zone

Before the seeding, according to the requirements of the quantity of rice varieties, rotate the seeding quantity adjustment disk to adjust the number of openings of each group of cavities into the variety. After the discharge plate is rotated, the rice seeds are charged into the metering hole through the influence of their own gravity and population side pressure.

When the sector is transferred to the filling zone, the rice seeds in the metering hole will be under the constraints of its own gravity and the bottom plate and the top plate, lying on the metering hole, and under the blockage of the limit rice species board, the bottom rice is stranded in the metering hole, and the upper excess rice will drop out from holes under their own gravity, and return to the filling zone. As the discharge plate continues to rotate, the rice in the metering holes declines along the transfusion curve cavity and converges at the exit. When the outlet which is equipped with rice seeds arrive at the dropping zone, rice is discharged. The seedlings of multiple metering holes in a group of cavities do not interfere with each other. Before the outlets move to the dropping zone, the rice seeds in multiple curves gather at the outlet, as shown in Fig.3 (a).

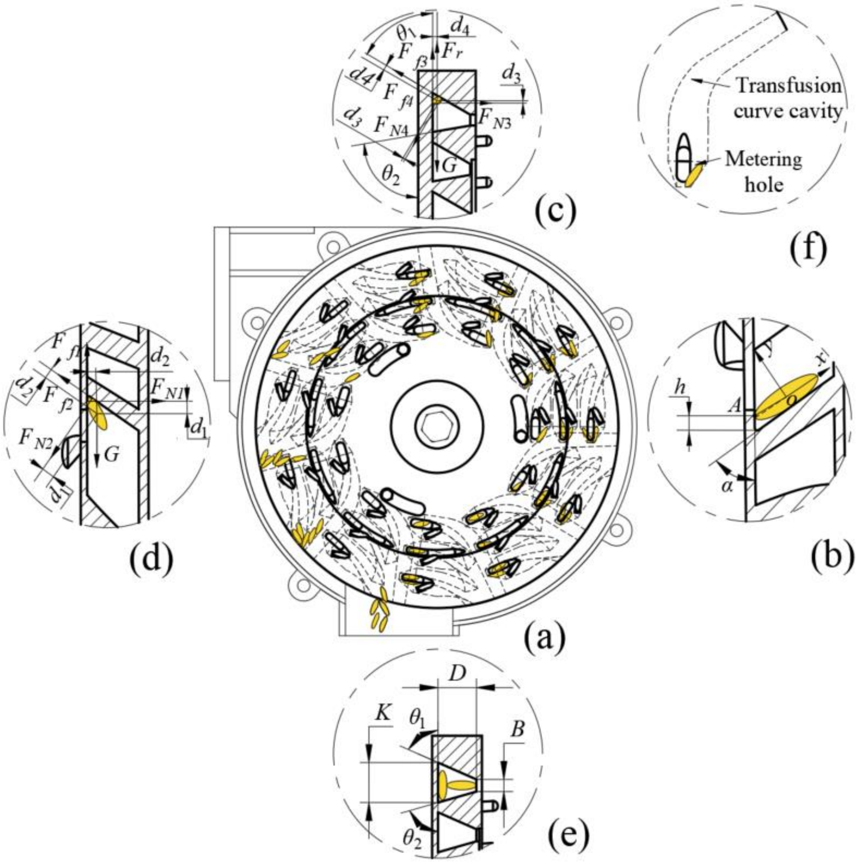

Fig. 3 - The diagram of seeding process.

(a) The seeding process; (b) The diagram of metering hole slope angle; (c) The status chart of cavity outer plane pick up rice seed; (d) The status chart of metering hole slope and seed-limiting plate pick up rice seed; (e) The sectional schematic diagram of transfusion curve cavity; (f)The diagram of the cavity composition.

The shape and size of seed-inlets

The shape and size of rice seeds are the main basis of the design parameters of the seed-inlets. The shape of rice seeds is similar with the spindle body. It is commonly used in three axial sizes of length, width, and thickness. The average three-axis size of the familiar rice species were counted, as shown in Fig. 4.

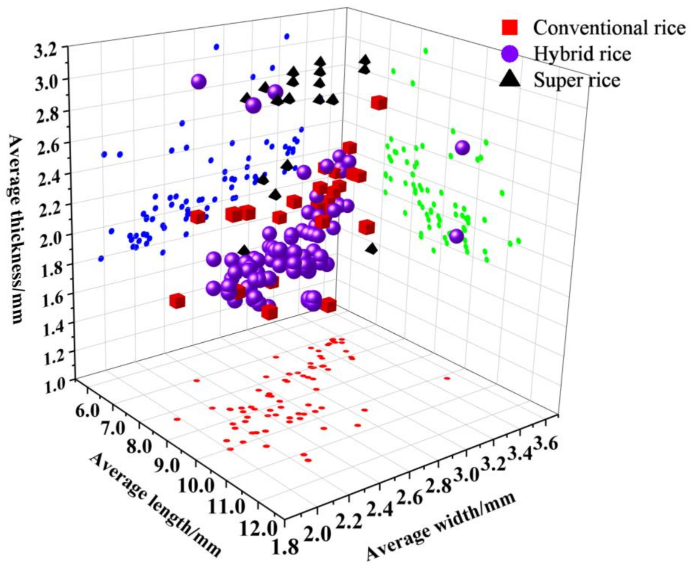

Fig. 4 - Familiar rice species three-axis size distribution map

It can be seen from the Fig. 4 that the average three-axis size distribution of super hybrid rice, hybrid rice and conventional rice does not have a significant distinction, as it is intertwined. However, regardless of variety, the length of the rice species is large, mainly distributed between 6.5-11.5 mm.

The range of the width size and thickness size is relatively concentrated, and the range of distribution is 2-3.5 mm and 1.5-3.1 mm, respectively. The three-axis size of common rice species is shown in Table 1. The rice seeds have obvious length and width structural characteristics. Therefore, the distribution way of rice seeds in the filling zone is also an important reference for the shape of seed-inlets.

Table 1

Three axis size of the frequent rice species

	Three axis median value (Length × width × thickness)	Maximum length	Maximum width	Minimum thickness
Size / mm	8.75×2.69×2.07	11.29	3.52	1.50

Studies have shown that rice seeds are distributed in the same consistent way in the direction of their long shafts and the rotation lines in the seed filling zone (*Zhang et al., 2023*). Therefore, the shape of seed-inlets is designed as round waist shape, and the horizontal direction of the seed-inlet is distributed in the direction of the discharge plates' cut line, as shown in Fig. 5. The structure size of the seed-inlets are mainly length and width size. Based on super hybrid rice, hybrid rice and conventional rice, the appropriate quantity of hole seeding, the regulation of the adjusting hole seeding quantity and the distribution posture of rice seeds in the filling zone, the width size of each seed-inlets of the combination cavity can be adjusted to adapt to the quantity of hole seeding of different rice varieties, and the length size of each seed-inlet should be consistent (*Rajaiah et al., 2015*), and should meet the formula (1).

$$L > a_{max} + l' \tag{1}$$

where:

a_{max} is the maximum length size of rice seeds, (mm);

l' is the bud length of rice seeds, (mm).

When the seed-metering device is opened only on the outermost side of the seed to adapt to the super hybrid rice requirement for the (1-3) grains per hole, the seed-inlet width B should meet the formula (2):

$$b_{max} < B < 4c_{min} \tag{2}$$

where:

b_{max} is the maximum width size of rice seeds, (mm);

c_{min} is the minimum thickness size of rice seeds, (mm), as shown in Fig. 5.

When the discharge plate is opened for two seed-inlets of the outer side to adapt to the hybrid rice requirement for the (2-5) grains per hole, the width size of the middle seed-inlet should be consistent with the outer seed-inlet. When the discharge plate is opened for three seed-inlets to adapt to the conventional rice requirement for the (5-10) grains per hole, the width size of the inner seed-inlet should be appropriately enlarged, and it also needs to be determined through the later seeding performance test.

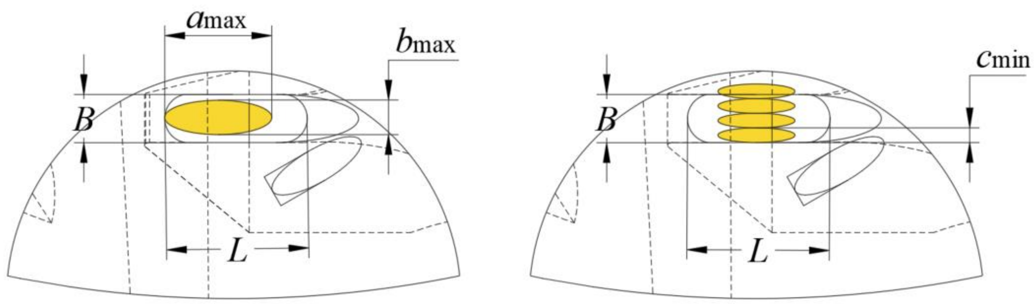

Fig. 5 - The diagram of the seed-inlet size

In order to avoid the entanglement of rice germination and affect normal seeding, the rice buds are generally not more than 2 mm after the rice is soaked in germination. Based on formula (1) and formula (2), combined with Table 1, the length size L of the seed-inlet should be larger than 13.29 mm, and this article takes 14 mm. The width size of the seed-inlet should be between 3.52-6 mm.

The metering hole slope angle

According to the working principle of the seed dispenser, the metering hole is an important part that determines the number of seed particles filled in a single cavity. The metering hole slope angle affects the successfully cleared excess rice seeds on the upper layer within the cavity. Therefore, the metering hole slope angle α should satisfy formula (3).

$$\alpha \geq arctan\,\mu \tag{3}$$

where:

μ represents the sliding friction coefficient between rice seeds, which is taken as 0.55 (*Jiang, 2021*);

α is the metering hole slope angle, (°).

It is not advisable for the metering hole slope angle to be too large, as it may result in a small angle between the metering hole inclined plane and the seed-limiting plate, causing the rice seeds to get stuck. This means that the rice seeds cannot successfully detach from the metering hole and slide into the transfusion curve cavity. If the rice seeds get stuck in the metering hole, there will be deformation due to the compression between the metering hole inclined plane and the seed-limiting plate. Therefore, the maximum value of the metering hole slope angle can be determined by considering the critical state where the rice seeds are in contact with the metering hole inclined plane but not subjected to compression. The spindle-shaped rice seeds were simplified into homogeneous and regular ellipsoids, and the force analysis was carried out, as shown in Figure 3(d).

Establish the force balance formula for rice seed, that is:

$$\begin{cases} \sum F_x = 0 & F_{N_1} - F_{f_2}\cos\alpha - F_{N_2}\sin\alpha = 0 \\ \sum F_y = 0 & F_{f_1} + F_{f_2}\sin\alpha - F_{N_2}\cos\alpha - mg = 0 \\ \sum M = 0 & F_{N_2}d_1 + F_{f_2}d_2 - F_{N_1}d_1 - F_{f_1}d_2 = 0 \end{cases} \tag{4}$$

$$\begin{cases} F_{f_1} = \mu F_{N_1} \\ F_{f_2} = \mu F_{N_2} \end{cases} \tag{5}$$

where: F_{N1} is the supporting force of rice seed for seed-limiting plate, (N);

F_{N2} is the supporting force of the rice seed for metering hole slope, (N);

F_{f1} is the friction force of rice seed for seed-limiting plate, (N);

F_{f2} is the friction force of rice seed for metering hole slope, (N);

G is the gravity of rice seed, (N);

d_1 is the supporting force lever, (m);

d_2 is the friction force lever, (m);

μ_1 is the friction coefficient of the discharge plate and the rice seed, which is 0.46 in this article;

From formula (4) formula (5), it can be seen that:

$$\left(F_{N_2} - F_{N_1}\right)d_1 + \left(F_{f_2} - F_{f_1}\right)d_2 = 0 \tag{6}$$

After sorting out the formula:

$$\left(F_{N_2} - F_{N_1}\right) + \left(d_1 + \mu d_2\right) = 0 \tag{7}$$

$$\begin{cases} F_{N_1} = F_{N_2} = F_N \\ F_{f_1} = F_{f_2} = \mu F_N \end{cases} \tag{8}$$

By substituting in formula (4), it can be obtained:

$$\begin{cases} \mu\cos\alpha + \sin\alpha = 1 \\ F_N\left(\mu + \mu\sin\alpha - \cos\alpha\right) - mg = 0 \end{cases} \tag{9}$$

It can be seen from the formula that if the rice seed is in the equilibrium state at this position and the gravity of the rice seed is constant, the supporting force on the slope decreases with the increase of the metering hole slope angle; when the metering hole slope angle increases to a certain value, the equilibrium state breaks with the operation of the seed-metering device, and the resultant force along the vertical direction refers to the metering hole inclined plane, and the rice seed is clamped by metering hole, and the metering hole slope angle is the pinch angle.

Also know that: (10)

$$\sin^2\alpha + \cos^2\alpha = 1$$

By substituting in formula (9) can be calculated

$$\alpha = \arccos\left(\frac{2\mu}{1+\mu^2}\right) \tag{11}$$

Diameter calculation α=40.60°. Therefore, the value range of the inclination angle of the metering hole should be 28.81° < α < 40.60°.

The height of seed-limiting plate

In order to ensure that the metering hole can "pocket" the bottom rice seeds, it is necessary to design a suitable height seed-limiting plate. Since the bottom rice seeds lie on it under the guidance of the metering hole inclined plane, the geometric relationship model between any single lying rice seed and the seed-limiting plate was established, as shown in Fig. 3(b). The cartesian coordinate system xoy was established by taking the centroid of rice seed as the coordinate origin.

Let (x_0, y_0) represent the coordinates of the intersection point A between the rice seeds and the seed-limiting plate. According to Fig. 3(b), the geometric expression for the height of the seed-limiting plate is:

$$h = \frac{y_0}{\cos\alpha} + \frac{c}{2\cos\alpha} \tag{1}$$

where: c is the average thickness of rice seed, (mm);

In the coordinate system xoy, the slope equation for seed-limiting plate projection is:

$$k = -\frac{c^2 x_0}{a^2 y_0} \tag{13}$$

where:

a is the average length of rice seed, (mm);

It can also be expressed by metering hole slope angle α: (14)

$$k = \tan\left(90° - \alpha\right)$$

By substituting in formula (12) and (13) can be calculated:

$$x_0 = -\frac{a^2 y_0 \tan\left(90° - \alpha\right)}{c^2} \tag{15}$$

Because tangent point A satisfies the elliptic equation:

$$\frac{4x_0^2}{a^2} + \frac{4y_0^2}{c^2} = 1 \tag{16}$$

Substituting equations (14) and (15) into equation (11) and rearranging, is obtained

$$h = \frac{c^2}{2\cos\alpha\sqrt{c^2 + a^2\cot^2\alpha}} + \frac{c}{2\cos\alpha} \tag{17}$$

Substituting the average length and thickness dimensions of the rice seed from Table 1 into the equation, the relationship curve between the seed-limiting plate height h and the metering hole slope angle α, can be plotted as shown in Fig. 6. The seed-limiting plate height h increases with the increase in the metering hole slope angle α. When the metering hole slope angle α is determined, the value of the seed-limiting plate height h is also determined.

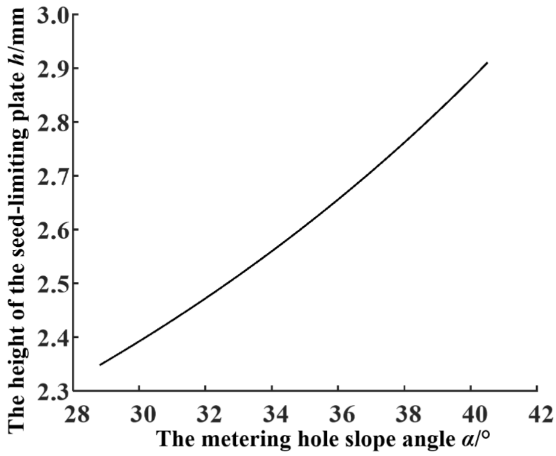

Fig. 6 - The diagram of h and α relationship

The cavity outer angle

Due to the small width of the seed-inlet of the metering hole, in order to ensure that the rice seed filling into the metering hole can move smoothly in the curved cavity, the section of the cavity is designed as a trapezoid expanded from one side of the seed-inlet, as shown in Fig. 3(c). The cavity outer angle is composed of the inner side, the outer and the bottom side of the cavity, which is divided into the outer angle and the inner angle. In order to ensure that the rice seeds filling into the metering hole do not get stuck into the cavity outer plane, ensure the smooth transportation of rice seed and the subsequent filling into the metering hole, and perform a force analysis on the rice seed at the cavity outer plane when they reach the top during motion.

The force equilibrium equation of rice seed being clamped in the cavity outer plane is:

$$\begin{cases} \sum F_x = 0 & F_{N_4}\cos\theta_1 + F_{f_4}\sin\theta_1 - F_{N_3} = 0 \\ \sum F_y = 0 & F_r + F_{f_3} + F_{f_4}\cos\theta_1 - F_{N_4}\sin\theta_1 - G = 0 \\ \sum M = 0 & F_{N_3}d_3 + F_{f_3}d_4 - F_{N_4}d_3 - F_{f_4}d_4 = 0 \end{cases} \tag{18}$$

$$\begin{cases} F_{f_3} = \mu F_{N_3} \\ F_{f_4} = \mu F_{N_4} \end{cases} \tag{19}$$

where:

F_{N3} is the supporting force of rice seed for cavity plane, (N);

F_{N4} is the supporting force of the rice seed for cavity outer plane, (N);

F_{f3} is the friction force of rice seed for cavity plane, (N);

F_{f4} is the friction force of rice seed for cavity outer plane, (N);

θ_1 is the cavity outer angle, (°);

θ_2 is the cavity inner angle, (°);

d_3 is the supporting force lever, (m);

d_4 is the friction force lever, (m).

From formula (18) and formula (19) can be obtained

$$\begin{cases} F_{N_3} = F_{N_4} = F_N^{'} \\ F_{f_3} = F_{f_4} = \mu F_N^{'} \\ \cos\theta_1 + \mu\sin\theta_1 = 1 \end{cases} \tag{20}$$

By substituting in formula (20) can be calculated

$$\theta_1 = \arcsin\left(\frac{2\mu}{1+\mu^2}\right) \tag{21}$$

After calculation, θ_1 is found to be 49.40°, which means that the angle between the inner and outer sides of the curved cavity should not be less than 49.40° in order to avoid the rice seed clamping by the plane of cavity.

The depth of the cavity

According to Fig. 3(e), in order to ensure that the rice seed do not get stuck in the cavity, the depth of the cavity D should satisfy formula (22):

$$D > a_{max} + l' + b_{max} \tag{22}$$

Based on Table 1, the depth of the curved cavity D is 16 mm.

The expression for the width K of the curved cavity bottom is as follows:

$$K > a_{\max} + \frac{b_{\max}}{\tan\theta_1} + \frac{b_{\max}}{\tan\theta_2} \tag{23}$$

When both the inner and outer angles are taken as the minimum value, the width range of curved cavity bottom is K > 14.31 mm, and it is set to 16 mm.

There exists the following geometric relationship between the cavity inner angle θ_2 and the depth of cavity D, the width of curved cavity bottom K, the width of seed-inlet B, cavity outer angle, as shown in Fig. 3(e). After other parameters are determined, the cavity inner angle θ_2 can be determined.

$$\theta_2 = \arctan\left(\frac{\sqrt{D^2 + \dfrac{D^2}{\cot^2\alpha}}}{K - B - \left(\dfrac{D}{\tan\theta_1}\right)}\right) \tag{24}$$

The equation of the transfusion curve cavities

When multiple cavities are involved in the seeding operation at the same time, the rice seeds in each cavity need to quickly gather at the seed outlet in the seed carrying link (*Kulaev et al., 2020; Laryushin et al., 2021*). Therefore, the trajectory of the transfusion cavities is designed as a brachistochrone curve in order to achieve the precision seeding of rice seeds, as shown in Fig. 3(a).

The curve equation is as follows:

$$\begin{cases} x_i = e_i t - e_i sin(t) - \pi e_i + f \\ y_j = -e_i cos(t) - g_i \end{cases} \tag{25}$$

where: *i* =1, 2, 3, 1 represents the outermost cavity of the discharge plate, e_1 is 12.88, 2 represents the middle cavity, e_2 is 10.30, 3 represents the innermost cavity, e_3 is 7.92, f, g_i respectively are the horizontal and vertical deviation distance between the starting point of the brachistochrone curve and the center of the discharge plate. Based on the principle of distributing the combined cavities as much as possible on the discharge plate, comprehensively referring to the diameter of the discharge plate and the length of the rice seeds, set f as 7mm, g_1 as 112.88mm, g_2 as 92.88 mm, g_3 as 71.88 mm.

RESULTS AND ANALYSIS

The performance testing of the seeding system on the test stand

The experimental apparatus and materials

The experimental apparatus for performance testing of the seeding system on the test bench is shown in Fig. 7.

The seed-metering device is driven by a three-phase asynchronous motor. A high-speed video camera (i-Speed 3, Olympus) is used to record the number of rice seeds discharged per hole during the seeding performance testing. The camera has a capture rate of 240 (f/s) and a resolution of 1280×1024 pixels.

The testing rice seeds include Wan Dao 153, Hybrid Rice II You 346, and Conventional Rice Te Sanai. Before the experiment, all rice seeds were under soaking and germination treatment to break the seed dormancy (*Hensh et al., 2022*). They were then placed in a cool and well-ventilated area to air-dry until the population became loose and free of clumps. This ensured the optimal conditions for mechanical direct seeding.

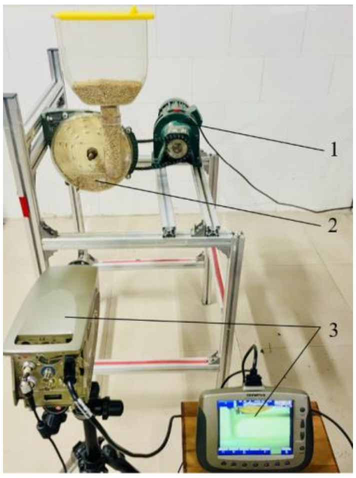

Fig. 7 - The diagram of seeding performance testing bench

1. The three-phase asynchronous motor; 2. The discharge plate; 3. The high-speed video camera;

The experimental method

According to the reference national standard GB-T25418-2022 (Rice direct seeder), the number of grains from 250 rice seed holes is continuously counted during stable seeding of the seed dispenser in each experimental group. For a set of experimental groups, the experiment is repeated three times, and the average value is obtained. The experimental evaluation indicators is given by calculation formula (26).

$$\begin{cases} M_j = \dfrac{n_{M_j}}{N} \times 100\% \\ Q_j = \dfrac{n_{Q_j}}{N} \times 100\% \\ R_j = \dfrac{n_{R_j}}{N} \times 100\% \\ P = \dfrac{m_P}{M_n} \times 100\% \end{cases} \tag{26}$$

In the formula, M represents the miss-seeding rate, (%); Q represents the qualified rate, (%); R represents the replay rate, (%); and N represents the total number of seed holes in a set of experimental groups. And, j=1, 2, and 3 respectively represent the number of openings of the seed-inlet for the discharge plate of each curved cavities set. When only one seed-inlet works, j=1, in this case, n_{M1} is the total number of holes which dropped out less than 1 seed, n_{Q1} is the total number of holes which dropped 1-3 seeds, and n_{R1} is the total number of holes which dropped out more than 3 seeds. When there are two seed-inlets opening on the outer side of the discharge plate, j=2, at this time, n_{M2} is the total number of holes which dropped out less than 2 seeds, n_{Q2} is the total number of holes which dropped 2-5 seeds, and n_{R2} is the total number of holes which dropped out more than 5 seeds. When all three seed-inlets opening simultaneously, j=3, at this time, n_{M3} is the total number of holes which dropped out less than 5 seeds, n_{Q3} is the total number of holes which dropped 5-10 seeds, n_{R3} is the total number of holes which dropped out more than 10 seeds. P represents the seed breakage rate in percentage (%). M_n represents the weight of seeds discharged during stable seeding for 1 minute, (kg). m_P represents the weight of damaged seeds among the discharged seeds, (kg). During the experiment, the speed of the discharge is set according to formula (27) (*Zha et al., 2020*).

$$n = \frac{60 v_d}{ks(1-q)} \tag{27}$$

where: v_d is the advance speed of the direct seeding machine, m/s, and 0.75 m/s is taken according to the general advance speed of the paddy field direct seeding machine;

k represents the number of curved cavities in the discharge plate, and in this case, the discharge plate has 11 groups.

s is seeding hole distance, mm,

q is the slip coefficient (Here, choose as 0.05).

Due to the difference in suitable seeding hole distance between super hybrid rice, hybrid rice and conventional rice, the distance is 180 mm, 150 mm and 140 mm respectively (*Zhang et al., 2020*). Therefore, the corresponding seeding speeds are 23.9 r/min, 28.7 r/min, and 30.8 r/min

The experimental design

Based on the previous theoretical analysis, the main parameters of metering hole structure which affect the performance of seeding device are the seed-inlet width B, the metering hole slope angle α, and curved cavity outer angle θ_1. To clarify the impact of the above structural parameters on seeding performance, a single-factor experiment will be conducted using Super Hybrid Rice Wan Dao 153 as the test crop, and the miss-seeding rate, qualified rate, and replay rate as the evaluation indicators. Test experimental factors and level setting refer to the results of the previous theoretical analysis, as shown in Table 2.

Table 2

Single factor test factors and levels

Test number No.	Factors		
	Seed-inlet width /mm	Metering hole slope angle /%	Curved cavity outer angle /%
1	3.6	30	55.0
2	3.8	32	62.5
3	4.0	34	70.0
4	4.2	36	77.5
5	4.4	38	85.0
6	-	-	92.5

In order to determine the optimal combination of metering hole structure parameters, a full-factor test refer to the single factor test results, with the miss-seeding rate, qualified rate, and replay rate as the evaluation indicators. The test level was set as shown in Table 3.

Table 3

Factors and levels in experiments

Test number No.	Factors	
	Seed-inlet width / mm	**Metering hole slope angle / °**
1	3.6	32
2	3.8	34
3	4.0	36

Based on the results of the single-factor and full-factor experiments, as well as the relationship between the results of seeding performance test of three types of rice—super hybrid rice, hybrid rice, and conventional rice—a variety compatibility experiment is performed by seeding different rice varieties with different numbers of seed-inlets on the discharge plate to ascertain the appropriate hole size for seeding super hybrid rice and conventional rice.

The experimental results and analysis

The effect of seed-inlet width on seeding performance

During the single factor test of seed-inlet width, the metering hole slope angle α and the cavity outer angle θ_1 were respectively maintained at 34° and 77.5°, the experimental results are as shown in Fig. 8.

According to Fig. 8, it can be observed that as the seed-inlet width increases, the miss-seeding rate of the seed-metering device decreases significantly at first and then gradually decreases, the replay rate increases slowly at first and then rapidly increases, and the qualified rate initially increases and then decreases. When the seed-inlet width is relatively small, it becomes difficult for the seeds to filling into the seed-inlet, resulting in a higher miss-seeding rate and a lower replay rate. As the seed-inlet width increases, the rice seed can fill into the seed-inlet smoothly, resulting in a significant decrease in miss-seeding rate, a slight increase in replay rate, and an overall increase in the qualified rate. When the seed-inlet width is too large, an excessive quantity of rice seeds is filled into the seed-inlet, resulting in a significant increase in replay rate and a gradual decrease in miss-seeding rate. As a result of the increased replay rate, the overall qualified rate decreases noticeably. It can be observed that the suitable seed-inlet width for the discharge plate should be in the range of 3.6-4.0 mm. At this range, the seed-metering device achieves a qualified rate of 85% or higher.

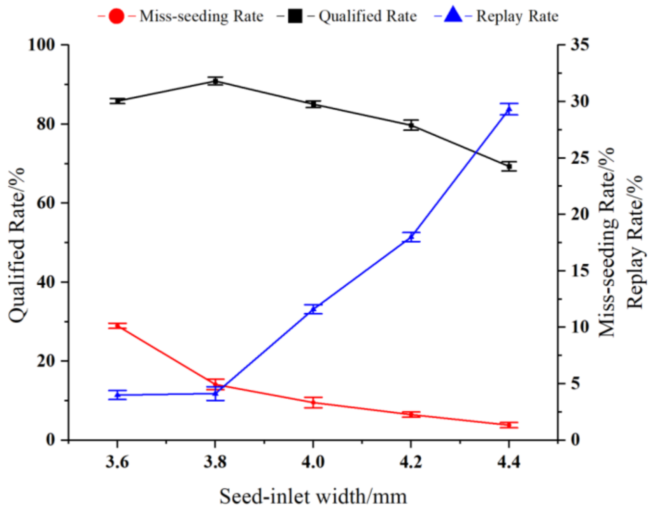

Fig. 8 - Test results of seed-inlet width

The effect of metering hole slope angle on seeding performance

In the single-factor experiment of the metering hole slope angle, the seed-inlet width *B* and the curved cavity outer angle θ_1 were respectively maintained at 3.8 mm and 77.5°. The experimental results as shown in Fig. 9.

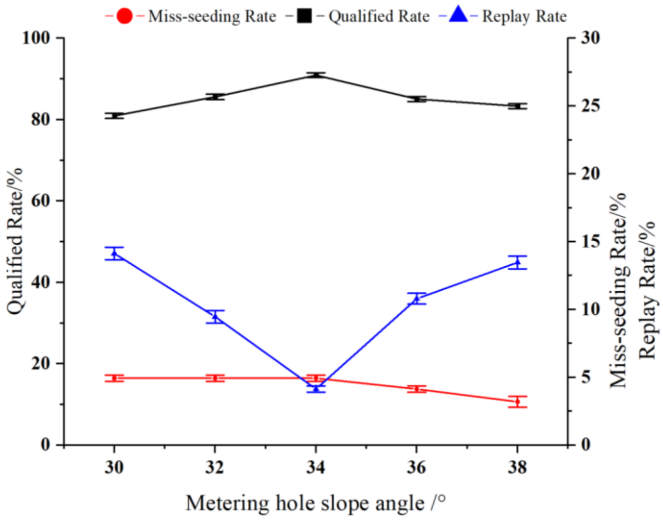

Fig. 9 - Test results of metering hole slope angle

From Fig. 9, it can be observed that as the metering hole slope angle increases, the miss-seeding rate of the seed-metering device decreases slowly, the replay rate decreases significantly at first and then increases significantly, and the qualified rate first increases and then decreases. When the metering hole slope angle is smaller, the height of seed-limiting plate is lower. As the angle increases, the height of seed-limiting plate increases, which lead to the metering hole inclined plane gradually becomes steeper. When the metering hole slope angle is small, the metering hole inclined plane is gentle, and the height of seed-limiting plate has a lesser impact on seeding performance. However, as the metering hole slope angle increases, the height of seed-limiting plate also increases, resulting in a phenomenon where the miss-seeding rate remains basically unchanged while the replay rate decreases significantly. In the later stage, when the metering hole inclined plane is steeper, the height of seed-limiting plate has a significant impact on the seeding performance. As the metering hole slope angle increases, the height of seed-limiting plate also increases. In this case, it is difficult for the seed-metering device to clear the superfluous seeds, resulting in a decrease in miss-seeding rate and an increase in replay rate.

The effect of cavity outer angle on seeding performance

In the single-factor experiment of the cavity outer angle, the seed-inlet width *B* and the metering hole slope angle α were respectively maintained at 3.8 mm and 34°. The experimental results as shown in Fig.10.

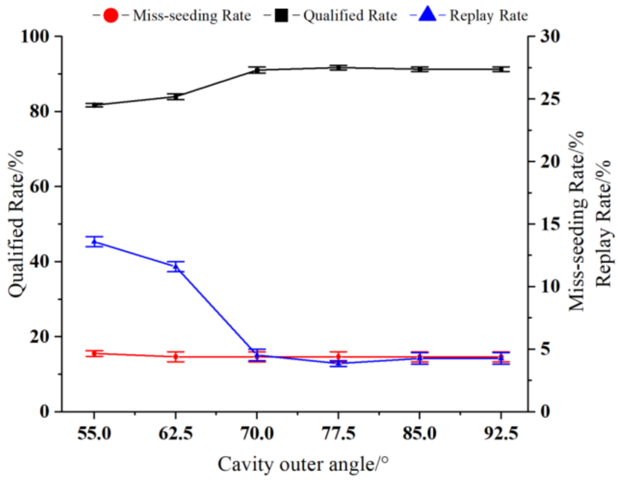

Fig. 10 – Test results of cavity outer angle

According to Fig. 10, it can be observed that as the cavity outer angle increases, the miss-seeding rate remains basically unchanged, while the qualified rate initially increases and then stabilizes. On the other hand, the replay rate initially decreases and then stabilizes. When the cavity outer angle is smaller, the cavity outer plane is steeper, making it easier for the rice seed to enter the seed-inlet. Additionally, it can accommodate more rice seeds and is not easily cleared out. This results in a higher replay rate. As the cavity outer angle increases, the cavity outer plane becomes flatter, which improves the phenomenon of overfilling with rice seed. And, the superfluous seeds are easily cleared out from the seed-inlet. As a result, the replay rate significantly decreases, and the qualified rate increases. When the cavity outer angle increases to 70° or above, the cavity outer plane becomes flatter. This prevents excessive accumulation of rice seeds at the cavity outer angle, it becomes easier to clear out superfluous seeds, resulting in all the evaluation indicators stabilizing and maintaining at a good level of seeding performance. The qualified rate consistently floats above 90%, and the miss-seeding rate remains below 5%.

The full factor experiment

The results of the full factor experiment are shown in Fig. 11.

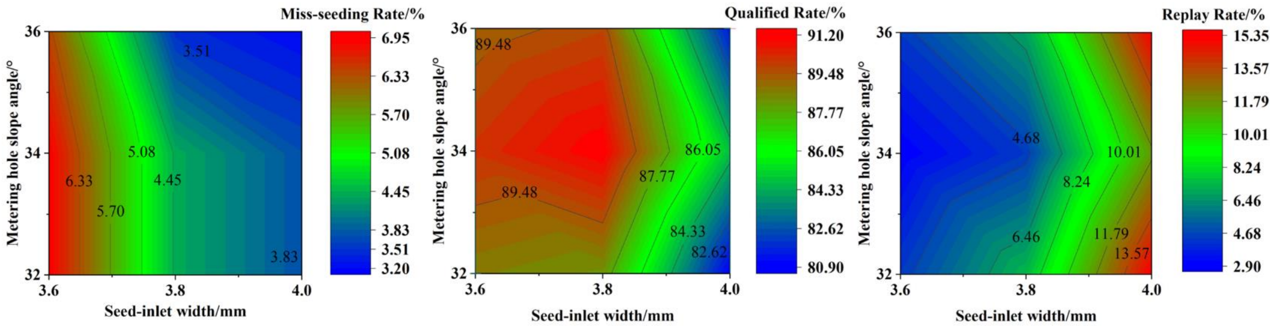

Fig. 11 - Test results of the full factor experiment

In order to analyze the impact of various experimental factors on the evaluation indicators, a two-dimensional contour plot depicting the influence of experimental factors on the evaluation indicators can be constructed based on the data of the full factor experiment. According to Fig. 11, it can be observed that the color distribution in the plot shows distinct levels of change with the variation in the seed-inlet width. This indicates that the evaluation indicators exhibit significant variations with the changing in the seed-inlet width. Within the range of the experiment for the metering hole slope angle, it can be observed that the results of experiment for intermediate horizontal experimental factors are better than the two sides' horizontal experimental factors, with lower incidences of missing and replay rates. Therefore, it can be concluded that the seed-inlet width has a more significant impact on the seeding performance. As the seed-inlet width increases, the miss-seeding rate decreases while the replay rate increases, and the qualified rate initially remains stable, but later decreases. As the metering hole slope angle increases, the miss-seeding rate remains unchanged at first and then decreases, the replay rate initially decreases and then increases, and the qualified rate initially increases and then decreases. The results of the full factor experiment are consistent with those of the single-factor experiment.

Minitab 21 software was used for regression analysis of the test results, and regression equations (28) were established between each evaluation indicators of seeding performance and the seed-inlet width and the metering hole slope angle. The results of the analysis of variance are shown in Table 4.

$$\begin{cases} M = 1.57 - 2.095\,A + 0.0914\,B + 0.2712\,A^2 - 0.000775\,B^2 - 0.00081\,A \bullet B \\ Q = -30.30 + 7.22\,A + 0.639\,B - 0.972\,A^2 - 0.00572\,B^2 - 0.0001\,A \bullet B \\ R = 29.72 - 5.11\,A - 0.731\,B + 0.700\,A^2 + 0.00650\,B^2 + 0.00081\,A \bullet B \end{cases} \tag{28}$$

Table 4

The table of analysis of variance

	M				Q				R			
R^2	99.46%				98.27%				99.09%			
S	0.0018				0.0082				0.0075			
Source of variance	DF	SS	F	P	DF	SS	F	P	DF	SS	F	P
Model	5	0.0018	111.22	**	5	0.0115	34.13	**	5	0.0183	65.38	**
A	1	0.0002	58.82	**	1	0.0023	33.73	**	1	0.0011	20.30	**
B	1	0.0000	6.20	*	1	0.0010	14.63	*	1	0.0013	22.95	**
A*A	1	0.0002	72.44	**	1	0.0030	44.95	**	1	0.0016	27.96	**
B*B	1	0.0000	5.91	*	1	0.0011	15.57	*	1	0.0017	24.11	**
A*B	1	0.0000	0.13	0.742	1	0.0000	0.000	0.996	1	0.0000	0.010	*
Error	3	0.0000			3	0.0002			3	0.0002		
Total	8	0.0018			8	0.0117			8	0.0185		

(is significant effects, P <0.05; ** is extremely significant effects, P <0.01)*

According to Table 4, the regression models for the miss-seeding rate, qualified rate, and replay rate of the seed-metering device are all extremely significant. The correlation coefficients R^2 for each regression models respectively are 99.46%, 98.27%, and 99.09% for the miss-seeding rate, qualified rate, and replay rate, which are very close to 100%. The standard error of regression S is less than 0.01, which indicates that the equation of quadratic regression models fit very well with the actual situation. It can accurately reflect the relationship between the performance of the seed discharge and the seed-inlet width and the metering hole slope angle, and can better predict the test results.

In addition, seed-inlet width has significant effects on the miss-seeding, qualified and replay rate of seed-metering device. The metering hole slope angle has significant effects on the qualified rate and replay rate, but not on the miss-seeding rate. The reason may be that the metering hole inclined plane gradually becomes steeper and the height of seed-limiting plate is higher within the range of the parameter for the metering hole slope angle, so the seeds which filled into the metering hole is difficult to clear. Therefore, with the increase of metering hole slope angle, the miss-seeding rate does not change much, only decreases slightly. As a result, the influence of metering hole slope angle on the miss-seeding rate of seed-metering device is not significant.

In order to clarify the optimal combination of the seed-inlet width and the metering hole slope angle, a multi-objective optimization model is established based on the regression models of each evaluation indicators of seeding.

$$\begin{cases} \min M \\ \max Q \\ \min R \\ 3.6 \le A \le 4.0 \\ 32 \le B \le 36 \end{cases} \tag{29}$$

The response optimizer in Minitab 21 software was used to solve the optimization model. The optimal combination of structural parameter predicted that seed-inlet width was 3.79 mm and metering hole slope angle was 35.07°. In the predictor, the miss-seeding rate was 3.88%, the qualified rate was 90.39%, and the replay rate was 5.73%.

To verify the reliability of the optimization results, the seed-inlet width and the metering hole slope angle were respectively set to 3.80 mm and 35°. And the discharge plate was processed to carry out seeding validation experiments, the experimental results are shown in Table 5. From Table 5, it can be observed that the results of the optimization model are consistent with the results of seeding validation experiments, which indicates that the optimization results are reliable. The results indicated that the appropriate seed-inlet width is 3.80 mm and the metering hole slope angle is 35° for super hybrid rice.

Table 5

Results of validation experiment

Test number No.	Test results		
	Miss-seeding Rate/%	Qualified Rate/%	Replay Rate/%
1	4.00	90.80	5.20
2	3.60	90.80	5.60
3	4.00	90.40	5.60
Average	3.87	90.67	5.46

The hybrid rice seeding experiment

Based on the appropriate structure parameters of metering hole for super hybrid rice and the required hole-seeding quantity what have multiplied relationship between super hybrid rice and hybrid rice, the hole-seeding quantity of hybrid rice is approximately double that of super hybrid rice. Therefore, the structure of metering hole for seed-inlet width of 3.8 mm and metering hole slope angle of 35° were adopted. Two rows of inlets were opened on the outer circumference of the discharge plate to conduct hybrid rice seeding experiments, repeated three times, with the experimental results shown in Table 6.

Table 6

Results of seeding experiment of hybrid rice

Test number No.	Test results		
	Miss-seeding Rate / %	**Qualified Rate / %**	**Replay Rate / %**
1	3.60	91.20	5.20
2	3.60	90.40	6.00
3	4.00	90.80	5.20
Average	3.73	90.80	5.47

As shown in Table 6, when the dimensions of the two rows of metering holes on the outer circumference of the discharge plate are the same (seed-inlet width of 3.8 mm and metering hole slope angle of 35°), the results of the experiments was miss-seeding rate of 3.73%, qualified rate of 90.80%, and replay rate of 5.47%. This meets the agronomic requirements for precise hole-seeding of hybrid rice.

The conventional rice seeding experiment

Based on the two-factor full factorial experiment results of the seed-inlet width and the metering hole slope angle, there was a significant impact of the seed-inlet width on the miss-seeding rate, qualified rate, and replay rate, while the metering hole slope angle had no significant impact on the miss-seeding rate. Based on the principle of "prefer to be replay rather than missing" in direct seeding of rice, where the metering hole slope angle can be maintained, the quantity of seeding can be adjusted only by changing the seed-inlet width. Strive for a higher qualified rate while maintaining a low miss-seeding rate. Based on the experimental results of hybrid rice and the relationship between the required hole-seeding quantity conventional rice and hybrid rice, it is observed that the required hole-seeding quantity for conventional rice is approximately twice that of hybrid rice. To meet the planting requirements of 5-10 seeds per hole for conventional rice, three seed-inlet must be opened of the combined cavity. In addition, the outer two circles of the seed-inlet should maintain suitable dimensions for hybrid rice seeding. This means that the seed-inlet width is 3.8 mm and the metering hole slope angle is 35°. An experiment for the innermost seed-inlet width can be conducted. Due to the stacking shape of the rice seeds inside the seed-metering device, the filling area of the inner-side inlet is smaller than the two outer-side inlets. This leads to a difference in the optimal seeding width between the outer-side inlets and the inner-side inlet when using the same structural parameters. Based on the reference dimensions for suitable seed-inlet width for super hybrid rice and hybrid rice, three different levels can be set for the innermost seed-inlet width: 5.2 mm, 5.4 mm and 5.6 mm. The experimental results are shown in Fig. 12.

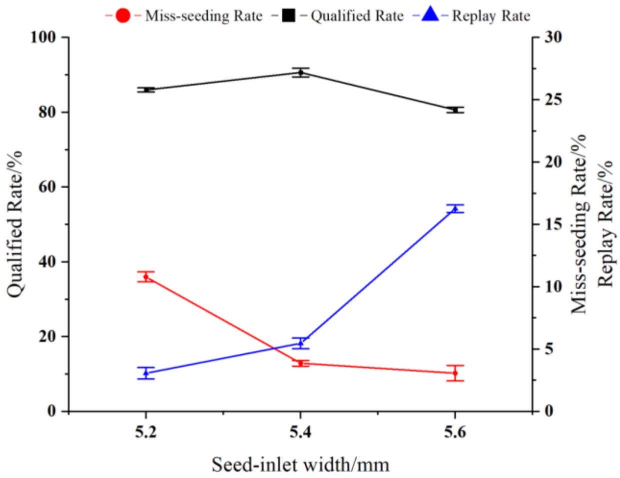

Fig. 12 – Test results of the conventional rice seeding experiment

According to Fig. 12, it can be observed that as the innermost seed-inlet width for the discharge plate increases, the miss-seeding rate decreases significantly at first and then decreases slightly. Meanwhile, the replay rate increases slightly at first and then increases significantly. The qualified rate initially increases and then decreases. These patterns of change are consistent with the results of the single-factor experiment on seed-inlet width. Based on the analysis, it can be concluded that when the innermost seed-inlet width for the discharge plate is set to 5.4 mm, the seeding performance is optimal.

At this width, the miss-seeding rate is 3.53%, the qualified rate is 90.67%, and the replay rate is 5.80%. It can meet the required hole-seeding quantity of conventional rice precision hole. If the seed-inlet width is too small, the miss-seeding rate will increase sharply. If it is too large, the replay rate will increase sharply, and the miss-seeding rate does not change much. Therefore, the optimal for the innermost seed-inlet width of conventional rice planting is determined to be 5.4 mm.

The seed breakage rate experiment

According to the reference national standard GB-T25418-2022 (Rice direct seeder), experiments were conducted with suitable seed-metering device apparatus structural parameters for three types of rice. The experiments focused on the seed breakage rate during rice seeding, and were repeated 5 times. The results of the experiments are shown in Table 7.

Table 7

Results of seed breakage rate

Test number No.	Test results of seed breakage rate		
	Wan Dao 153/%	Ⅱ You 346/%	Te Sanai /%
1	0.20	0.14	0.32
2	0.20	0.24	0.49
3	0.17	0.34	0.47
4	0.18	0.28	0.38
5	0.20	0.22	0.44
Average	0.19	0.24	0.42

From Table 7, it can be observed that the seed breakage rates for all three types of rice which are used by the seed-metering device are less than 0.5%. These are all below the standard requirement of 0.8% for seed breakage rate. This indicates that the design of the seed-metering device is reasonable and meets the planting agronomic requirements for precise hole-seeding.

The field validation test

In order to test the field seeding performance of the combined cavity-type rice precision hole-drop seed-metering device, a field seeding experiment was carried out in June 2023.

Before experiment, a rotary tiller was used to plough the experimental field, then irrigate and bubble the field, ensuring a smooth surface without crop residues and weeds. Taking filed experiment after the field was allowed to static precipitation for 2 days, and there was no standing water on the surface.

Install the seed-metering device on the rice direct seeding machine. The seed-metering device is driven by the ride-on chassis of the direct seeding machine. Adjust the discharge plate to the required state for seeding the rice seeds. The seeding operation is shown in Fig. 13.

Fig. 13 - The diagram of the seed-metering device works

During the experiment, the speed of the direct seeding machine was kept stable at 0.75 m/s, and the discharge plate speed was adjusted to match the required speed for the rice seeds. Every 250 holes were regarded as a group, the number of hole seeding, the hole diameter, and the hole distance were counted. Each variety was repeated three times for experimentation and the average values were obtained. The experimental results are shown in Table 8.

Table 8

Results of field validation test

Species	Test results of field validation test				
	Miss-seeding Rate %	Qualified Rate %	Replay Rate %	Hole diameter mm	Hole distance mm
Wan Dao 153	2.67	86.33	11.00	19.82	175.77
Ⅱ You 346	2.53	86.34	11.13	25.43	146.87
Te Sanai	2.33	90.33	7.34	33.3	140.91

As shown in Table 8, for seeding super rice Wan Dao 153 using outermost seed-inlets, the miss-seeding rate is 2.67%, the qualified rate (1-3 grains per hole) is 86.33%, average hole diameter is 19.82 mm, average hole distance is 175.77 mm, the requirement of hole distance is 180 mm. For seeding hybrid rice II You 346 using outer two seed-inlets, the miss-seeding rate is 2.53%, the qualified rate (2-5 grains per hole) is 86.34%, average hole diameter is 25.43 mm, average hole distance is 146.87 mm, the requirement of hole distance is 150 mm. For seeding conventional rice Te Sanai using all three seed-inlets, the miss-seeding rate is 2.33%, the qualified rate (5-10 grains per hole) is 90.33%, average hole diameter is 33.31 mm, average hole distance is 140.91 mm, the requirement of hole distance is 140 mm. The seeding requirements are met for the three varieties of rice seeds. Compared with bench test, field test had lower miss-seeding rate, higher replay rate and slightly lower qualified rate. The reason is that in the field test, due to the vibration of the machine, the number of seeds filling into the seed-metering device increases, resulting in a higher replay rate and a lower miss-seeding rate.

CONCLUSIONS

(1) In order to meet the different seeding requirement quantity of super rice, hybrid rice, and conventional rice, a seeding quantities selectable combined cavity-type precision hole-drop seed-metering device was designed which used an innovative combined seeding method. By adjusting the number of metering holes involved in seeding, it could realize the adjustment of the seeding quantity. This design shows promising practical prospect.

(2) Single factor and full factor bench seeding tests were carried out on the structural parameters of the seed-inlet width, the metering hole slope angle, and cavity outer angle, which affected the seeding performance of the seed-metering device. Under the appropriate structural parameters, that is, when the width of outer and middle seed-inlets is 3.8 mm, the innermost seed-inlet width is 5.4 mm, the metering hole slope angle is 35°, the cavity outer angle is 85°, the precision filling function can adapt to different seeding quantity of different varieties of rice, and has been verified by bench and field seeding tests.

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