Experimental study on the performance of bowl-tray rice precision seeder

Yi Shujuan, Liu Yongfen, Wang Chun*, Tao Guixiang, Liu Haiyan, Wang Ruihan

(*Engineering College, Heilongjiang Bayi Agricultural University, Daqing 163319, Heilongjiang Province, China*)

Abstract: In order to optimize the parameters of bowl-tray rice precision seeder and improve its performance, three major factors respectively at five levels, including shaped hole diameter, vertical displacement of rice seeds and rotating speed of cam, were tested, the quadratic orthogonal rotational regression experiments were conducted, and the effects on seeding rate, leakage sowing rate and the injury rate were investigated. The test results show that factors affecting rice seeding rate are in the order of shaped hole diameter, rotating speed of cam and vertical displacement of rice seeds. The factors affecting rice planting leakage rate are in the order of shaped hole diameter, vertical displacement of rice seeds and rotating speed of cam, and the factors affecting rice injury rate are in the order of rotating speed of cam, vertical displacement of rice seeds and shaped hole diameter. Optimal parameters (shaped hole diameter: 10 mm, vertical displacement of rice seeds: 27 mm, rotating speed of cam: 13 r/min) and performance index (seeding rate: 95.43%, leakage sowing rate: 0.37%, injury rate: 0.58%) provided the basis for design and performance improvement of the bowl-tray rice precision seeder.

Keywords: bowl-tray rice precision seeder, rice seed, sowing performance, seed injury, shaped hole, quadratic orthogonal rotary regression experiment, optimal design

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1 Introduction

Rice-tray seedling has become the dominant direction since it can fundamentally relieve some unfavorable factors such as low temperature at cold regions in China[1]. Among them, the flat–tray seedling has been widely used, realizing the agricultural mechanization with some advantages including seedling earlier, intertwining seedling root, neat and strong seedling. However, in the process of mechanical planting, the seeding needle must divide the intertwining seedling root mechanically due to the unique structure of flat-tray, resulting in inevitable injury of seedlings and its root. Seedling stage needs five to seven days at least. Comparatively speaking, bowl-tray seedlings have some advantages such as disconnecting the bowl-tray and hole, preventing the spread of the disease and protecting the roots from being injured in the process of planting. Raising rice seedling in bowl-tray can shorten recovery period of rice seeding and increase yield of survival seedlings[2-6]. The mechanization technology of bowl-tray seeding is relatively mature in Japan but the price of the rice planter is high and not suitable for large scale application[7,8].

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Biographies: Yi Shujuan, PhD, Professor, Research focuses on farm machine and rice production mechanization, Tel: +86 13836961877 Email:yishujuan_2005@126.com. **Liu Yongfen,** PhD student, Research focuses on rice production mechanization; Email: liuyognfen@163.com. **Tao Guixiang,** PhD, Associate Professor, Research focuses on rice production mechanization; Email: tgx1996@163.com. **Liu Haiyan,** Master Candidate, Research focuses on rice production mechanization; Email: liuhaiyan@163.com. **Wang Ruihan,** Master Candidate, Research focuses on rice production mechanization; Email: wangruihan@163.com.

***Corresponding author: Wang Chun,** PhD, Professor, Research focuses on agricultural engineering and mechanization; Email: wangchun1963@163.com.

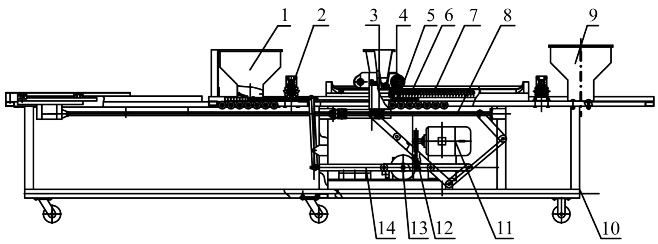
At present, bowl-tray rice precision seeder in China mainly includes two types, i.e., air suction seeder and mechanical suction seeder according to its working principle. Air suction seeder relies mainly on the physical strength to suck rice, while mechanical suction seeder relies mainly on the weight of seed and machinery to complete seeding. At present, the research on bowl-tray rice precision seeder has achieved certain progress. Experts and scholars in China have completed a lot of research, finding out that there are still some problems to be solved in the current machine type, such as the low seeding rate, high injury rate of seedling[9-14]. Therefore, it is necessary to research and develop a new type of bowl-tray rice precision seeder that can improve the current situation of high injury rate and low rate of sowing, which will be of a positive significance to improve the mechanization of rice bowl-tray seedling. However, in the process of sowing, the related parameters of seeder parts influence each other[15,16]. How to determine these parameters to ensure the qualified rate of seeding and the stable seeding performance is the key to ensure the quality of seeding. Therefore, the objectives of this study were: (1) to investigate the effects of experimental factors, including shaped hole diameter, vertical displacement of rice seeds and rotating speed of cam, on seeding rate, leakage sowing rate, and the injury rate; (2) to develop the model between experimental factors and seeding rate, leakage sowing rate, and the injury rate; and (3) to optimize the process parameters of the bowl-tray rice seeding mechanism.

2 Materials and methods

2.1 Test equipment and materials

As shown in Figure 1, rice bowl-tray precise seeding test-bed is mainly composed of subsoil box, compaction wheel, seed box, seed-brushing wheel, shaped hole plate, plate turnover, seed raising tray, push rod of seed box, surface soil box, frame, motor, transmission chain, speed reducer and connecting rod to frame body.

The plate pusher and sowing body will make longitudinal parallel movement driving by the motor, through chain wheel of motor, chain, chain wheel of speed reducer, speed reducer, and crank-link mechanism (crank fixed on both ends of the output shaft of speed reducer). When the crank runs a circle, the crank-link mechanism will drive the plate pusher and sowing body device to move a distance of one seed raising tray, which arrives at below subsoil box after finishing compacting soil. Then the compacted seed raising tray reaches the place under the seeding apparatus. Shaped-hole plates fill seed twice. In the seed-filling process, the crank drives connecting rod of the plate pusher to realize the reciprocating linear motion of seed box through the push rod of seed box.



1. Subsoil box; 2. Compaction wheel; 3. Seed box; 4. Seed-brushing wheel; 5. Shaped hole plate; 6. Plate turnover; 7. Seeding raising tray; 8. Push rod of seed box; 9. Surface soil box; 10. Frame; 11. Motor; 12. Transmission chain; 13. Speed reducer; 14. Connecting rod to frame body

Figure 1 Schematic diagram of experiment platform of bowl-tray rice precision seeder

The seed box equipped with baffle inside can control the falling of rice seeds. The two sides of the seed box were equipped with seed-brushing wheels to follow its movement. In the filling process of sowing device, the baffle was opened. Rice seeds fell to the surface of shaped-hole plate by gravity, inertial force down. Under the drive of seed-brushing wheels, seeds were filled to the shaped hole and the spare seeds were brushed out to guarantee that 3-5 seeds were in a shaped hole. When one tray supplied, seed box would finish one reciprocating motion completing two filling processes. After filling, with the cooperation between flap assembly installed at the bottom of shaped-hole plate and plate-turnover, the shutter was opened through the drive of some instruments such as eccentric wheel, drive rod, rocker at both ends of output shaft of speed reducer. Under the action of their own gravity and inertial force, rice seeds in shaped hole fell into seed raising tray. The sowing process was completed.

Main structural parameters: the shape of shaped hole cavity is cylindrical as shown in Figure 2. Diameter of a shaped hole is 8-12 mm and the depth of a shaped hole is 2-6 mm. The seed box is rectangular equipped with internal baffle. Diameter of a seed-brushing wheel is 78 mm, the height of brushing seeds is 3 mm, the center distance of a shaped hole is 19.3 mm and the width of a seeds box is 342 mm. The shape of seed raising tray is quadrate, with a size of 18 mm × 18 mm. The rotation speed of a cam is 9-17 r/min and the vertical displacement of seeds is 21-37mm. The seeds used in this test were Kongyu 131 that were widely used in Heilongjiang Province. The germinal length is 1-2 mm, thousand kernel weight is 39 g and moisture content is 23%.

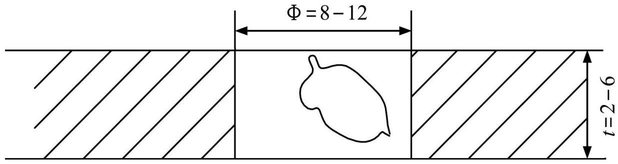


Figure 2 Sketch of shaped hole

2.2 Experimental method

According to the production of common data and previous test results[16], when the diameter of seed-brushing wheel is 78 mm, the height of brushing seeds being 3 mm, the center distance of shaped hole being 19.3 mm, the width of seeds box being 342 mm, the shaped hole being roundness, the shape of seed-raising tray being quadrate and the size of seeds box being 18 mm × 18 mm, the factors affecting performance of the seeding apparatus were further researched in the case of combination of various factors. Past test results indicated that the performance parameters mainly include shaped hole diameter, the vertical displacement of rice seeds and the rotating speed of cam. Therefore, this study would select shaped hole diameter (x_1), the vertical displacement of rice seeds (x_2), the rotating speed of cam (x_3) as test factors. The rice seeding rate, leakage rate and the injury rate were taken as index using the quadratic orthogonal rotary regression experiment design[17-19]. The statistical analysis method of quadratic orthogonal rotary regression can overcome the disadvantage of the orthogonal experiment method. Computer simulation and optimization were used to find out the best combination of multiple factors and changing trend. The coding of factor levels is shown in Table 1.

Table 1 Code and level of factors

Code value	Shaped hole diameter x_1/mm	Vertical displacement of rice seeds x_2/mm	Rotating speed of cam x_3/r·min^{-1}
asterisk on the arm (+y)	11.7	35.7	16.4
upper level (1)	11	33	15
zero level (0)	10	29	13
lower level (-1)	9	25	11
asterisk under the arm (-y)	8.3	22.3	9.64
Δj	1	4	2

Note: X_1, X_2, X_3 represent the coded value of x_1, x_2, x_3, j=1, 2, 3.

Before the test, a certain amount of rice was filled into seed box. At the start of the test, the switch of the box was closed. When the frequency converter reached a certain frequency and the motor speed was stable and to the buffer, the switch of the box should be turned on. Seeds were filled into the shaped hole due to the combined action of seeds gravity, seed-brushing wheel and seed-scraping plate. When the box finished a process of reciprocating seed filling (before the flap was opened), trial operation was finished and a test was completed before the flap was opened. The reported value is the average value from three observations. Moisture content was measured by computer moisture meter (Shanghai Qingpu Oasis Testing Instrument Co., LTD., type LDS-1F, the error ≤ ±0.5%, or less repetition error ≤ ±0.2%, measuring range 3% to 35%); the pass rate of seed-filling and cavity rate were calculated according to the number of rice in shaped hole after filling seed respectively by counting the number of cells with 3-5 grain/cave and the number of cells with 0 grain/cave[20]. According to the research experience of other researchers[21], the main judgment of injury is whether the rice will continue to grow in the same environment. If the rice continues to grow it means that the rice seed is not injured; if not, it means the rice seed was injured. Injury rate was calculated as follows. One hundred seeds were selected randomly in shaped hole after sowing and were sprouted at the same environment as the original, observing the germination conditions, calculating the number of seeds that did not continue to sprout. Repeating three times and taking the average value.

3 Results and analysis

3.1 Test results

According to the design matrix of experimental factors, the experiments were conducted on the self-developed test-bed and the test results were shown in Table 2.

Table 2 Results of experimental design

Serial number	Shaped hole diameter x_1/mm	Vertical displacement of rice seeds x_2/mm	Rotating speed of cam x_3/r·min^{-1}	Leakage seeding rate/%	Seeding rate /%	Injury rate /%
1	11.0	35.7	15.0	0	84.463	0.921
2	11.0	35.7	11.0	0	82.602	0.825
3	11.0	25.0	15.0	0.185	84.704	0.756
4	11.0	25.0	11.0	0.093	82.178	0.878
5	9.0	35.7	15.0	4.189	84.858	0.634
6	9.0	35.7	11.0	5.291	84.973	0.574
7	9.0	25.0	15.0	1.852	88.154	0.663
8	9.0	25.0	11.0	3.175	87.126	0.75
9	8.3	29.0	13.0	7.291	74.537	0.791
10	11.7	29.0	13.0	0	70.351	0.958
11	10.0	22.3	13.0	0.755	93.364	0.731
12	10.0	35.7	13.0	1.296	92.274	1.037
13	10.0	29.0	9.64.	0.848	89.475	0.751
14	10.0	29.0	16.4	0.741	90.648	0.954
15	10.0	29.0	13.0	1.214	93.648	0.466
16	10.0	29.0	13.0	1.574	94.296	0.591
17	10.0	29.0	13.0	0.288	97.538	0.436
18	10.0	29.0	13.0	0.371	95.426	0.581
19	10.0	29.0	13.0	0.37	96.611	0.385
20	10.0	29.0	13.0	1.502	96.038	0.391
21	10.0	29.0	13.0	2.139	94.37	0.521
22	10.0	29.0	13.0	0.463	96.889	0.625
23	10.0	29.0	13.0	0.565	94.853	0.426

3.2 Regression model and primary and secondary order of experimental factors

The test data were analyzed by using quadratic orthogonal rotary regression in DPS data processing system. The regression equations of seeding rate, the leakage seeding rate and the injury rate are given as follows:

$$y_1=95.51-1.33x_1-0.52x_2+0.53x_3-8.07x_1^2-8.07x_2^2-1.85x_3^2+0.70x_1x_2+0.43x_1x_3-0.23x_2x_3 \quad (1)$$

$$y_2=0.94-1.94x_1+0.37x_2-0.18x_3+0.95x_1^2+0.02x_2^2-0.06x_3^2-0.59x_1x_2+0.31x_1x_3+0.02x_2x_3 \quad (2)$$

$$y_3=0.49+0.08x_1+0.03x_2+0.02x_3+0.11x_1^2+0.11x_2^2+0.09x_3^2+0.04x_1x_2+0.0001x_1x_3+0.05x_2x_3 \quad (3)$$

where, y_1 is seeding rate, %; y_2 is leakage seeding rate, %; y_3 is the injury rate, %; x_1 is shaped hole diameter, mm; x_2 is the vertical displacement of rice seeds, mm; x_3 is the rotating speed of cam, r/min.

To test the significance of regression equation, F test was used for Equation (1). According to lack-of-fit test of $F_1 = 0.15 < F_{0.05}(5,8) = 3.69$, the lack of fit is significant at the level of α=0.05; because of $F_2 = 105.67 > F_{0.01}(9,13) = 4.19$, it is showed that regression equation itself is significant at the level of α=0.01 and the equation fits well with the experimental data. According to the T test of regression coefficients, b_2, b_3, b_{12}, b_{13} and b_{23} are greater than $t_{0.05}(13)$=2.6, reaching more than 0.05 significant level. Eliminating the insignificant factors, the model between experiment factors and the seeding rate is given as follows:

$$y_1=95.157-1.33x_1-8.07x_1^2-0.87x_2^2-1.85x_3^2 \quad (4)$$

Similarly, the models between experiment factors and seeding leakage rate and injury rate are shown as follows respectively:

$$y_2=0.94-1.94x_1+0.37x_2+0.95x_1x_2 \quad (5)$$

$$y_3=0.49+0.08x_1+0.11x_1^2+0.11x_2^2+0.09x_3^2 \quad (6)$$

The test of regression coefficients of (4), (5) and (6) are concluded that the primary and secondary orders of factors affecting seeding rate are shaped hole diameter, the rotating speed of cam and the vertical displacement of rice seeds, respectively; the order of factors affecting leakage seeding rate is shaped hole diameter, the vertical displacement of rice seeds and the rotating speed of cam, respectively; the order of factors affecting injury rate is the rotating speed of cam, the vertical displacement of rice seeds and shaped hole diameter, respectively.

3.3 Multi-factorial response diagram analysis

The quadratic regression equation between shaped hole diameter, the vertical displacement of rice seeds, the rotating speed of cam and seeding rate, leakage seeding rate, the injury rate has been obtained. According to the equation, the relationships between seeding rate, leakage seeding rate, injury rate and various factors are shown in Figures 3-5.

3.3.1 Effect of experimental factors on seeding rate

Figure 3 exhibits the interaction of shaped hole diameter and vertical displacement of rice seeds on seeding rate. As shown in Figure 3, higher region of seeding rate appears when shaped hole diameter and vertical displacement of rice seeds are at zero level. When shaped hole diameter is fixed, the change of seeding rate with the vertical displacement of rice seeds is not significant; when the vertical displacement of rice seeds is fixed, seeding rate increases with the increase of shaped hole diameter first and then decrease. The highest point appears when shaped hole diameter is at zero level. When shaped hole diameter is below zero, seeding rate increases with the increase of shaped hole diameter; when shaped hole diameter is above zero, seeding rate decreases with the increase of shaped hole diameter. In the course of interaction of shaped hole diameter and the vertical displacement of rice seeds, shaped hole diameter is the main factor influencing the seeding rate.

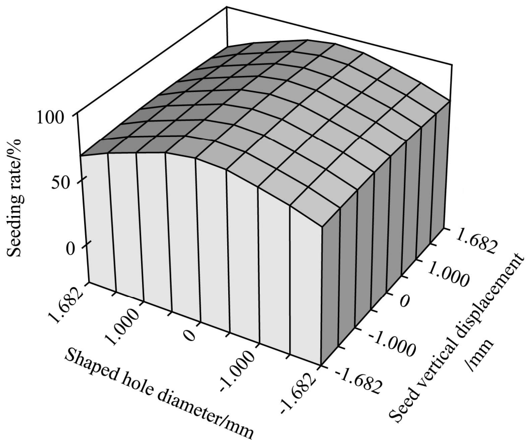


Figure 3 Interaction of shaped hole diameter and the vertical displacement of rice seeds

Figure 4 exhibits the interaction of shaped hole diameter and the rotating speed of cam on seeding rate. As shown in Figure 4, when shaped hole diameter is fixed , the change of increasing seeding rate with rotating speed of cam is mild; when the rotating speed of cam is fixed, seeding rate increases with the increase of shaped hole diameter first, and then decreases and changes significantly. The higher region of seeding rate appears when shaped hole diameter is at zero level. When shaped hole diameter is below zero, seeding rate increases with the increase of shaped hole diameter; when shaped hole diameter is above zero, seeding rate decreases with the increase of shaped hole diameter. In the course of interaction of shaped hole diameter and the rotating speed of cam, shaped hole diameter is the main factor influencing the seeding rate.

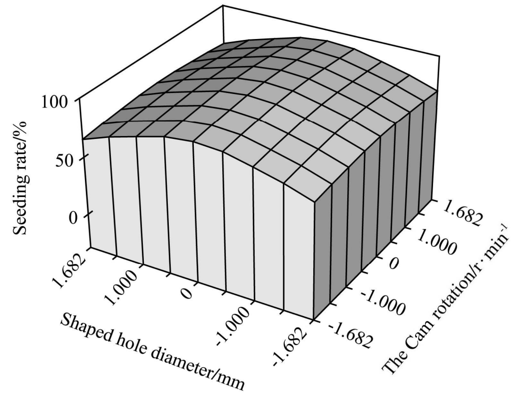


Figure 4 Interaction of shaped hole diameter and cam rotating speed

Figure 5 exhibits the interaction of the vertical displacement of rice seeds and the rotating speed of cam on seeding rate. As is shown in the Figure 5, when the vertical displacement of rice seeds is fixed, the increase of seeding rate with the rotating speed of cam is mild and the overall trend is that decrease follows increase; when the rotating speed of cam is fixed, seeding rate increases with the increase of the vertical displacement of rice seeds firstly, then decreases and change insignificantly. In the course of interaction of vertical displacement of rice seeds and rotating speed of cam, rotating speed of cam is the main factor influencing the seeding rate.

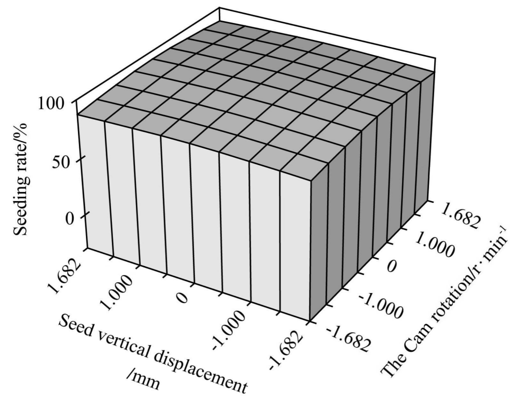


Figure 5 Interaction of vertical displacement of rice seeds and cam rotating speed

3.3.2 Effects of test factors on leakage seeding rate

Figure 6 exhibits the interaction of shaped hole diameter and the vertical displacement of rice seeds on leakage seeding rate. As shown in Figure 6, when shaped hole diameter and vertical displacement of rice seeds are at the level above one at the same time, leakage seeding rate is minimum. When shaped hole diameter is at a lower level, leakage seeding rate increases slowly with the increase of the vertical displacement of rice seeds; when shaped hole diameter is at a higher level, leakage seeding rate decreases slowly with the increase of the vertical displacement of rice seeds; when the vertical displacement of rice seeds is fixed, leakage seeding rate decreases with the increase of shaped hole diameter; when the vertical displacement of rice seeds is at a higher level, leakage seeding rate changes greatly with the increase of shaped hole diameter. In the course of interaction of shaped hole diameter and the vertical displacement of rice seeds, a conclusion that the main factor influencing the leakage seeding rate is shaped hole diameter is drawn by comprehensive analysis.

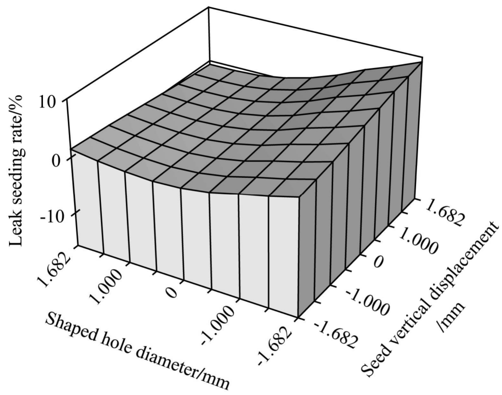


Figure 6 Interaction of shaped hole diameter and the vertical displacement of rice seeds

Figure 7 exhibits the interaction of shaped hole diameter and rotating speed of cam on leakage seeding rate. As shown in the Figure 7, when shaped hole diameter is fixed, the increase of leakage seeding rate with the rotating speed of cam is mild, and the increase is modest; when the rotating speed of cam is fixed, the leakage seeding rate increases with the increase of shaped hole diameter and changes significantly. In the course of interaction of shaped hole diameter and rotating speed of cam, the main factor influencing the leakage seeding rate is shaped hole diameter according to comprehensive analysis.

Figure 8 exhibits the interaction of the vertical displacement of rice seeds and the rotating speed of cam on leakage seeding rate. As shown in the Figure 8, the rotating speed of cam influences on the leakage seeding rate less than the vertical displacement of rice seeds. The leakage seeding rate decreases with the reduction of the vertical displacement of rice seeds and when the vertical displacement of rice seeds is at a lower level, leakage seeding rate reaches the minimum. In the course of interaction of the vertical displacement of rice seeds and the rotating speed of cam, the main factor influencing the leakage seeding rate is the vertical displacement of rice seeds according to comprehensive analysis.

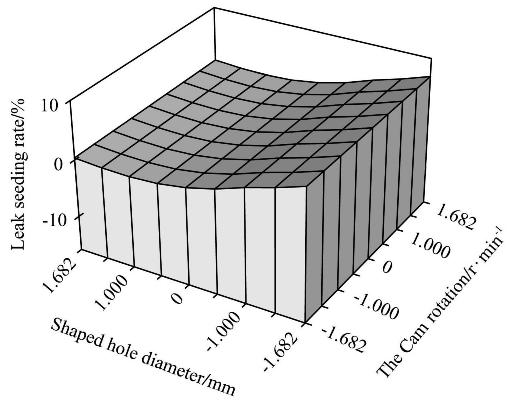


Figure 7 Interaction of shaped hole diameter and the rotating speed of cam

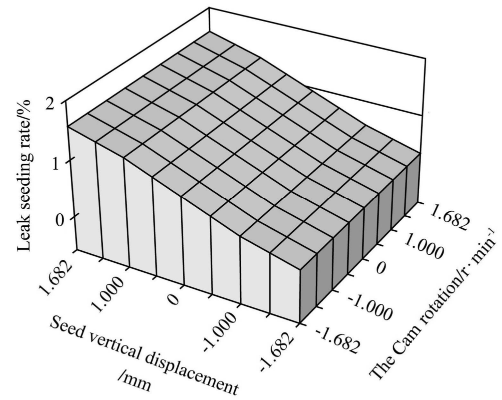


Figure 8 Interaction of the vertical displacement of rice seeds and the rotating speed of cam

3.3.3 Effect of experimental factors on the injury rate

Figure 9 shows the effect of shaped hole diameter and the vertical displacement of rice seeds on the leakage seeding rate. As shown in the Figure 9, when the vertical displacement of rice seeds is fixed, the injury rate deceases firstly and then increases with the increase of shaped hole diameter; when shaped hole diameter is fixed, the injury rate decreases firstly and then increases with the increase of the vertical displacement of rice seeds. The region of less injury rate appears when shaped hole diameter and the vertical displacement of rice seeds are all at zero level. The significant factor influencing the injury rate is the vertical displacement of rice seeds.

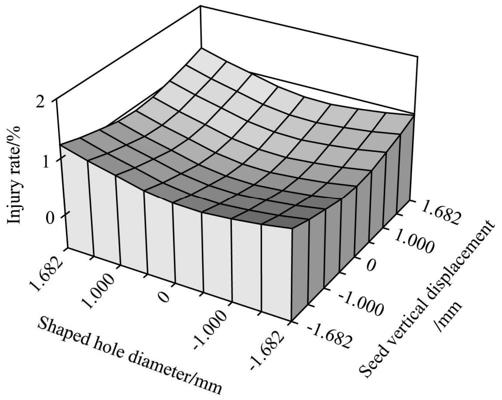


Figure 9 Interaction of shaped hole diameter and the vertical displacement of rice seeds

Figure 10 exhibits the effects of shaped hole diameter and rotating speed of cam on injury rate. As shown in Figure 10 , when rotating speed of cam is fixed, the injury rate deceases firstly and then increases with the increase of shaped hole diameter; when shaped hole diameter is fixed, the injury rate deceases firstly and then increases with the increase of rotating speed of cam and changes greatly. In the interaction of shaped hole diameter and rotating speed of cam, the main factor influencing the injury rate is rotating speed of cam.

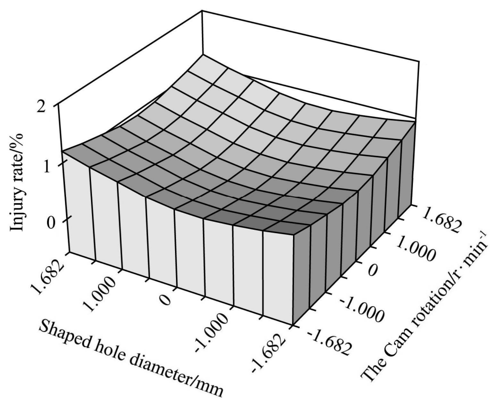


Figure 10 Interaction of shaped hole diameter and the rotating speed of cam

Figure 11 exhibits the interaction of the vertical displacement of rice seeds and the rotating speed of cam on injury rate. As shown in the Figure 11, when the rotating speed of cam is fixed, the injury rate deceases firstly and then increases with the increase of the vertical displacement of rice seeds, but the change is not clear; when the vertical displacement of rice seeds is fixed, the injury rate deceases firstly and then increases with the increase of the rotating speed of cam. In the interaction of the vertical displacement of rice seeds and the rotating speed of cam, the main factor influencing the injury rate is the rotating speed of cam.

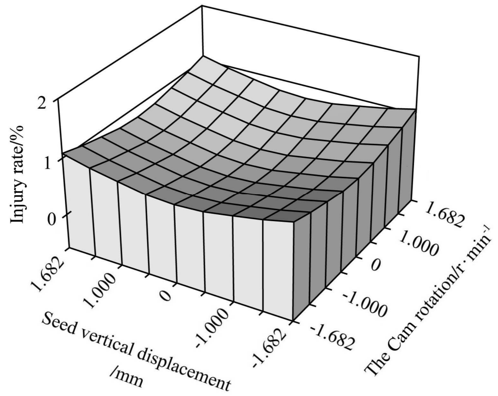


Figure 11 Interaction of the vertical displacement of rice seeds and the rotating speed of cam

4 Optimization of performance index

According to the performance requirement of the seeding device, three regression equations of performance index such as leakage seeding rate, injury rate and seeding rate were taken as the index, respectively. The main objective function method was used with the help of MATLAB software to optimize the solution, obtaining the best parameter combination scheme under different objective functions. The optimum parameter combinations are shown in Table 3.

Table 3 Optimum parameters combination plan of different objective functions

Objective function	Shaped hole diameter x_1 /mm	Vertical displacement of rice seeds x_2 /mm	Rotating speed of cam x_3 /r·min^{-1}
Seeding leakage rate	10.01	26.79	13.01
Qualified rate	+9.961	26.63	13.00
Injury rate	+9.920	28.33	13.05

The optimum parameters are shaped hole diameter of 10 mm , the vertical displacement of rice seeds of 27 mm and rotating speed of cam of 13 r/min.

5 Experimental verification

According to the above research, the performance indexes are leakage seeding rate of 0.37%, seeding rate of 95.43%, injury rate of 0.58% under the condition of rectangular seed box with a baffle, seed-brushing wheel diameter of 78 mm, height of brushing seeds of 3 mm, the center distance of shaped hole of 19.3 mm, width of seed box of 342 mm, square seed raising tray (18 mm × 18 mm) and circular shaped hole, bud seeds of Kongyu 131 and bud length of 1-2 mm. According to the literature[13], the technical-economic indicators of the bowl-tray rice seeder are single particle rate of sowing > 95%, leakage seeding rate < 3% and injury rate < 3%. It is verified that the above performance index can meet the technical requirements.

6 Conclusions

1) Through quadratic orthogonal rotary regression analysis, the nonlinear regression model has been established. The model can be used to describe the relationship among shaped hole diameter, vertical displacement of rice seeds, rotating speed of cam, seeding rate, leakage seeding rate and injury rate, which lays a theoretical foundation for optimization and improvement of parameters of bowl-tray rice precision seeder.

2) The order of factors affecting seeding rate is shaped hole diameter, the rotating speed of cam and the vertical displacement of rice seeds; the order of factors affecting leakage seeding rate is shaped hole diameter, the vertical displacement of rice seeds and the rotating speed of cam; the order of factors affecting injury rate is the rotating speed of cam, the vertical displacement of rice seeds and shaped hole diameter. The parameter adjustment of seeder should give priority to shaped hole diameter and then the rotating speed of cam for fine-tuning.

3) The conclusion has been drawn that the optimal process parameters for bowl-tray rice precision seeder is shaped hole diameter of 10 mm, the vertical displacement of rice seeds of 27 mm and the rotating speed of cam of 13 r/min.

4) The performance indexes verified through experiment are leakage seeding rate of 0.37%, seeding rate of 95.43% and injury rate of 0.58%. Compared with the index of the bowl-tray rice seeder (single particle rate of sowing > 95%, leakage seeding rate < 3% and injury rate < 3%), the resulting performance index can meet the technical requirements.

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