PARAMETER OPTIMIZATION AND EXPERIMENT OF SLIDER-HOLE-WHEEL SEED-METERING DEVICE BASED ON DISCRETE ELEMENT METHOD
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基于离散元法的滑片型孔轮式排种器参数优化与试验

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ABSTRACT
To improve the adaptability and precision of the slider-hole-wheel seed-metering device to meet the requirements of precision sowing, the single factor simulation experiments and the three factors three levels of orthogonal simulation experiments were carried out based on the discrete element method. The rotation speed of the seeding shaft, the shape of the hole, and the depth of the hole were set as experiment factors. The results of simulation experiments showed that the qualified rate was the highest when the rotation speed of the seeding shaft was 30 r/min, the shape of the hole was oval, and the depth of the hole was 9 mm. The qualified rate, replay rate, and miss-seeding rate were 89.09%, 3.64%, and 7.27%，respectively. The hybrid rice seeds of Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 were chosen as the materials for the bench and field seeding performance tests to verify the reliability of the simulation results. The test results showed that the qualified rate of Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 seed in bench tests were 85.07%, 85.20%, and 82.13%, and the qualified rate of Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 seed in field tests were 82.13%, 82.27%, and 80.53%. The seeding performance with the three kinds of rice seeds could meet the agronomic requirements for precision sowing of hybrid rice. The paper provided the basis for the structure optimization and seeding performance improvement of the slider-hole-wheel seed-metering device.

摘要
为了提高滑片型孔轮式排种器的适应性和排种精度，满足水稻精量穴播要求，采用离散元法，以排种轴转速、型孔形状、型孔深度为试验因素，开展了单因素仿真试验和 3 因素 3 水平正交仿真试验。仿真结果表明，在排种轴转速为 30 r/min、型孔形状为椭圆形、型孔深度为 9 mm 时，排种合格率最高，合格率、重播率、漏播率分别为 89.09%、3.64%、7.27%。为了验证仿真结果的可靠性，以中农 2008、创两优 4418 和冈优 898 为试验材料，进行了排种器台架性能试验和田间播种试验。试验结果表明，中农 2008、创两优 4418、冈优 898 种子台架试验排种合格率分别为 85.07%、85.20%、82.13%，中农 2008、创两优 4418、冈优 898 种子田间试验播种合格率分别为 82.13%、82.27%、80.53%，3 种水稻种子的排种性能均能满足杂交水稻精量播种的农艺要求。该研究为滑片型孔轮式排种器结构优化及排种性能提升提供了依据。

INTRODUCTION
Rice precision hill-direct-seeding is a light and simple planting technology with saving costs and improving efficiency (*Zhang et al.*, *2018*). In recent years, rice precision hill-direct-seeding has become a development trend (*Xing et al*., *2018*; *Tian et al*., *2021*). The seed-metering device is the core working part of the hole direct broadcast machine, and its performance directly determines the seeding quality *(Jia et al., 2018; Ye et al., 2021; Chen et al., 2021).*

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The discrete element method is used as a new numerical method to deal with discontinuous media problems which are developing these years, and is used in many fields *(Ketterhagen, 2011; Liu et al., 2020; Xu et al., 2021*). The EDEM software can be used to simulate the seed-metering device process, which can conveniently and accurately test the seeding performance, determine its structural parameters and working parameters, and reduce the number of bench tests and field tests (*Xue et al., 2019; Wang et al., 2021*). EDEM software was used to analyze the filling process of the cell-belt rice precision seed-metering based on friction, and obtain influence rules of the filling performance with cell-belt velocity, cell-belt inclined angle, and seed layer thickness (*Liu et al.*, *2019*).

EDEM software was used to simulate and optimize the structure parameters and working parameters of the spoon taking seed and the piston pricking hole for the seed-metering device (*Zhou et al., 2018*). EDEM software was used to simulate and analyze four kinds of the groove wheel seeding devices, and obtained the optimal structural parameters of the devices (*Xu et al., 2018*).

EDEM software was used to simulate the seed-metering device seeding process of three kinds of sphericity rice seeds at six seeding wheel speeds, and the seeding performance change law of rice seeds at different seeding wheel speeds was obtained (*Zhu et al., 2018)*. These application studies have achieved satisfactory research results on the optimization of the seed-metering device working parameters and the improvement of the seeding performance. However, the above studies simply consider the effects of working parameters on the seeding performance of the seed-metering device and have not comprehensively optimized structural parameters and working parameters of the seed-metering device.

Therefore, according to the agronomic requirements of precision hill-direct-seeding of hybrid rice, EDEM software was used to simulate the seeding performance of the self-developed slider-hole-wheel seed-metering device and comprehensively optimize the structure and working parameters of the seed-metering device. Chuangliangyou 4418 rice seeds with moderate seed sphericity were selected as material, the rotation speed of the seeding shaft, the shape of the hole, and the depth of the hole were used as test factors, and the qualified rate, the replay rate, and the miss-seeding rate were taken as evaluated indicators. The single factor simulation tests and three factors three levels of orthogonal simulation tests were performed to determine the optimal parameter combination for seeding performance. Finally, the reliability of simulation results was verified by bench tests and field tests based on the test materials of Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 rice seeds.

MATERIALS AND METHODS

Structure and working principle

The slider-hole-wheel seed-metering device is composed of a seeding wheel, eight slip sheets, a cleaning brush, a cleaning shaft, a shield shell, two convex blocks, a seed limiting plate, a seed pipe, a seeding shaft, and two flanges, as shown in Fig. 1. During the operation, rice seeds are filled into the seed chamber composed of the seed-metering device shell and seed limiting plate. The seeds in the seeding chamber flow into the filling area under the action of gravity, and the inclined structure at the bottom of the seeding chamber ensures that the seeds continuously flow into the filling area. In the filling area, the seeding wheel and slip sheets embedded in the seeding wheel are driven by the seeding shaft which made a circular movement with the seeding shaft, and rice seeds are filled into the hole of the seeding wheel.

The seeds in the hole are taken into the seed cleaning area by the seeding wheel, and the excess seeds outside the hole will be removed by the cleaning brush, and the cleared seeds will go in the filling area for secondary seeding. The seeds in the hole are entered in the seed protection area with the seeding wheel.

When the slip sheet is rotated with the seeding wheel to end point A of the cleaning brush working area, it touches the bump on the inner side of the right flange, and the slip sheet is pushed to the other side to cover the hole, so as to ensure that the seeds will not fall out of the hole at the seed protection stage, which plays the role of seed protection. As the slide sheet rotates with the seeding wheel to point B, the slide sheet is pushed to its original position by the convex block on the inner side of the left flange, which fits into the hole. At this time, the seeds enter the dropping area, and the seeds fall from the seed pipe into the seed groove by gravity and centrifugal force to complete the precision sowing (*Zhu et al*., *2018*). The schematic diagram of the seeding process is shown in Fig. 2.

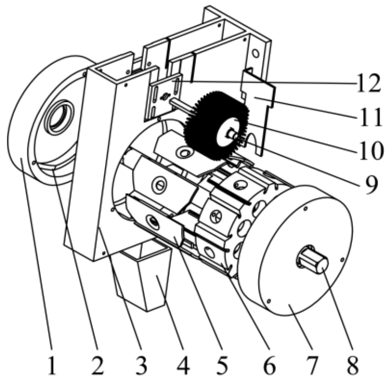

Fig. 1 - Structural diagram of the seed-metering device

1) Left flange; 2) Convex block; 3) Shield shell; 4) Seed pipe; 5) Slip sheet; 6) Seeding wheel; 7) Right flange; 8) Seeding shaft; 9) Cleaning shaft; 10) Cleaning brush; 11) Seed limiting plate; 12) Fixed plate

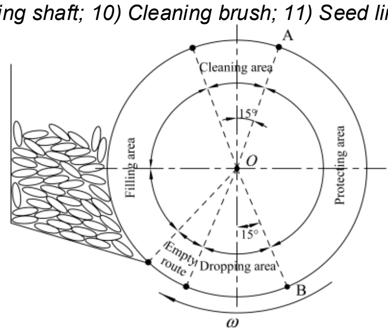

Fig. 2 - Structural diagram of seeding process

Test method

The EDEM software was used to analyze the factors affecting the seeding performance of the seed-metering device. Chuangliangyou 4418 rice seeds were taken as material, the rotation speed of the seeding shaft, the shape of the hole, and the depth of the hole were taken as test factors, and the qualified rate, the replay rate, and the miss-seeding rate were taken as evaluation indexes. The single factor simulation tests and three factors three levels of orthogonal simulation tests were carried out to determine the optimal parameter combination for seeding performance. Taking Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 rice seeds as experimental materials, the reliability of the simulation results were verified by bench tests and field tests.

Tests evaluation index

According to the agronomic requirements of precision hill-direct-seeding of hybrid rice, and referring to the standard of testing methods of single seed drills, the qualified rate Y_1, replay rate Y_2, miss-seeding rate Y_3, injury rate I, and variation coefficient of hill spacing V were selected as the test indicators (*Shi et al.*, *2014*), and these indicators can be calculated as follows:

1) When the number of seeds per hole is 2 to 4, it is qualified, then the qualified rate Y_1 is

$$Y_1 = \frac{n_1}{N} \times 100\% \tag{1}$$

2) When the number of seeds per hole is greater than (or equal to) 5, it is replay, then the replay rate Y_2 is

$$Y_2 = \frac{n_2}{N} \times 100\% \tag{2}$$

3) When the number of seeds per hole is less than (or equal to) 1, it is miss-seeding, then the miss-seeding rate Y_3 is

$$Y_3 = \frac{n_3}{N} \times 100\% \tag{3}$$

4) When the seed is broken, it is the seed injury, then the seed injury rate I is:

$$I = \frac{n_4}{N} \times 100\% \tag{4}$$

5) The variation coefficient of hill spacing V can be calculated from the acupoint distance and standard deviation, and the calculation formula is:

$$\bar{x} = \frac{\sum x_i}{N} \tag{5}$$

$$S = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N-1}} \tag{6}$$

$$V = \frac{S}{\bar{x}} \times 100\% \tag{7}$$

Where:

N is the number of theoretical seeds; n_1 is the number of qualified seeds; n_2 is the number of replay seeds; n_3 is the number of miss-seeding seeds; n_4 is the number of broken seeds; $\bar{x}$ is the average hill spacing, [mm]; S is the standard deviation, [mm].

Simulation tests

In EDEM software, the particle-particle and particle-geometric boundary contact models were all non-sliding contact models (*Khatchatourian et al.*, *2014*). The slip sheets were set to rotation and translation. The seeding wheel and the cleaning brush were rotated, the rotation speed of the cleaning brush was three times the rotation speed of the seeding wheel. The direction of gravity acceleration was set to the negative direction of the Y-axis, and the value was 9.80 m/s^2. According to the function and processing requirements of the seed-metering device, all parts of the seed-metering device were set as stainless steel, except for the cleaning brush of plastic.

The physical parameters of rice seeds, cleaning brush, and stainless steel, which include shear modulus, density, and Poisson's ratio were setting as shown in Table 1.

The physical mutual contact mechanical parameters setting of each component material are shown in Table 2 (*Wen*, *2018*).

Table 1

Physical parameters

Material	Shear modulus (Pa)	Density (kg·m^{-3})	Poisson's ratio
Rice seeds	1.8×10^8	1200	0.30
Cleaning brush	1.0×10^8	1500	0.40
Stainless steel	7.9×10^7	7850	0.28

Table 2

Contact mechanical parameters

Material	Coefficient recovery coefficient	Static friction coefficient	Rolling friction coefficient
Rice-rice	0.30	0.56	0.15
Rice-cleaning brush	0.45	0.50	0.20
Rice-stainless steel	0.52	0.50	0.10

The shape of the rice seeds is spindle-shaped, with narrow ends at both ends, wide and thick in the middle, and there is no cohesion between particles. This paper used Chuangliangyou 4418 rice seed (9.00 mm×2.30 mm×1.84 mm) as material. To simplify the grain model and reflect the shape of rice grains more realistically in the EDEM software, a multi-sphere combination filling method was used to establish a combination model with a shape similar to the Chuangliangyou 4418 rice seed. The model consists of a total of 24 spherical spindles with the same triaxial size as the actual triaxial size of the Chuangliangyou 4418 rice seeds, as shown in Fig. 3.

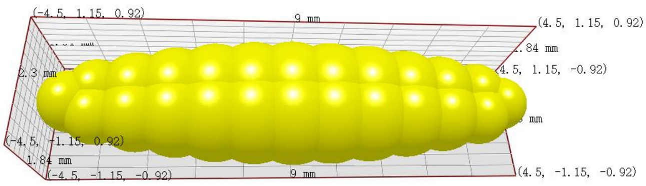

Fig. 3 - The rice model

SolidWorks software was used to build the three-dimensional model of the seed-metering device, and the model of the seed-metering device saved as IGES format was imported into EDEM software. To ensure continuous filling seeds, a certain amount of seeds should be stored in the seed filling room. The total number of particles generated by the particle factory was set to 4000, the time for particles to generate was 1 s, and the seeding wheel starts to move at 1.5 s. The total simulation time was set to 30 s (*Liu et al., 2021*), as shown in Fig. 4.

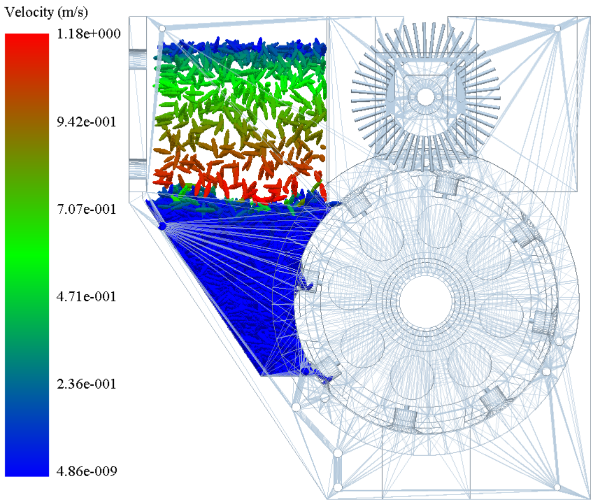

Fig. 4 - The seed-metering device simulation process in EDEM

(1) Single factor simulation tests

a) Effect of the rotation speed of the seeding shaft on seeding performance

When the shape of the hole was set as cylindrical (diameter 10 mm) and the depth of the hole was set as 8 mm, the rotation speeds of the seeding shaft were respectively set as 15 r/min, 20 r/min, 25 r/min, 30 r/min, 35 r/min, and 40 r/min for the simulation tests of the seeding performance. Through the simulation experiments of the seeding performance of the device under different rotation speeds of the seeding shaft, the qualified rate, replay rate, and miss-seeding rate of the whole number were calculated.

b) Effect of the shape of the hole on seeding performance

When the rotation speed of the seeding shaft was set as 30 r/min and the depth of the hole was set as 8 mm, the shapes of the hole were respectively set as diamond (long side diagonal 12 mm × short side diagonal 10 mm), oval (long axis 14 mm × short axis 8 mm), and cylindrical (diameter 10 mm) for the simulation tests of the seeding performance. Through the simulation experiments of the seeding performance of the device under the different shapes of the hole, the qualified rate, replay rate, and miss-seeding rate of the whole number were calculated.

c) Effect of the depth of hole on seeding performance

When the shape of the hole was set as oval and the rotation speed of the seeding shaft was set as 30r/min, the depths of the hole were respectively set as 7 mm, 8 mm, 9 mm, 10 mm, and 11 mm for the simulation tests of the seeding performance. Through the simulation experiments of the seeding performance of the device under the different depths of the hole, the qualified rate, replay rate, and miss-seeding rate of the whole number were calculated.

(2) Orthogonal simulation tests

Based on the results of the single factor simulation tests, the rotation speed of the seeding shaft, the shape of the hole, and the depth of the hole were selected as test factors. Each factor was set at 3 levels, and three factors three levels of orthogonal tests were performed. The orthogonal factors and levels table was shown in Table 3.

Table 3

Orthogonal factors and levels table

Level	*A* Rotating speed ($r \cdot min^{-1}$)	*B* Shape of the hole (mm)	*C* Depth of the hole (mm)
1	25	Diamond	8
2	30	Cylindrical	9
3	35	Oval	10

Without considering the interaction between the three factors, the L_9 (3^4) three factors three levels orthogonal table were used in these experiments. There was one empty column in the L_9 (3^4) orthogonal table, and the orthogonal tests scheme was shown in Table 4.

Table 4

Orthogonal tests scheme

Test number	Factors			
	A	***B***	**Empty column**	***C***
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Bench tests

To verify the reliability of the simulation results, bench tests of the seed-metering device on the seeding performance was conducted. The test site was in the precision seeding laboratory of Anhui Agricultural University. The test equipment was the JPS-12 type seed-metering device performance test bench which was developed by the Heilongjiang Agricultural Machinery Engineering Research Institute. The seed-metering device was fixed on the bracket, the seeding shaft was driven by the test bench chain, and the speed of the seed bed belt was adjusted according to the speed of the seeding shaft. The seeds fall into the oil belt on the seed bed belt to prevent the seeds from bouncing during the falling process, as shown in Fig. 5.

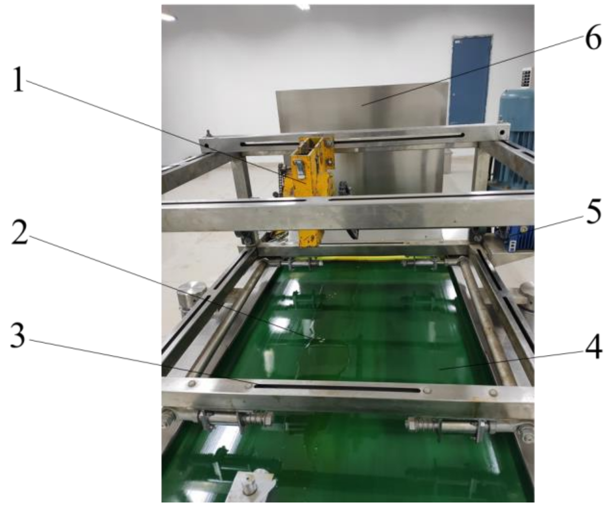

Fig. 5 - Seed-metering device bench tests

1) Seed-metering device; 2) Seeds; 3) Bracket; 4) Seedbed belt; 5) Motor; 6) Lighting device

Field tests

To test the field seeding performance of the seed-metering device, which was installed on a precision dry-seeding-sowing machines, and these field seeding tests were carried out in the agricultural field of Anhui Agricultural University, in May, 2020. Before these tests, the field soil was plowed with a rotary tiller to make it lose and level. The average plowing depth was 11.2 cm, and the average soil solidity was 390.8 kPa. These rice varieties of Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 were selected in turn for sowing tests, and these tests were conducted in accordance with national standards (*Press*, *2006*). During these tests, the forward speed of the unit was about 4.5 km/h, the rotation of the seed-metering device was driven by the direct-current motor, and the average working speed of the seed-metering device was about 30 r/min.

RESULTS AND ANALYSIS

Simulation tests

Single factor simulation tests

(1) Effect of the rotation speed of the seeding shaft on seeding performance

When the shape of the hole was cylindrical and the depth of the hole was 8 mm, the relationship curves between the rotation speeds of the seeding shaft and the evaluation indexes are shown in Fig. 6.

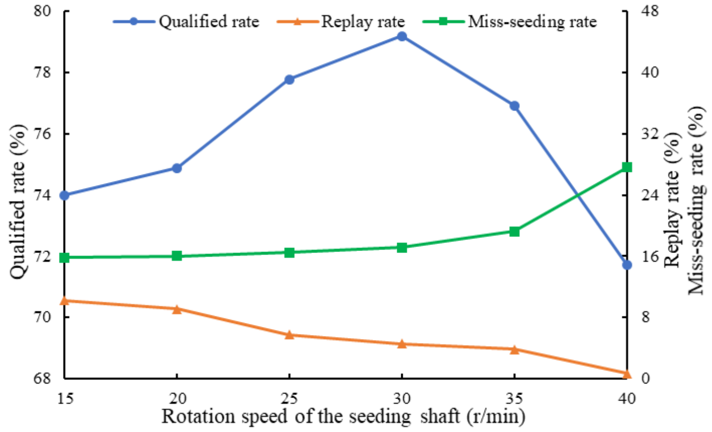

Fig. 6 - Relationship curves between rotation speeds of the seeding shaft and evaluation indexes

As shown in Fig. 6, when the rotation speed of the seeding shaft increased, the qualified rate increased first, and then decreased. The miss-seeding rate was on the rise as a whole. The replay rate generally decreased. In the beginning, the rotation speed of the seeding shaft was low, and the time for the hole to pass through the filling place was longer, so the seeds were easier to be filled into the hole, and the replay rate was higher. As the rotation speed of the seeding shaft increased, the time for the hole to pass through the filling place became shorter, the probability of the seeds to fill in the hole decreased, and at the same time, the centrifugal force of the rice seeds increased, and the seeds were easily detached from the hole, which resulted in missing. When the rotation speed of the seeding shaft was 30 r/min, the qualified rate of the seeding performance was the highest, and the qualified rate, replay rate, and miss-seeding rate were 79.19%, 4.54%, and 16.37%, respectively.

(2) Effect of the shape of the hole on seeding performance

When the rotation speed of the seeding shaft was 30 r/min and the depth of the hole was 8 mm, the relationship curves between the shapes of the hole and the evaluation indexes are shown in Fig. 7.

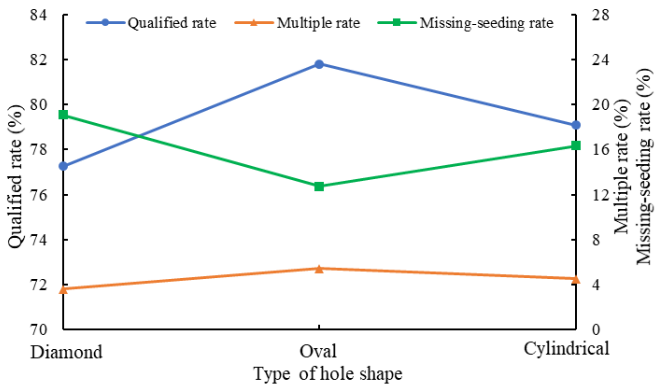

Fig. 7 - Relationship curves between shapes of the hole and evaluation indexes

As shown in Fig. 7, the qualified rate of the oval hole was the highest and the qualified rate of the diamond hole was the lowest, so the oval hole was suitable for sowing rice seeds of this size. Because the oval hole was similar to the outer contour of the rice seeds, it was easier for the rice seeds to fill the oval hole. The qualified rate of the oval hole was the highest, and the qualified rate, replay rate, and miss-seeding rate were 81.81%, 5.45%, and 12.74%, respectively.

(3) Effect of the depth of the hole on seeding performance

When the rotation speed of the seeding shaft was 30 r/min, the relationship curves between the depths of the hole and the evaluation indexes for oval hole are shown in Fig. 8.

As shown in Fig. 8, with the increase of the depth of the hole, the qualified rate increased first and then decreased, the replay rate increased in the whole curve, while the miss-seeding rate decreased in the whole curve. With the increase of the depth of the hole, the depth of the hole has better performance in the seed filling area. However, when the hole cavity was too large, the replay rate increased and the miss-seeding rate decreased. When the depth of the hole was 9 mm, the qualified rate of the seeding performance was the highest, and the qualified rate, replay rate, and miss-seeding rate were 89.09%, 3.64%, and 7.27%, respectively.

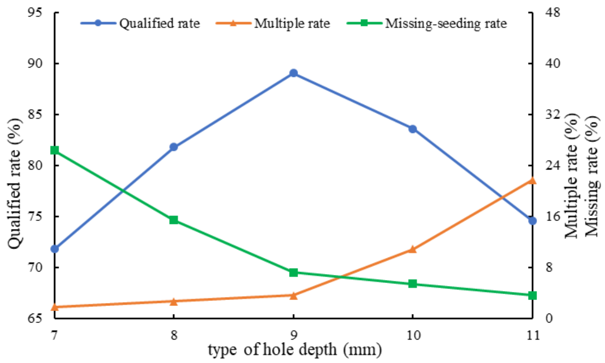

Fig. 8 - Relationship curves between depths of the hole and evaluation indexes for oval hole

Orthogonal simulation tests

The orthogonal tests scheme and results were shown in Table 5. The test results were analyzed by the range and variance analysis, as shown in Table 6 and Table 7, respectively.

Table 5

Results of orthogonal tests

Test number	Factors				Tests results		
	A	*B*	Empty column	*C*	Qualified rate (%)	Replay rate (%)	Miss-seeding rate (%)
1	1	1	1	1	74.44	5.56	20.00
2	1	2	2	2	84.44	6.67	8.89
3	1	3	3	3	83.33	8.89	7.78
4	2	1	2	3	82.72	7.27	10.01
5	2	2	3	1	79.09	4.54	16.37
6	2	3	1	2	89.09	3.64	7.27
7	3	1	3	2	82.31	3.84	13.85
8	3	2	1	3	83.08	6.92	10.00
9	3	3	2	1	77.69	3.07	19.24

Table 6

Range analysis

Index	Analysis items	*A*	*B*	Empty column	*C*
Qualified rate	k_1	80.74	79.82	82.20	77.07
	k_2	83.63	82.20	81.62	85.28
	k_3	81.03	83.37	81.58	83.04
	Range *R*	2.90	3.55	0.63	8.21
	Order	$C>B>A$			
	Optimal scheme	$C_2B_3A_2$			
Replay rate	k_1	7.04	5.56	5.37	4.39
	k_2	5.15	6.04	5.67	4.72
	k_3	4.61	5.20	5.75	7.69
	Range *R*	2.43	0.84	0.38	3.30
	Order	$C>A>B$			
	Optimal scheme	$C_1A_3B_3$			

Miss-seeding rate	k_1	12.22	14.62	12.42	18.54
	k_2	11.21	11.75	12.71	10.00
	k_3	14.36	11.43	12.67	9.26
	Range *R*	3.15	3.19	0.29	9.27
	Order	$C > B > A$			
	Optimal scheme	$C_3B_3A_2$			

From the analysis in Table 6, it can be seen that the order of factors affecting the seeding qualified rate was the depth of the hole, the shape of the hole, and the rotation speed of the seeding shaft, and the optimal scheme was $C_2B_3A_2$. The order of factors affecting the seeding replay rate was the depth of the hole, the rotation speed of the seeding shaft, and the shape of the hole, and the optimal scheme was $C_1A_3B_3$. The order of factors affecting the seeding miss-seeding rate was the depth of the hole, the shape of the hole, and the rotation speed of the seeding shaft, and the optimal scheme was $C_3B_3A_2$. From the analysis in Table 7, it can be seen that the depth of the hole had a highly significant effect on the seeding qualified rate. The rotation speed of the seeding shaft and the shape of the hole had a significant effect on the seeding qualified rate. The rotation speed of the seeding shaft and the depth of the hole had a significant effect on the seeding replay rate. The rotation speed of the seeding shaft, the shape of the hole, and the depth of the hole had a highly significant effect on the seeding miss-seeding rate. When the rotation speed of the seeding shaft was 30 r/min, the shape of the hole was oval and the depth of the hole was 9 mm, the qualified rate was the highest. The qualified rate, replay rate, and miss-seeding rate were 89.09%, 3.64%, and 7.27%, respectively.

Table 7

Variance analysis

Evaluated indicator	Variation source	Standard deviation square	Degrees of freedom	Mean square	F - Value	P - Value
Qualified rate	*A*	15.269	2	7.635	20.68	0.046*
	B	19.604	2	9.802	26.55	0.036*
	C	107.993	2	53.997	146.24	0.007**
	Error column	0.738	2	0.369		
Replay rate	*A*	9.769	2	4.884	40.29	0.024*
	B	1.075	2	0.538	4.43	0.184
	C	19.879	2	9.940	81.99	0.012*
	Error column	0.243	2	0.121		
Miss-seeding rate	*A*	15.494	2	7.747	106.50	0.009**
	B	18.498	2	9.249	127.15	0.008**
	C	159.360	2	79.680	1095.34	0.001**
	Error column	0.145	2	0.073		

Note: "" indicates significance at 0.05 level, "**" indicates the highly significance at 0.01 level.*

Bench tests

According to the results of the single factor simulation tests and the orthogonal simulation tests, the seed-metering device was installed on the experimental table, and the tests were carried out under the condition of the seeding shaft was 30 r/min and an oval hole depth was 9 mm. Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 rice seeds were selected for bench tests in turn, and the 250 consecutive holes were counted after the seed-metering device worked stably, and each group of tests was repeated three times. The average value was taken as the results of the tests, and the results were shown in Table 8.

Table 8

Results of bench tests

Varieties	Qualified rate (%)	Miss-seeding rate (%)	Replay rate (%)	Injury rate (%)	Hill spacing (mm)	Variation coefficient of hill spacing (%)
Zhongnong 2008	85.07	5.47	9.46	0.33	206.32	8.13
Chuangliangyou 4418	85.20	6.40	8.40	0.30	205.56	7.03
Gangyou 898	82.13	12.40	5.47	0.41	209.31	11.43

As shown in Table 8, under the conditions of the rotation speed of the seeding shaft was 30 r/min, the shape of the hole was oval, and the depth of the hole was 9 mm, the Chuangliangyou 4418 rice seed qualified rate was the highest of 85.20%, and the Gangyou 898 rice seed qualified rate was the lowest of 82.13%. The error between the Chuangliangyou 4418 rice seeds simulation tests and the bench tests were less than 5%, which proved that the simulation tests were reliable.

Field tests

In each group of field tests, the number of seeds and the hill spacing in 250 holes was counted continuously, and each group of tests was repeated three times. The average value was taken as the field test results. The test results are shown in Table 9.

As shown in Table 9, under the working conditions of the average speed of the seed-metering device of 30 r/ min and the forward speed of the unit of 4.5 km/h, Chuangliangyou 4418 seeds had the highest seeding qualified rate of 82.27%, and Gangyou 898 seeds had the lowest seeding qualified rate of 80.53%, and the injury rate was below 0.5%. The range of hill spacing distributes from 208 to 211 mm, and the variation coefficient of hill spacing among sowing points was lower than 16%. The slider-hole-wheel seed-metering device had good adaptability to rice seeds of different shapes, and can meet the agronomic requirements for rice precision hill-direct-seeding. However, the qualified rate of the three rice varieties was lower than that of the bench tests, mainly due to the impact of field vibration on the seed-metering device.

Table 9

Results of field tests

Varieties	Qualified rate (%)	Miss-seeding rate (%)	Replay rate (%)	Injury rate (%)	Hill spacing (mm)	Variation coefficient of hill spacing (%)
Zhongnong 2008	82.13	3.07	14.80	0.35	209.38	12.36
Chuangliangyou 4418	82.27	4.93	12.80	0.31	208.45	11.28
Gangyou 898	80.53	8.80	10.67	0.43	210.52	15.37

CONCLUSIONS

In this study, the rotation speed of the seeding shaft, the shape of the hole, and the depth of the hole were taken as experiment factors, and the qualified rate, replay rate, and miss-seeding rate were taken as the evaluation indicators. The single factor experiments and three factors three levels of orthogonal simulation experiments were carried out, and the results shows as follows. Single factor simulation tests showed that the seeding performance was the best when the rotation speed of the seeding shaft was 30 r/min, and the qualified rate was 79.19% under the conditions that the shape of the hole was cylindrical and the depth of the hole was 8 mm. The seeding performance was the best when the shape of the hole was oval, and the qualified rate was 81.81% under the conditions that the rotation speed of the seeding shaft was 30 r/min and the depth of the hole was 8 mm. The seeding performance was the best when the depth of the hole was 9 mm, and the qualified rate was 89.09% under the conditions that the rotation speed of the seeding shaft was 30 r/min and the shape of the hole was oval. Three factors and three levels of orthogonal simulation tests showed that the qualified rate was the highest under the rotation speed of seeding shaft was 30 r/min, the shape of the hole was oval and the depth of the hole was 9 mm, and the qualified rate, replay rate, and miss-seeding rate were 89.09%, 3.64%, and 7.27%, respectively. The bench tests showed that the seeding qualified rate of Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 rice seeds were 85.07%, 85.20%, and 82.13%, respectively. Field tests showed that the seeding qualified rate of Zhongnong 2008, Chuangliangyou 4418, and Gangyou 898 rice seeds were 82.13%, 82.27%, and 80.53%, respectively. The seed-metering device had good adaptability to rice seeds in different shapes and sizes and can meet the agronomic requirements of precision hill-direct-seeding in rice fields.

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REFERENCES

[1] Chen Y.L., Liu Z.E., Zhang M., et al. (2021). Research of seed group structure characteristics of vertical disc metering device based on discrete element method. *INMATEH-Agricultural Engineering*, Vol. 64, Issue 2, pp. 488-496.

[2] Jia H.L., Chen Y.L., Zhao J.L., et al. (2018). Design and key parameter optimization of an agitated soybean seed metering device with horizontal seed filling. *International Journal of Agricultural and Biological Engineering,* Vol. 11, Issue 2, pp. 76-87.

[3] Ketterhagen W. R. (2011). Modeling the motion and orientation of various pharmaceutical tablet shapes in a film coating pan using DEM. *International Journal of Pharmaceutics,* Vol. 409, Issue 1-2, pp. 137-149.

[4] Khatchatourian O. A., Binelo M. O.，de Lima R. F. (2014). Simulation of soya bean flow in mixed-flow dryers using DEM. *Biosystems Engineering,* Vol. 123, pp. 68-76.

[5] Liu C.L., Wang Y.L., Du X., et al. (2019). Filling performance analysis and verification of cell-belt rice precision seed-metering based on friction and repeated filling principle. *Transactions of the Chinese Society of Agricultural Engineering,* Vol. 35, Issue 4, pp. 29-36.

[6] Liu F., Li D.P., Zhang T., et al. (2020). Analysis and calibration of quinoa grain parameters used in a discrete element method based on the repose angle of the particle heap. *INMATEH-Agricultural Engineering,* Vol. 61, Issue 2, pp. 77-86.

[7] Liu J., Zhu D.Q., Tai, Q.L., et al. (2021). Design and experiment of adjustable socket-wheel precision fertilizer apparatus for dry direct-seeding rice. *INMATEH-Agricultural Engineering,* Vol. 63, Issue 1, pp. 121-130.

[8] Operating quality of film-covering hill-drop drill. (2006) In GB/T 25418-2010.

[9] Shi L.R., Wu J.M., Sun W., et al. (2014). Simulation test for metering process of horizontal disc precision metering device based on discrete element method. *Transactions of the Chinese Society of Agricultural Engineering,* Vol. 30, Issue 8, pp. 40-48.

[10] Tian L.Q., Xiong Y.S., Ding Z., et al. (2021). Design and performance test of direct seed metering device for rice hill. *INMATEH-Agricultural Engineering,* Vol. 64, Issue 2, pp. 257-268.

[11] Wen S. Design and experimental study of rice precision hill direct seed metering device. Master thesis of Anhui Agricultural University. 2018.

[12] Wang Y.B., Li H.W., Wang Q.J., et al. (2021). Experiment and parameters optimization of seed distributor of mechanical wheat shooting seed-metering device. *INMATEH-Agricultural Engineering,* Vol. 63, Issue 1, pp. 29-40.

[13] Xu B., Zhang Y.Q., Cui Q.L., et al. (2021). Construction of a discrete element model of buckwheat grain and calibration of parameters. *INMATEH-Agricultural Engineering,* Vol. 64, Issue 2, pp. 175-184.

[14] Xu H., Tao D.C., Tao Y.H., et al. (2018). Simulation and experimental research on rice seed metering device based on EDEM. *Journal of Agricultural Science and Technology,* Vol. 20, Issue 3, pp. 64-70.

[15] Xing H., Wang Z.M., Luo X.W., et al. (2018). Design of an active seed throwing and cleaning unit for pneumatic rice seed metering device. *International Journal of Agricultural and Biological Engineering,* Vol. 11, Issue 2, pp. 62-69.

[16] Xue P., Xia X., Gao P., et al. (2019). Double-setting seed-metering device for precision planting of soybean at high speeds. *Transactions of the Asabe,* Vol. 62, Issue 1, pp. 187-196.

[17] Ye S.B., Zheng D.C., Li W., et al. (2021). Design and test of negative pressure chamber rotary buckwheat seed metering device. *INMATEH-Agricultural Engineering,* Vol. 64, Issue 2, pp. 185-194.

[18] Zhu D.Q., Li L.L., Wen S.C., et al. (2018). Numerical simulation and experiment on seeding performance of slide hole-wheel precision seed-metering device for rice. *Transactions of the Chinese Society of Agricultural Engineering,* Vol. 34, Issue 21, pp. 17-26.

[19] Zhou F.J., Li X.L., Yin B.X. (2018). Design and experiment of seeding apparatus with spoon taking seeds and piston pricking hole for rice. *Journal of Northeast Agricultural University,* Vol. 49, Issue 8, pp. 73-82.

[20] Zhang M.H., Wang Z.M., Luo X.W., et al. (2018). Review of precision rice hill-drop drilling technology and machine for paddy. *International Journal of Agricultural and Biological Engineering,* Vol. 11, Issue 3, pp. 1-11.