OPTIMIZATION OF STIRRING PARAMETERS FOR MILLET FLUID SEED METERING BASED ON RESPONSE SURFACE METHODOLOGY
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基于响应面法的谷子流体排种器搅拌技术参数优化

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ABSTRACT

Fluid seeding is a new technology for drought resistance, water saving and yield increase in modern agriculture. To improve the uniformity of fluid seed metering of millet, the mechanical stirring device was added to the metering device, and the single-factor tests were carried out on the size parameters of the pump tube, the installation position and the parameters of mechanical stirring. The stirring speed, the ratio between the length of stirring paddle and the diameter of seed box and distance between the pump tube and the stirring paddle were selected as independent variables, and the right rate of hill distance, right rate of seeds per hill and rate of no seed hill were selected as response values. According to the test design principle of Central Composite Design, a response surface analysis method was used to establish mathematical models between each experimental factor and performance index, and the influencing factors of fluid seed metering were analyzed. The single-factor test results showed that when the pump tube was installed on the side of the seed box, and its inner diameter and wall thickness were 4.8 mm and 1.6 mm, respectively, the seeding performance was better. The response surface test results showed that the selected factors all have an influence on the performance of millet fluid seed metering, and the optimal stirring parameters were the stirring speed of 30 r/s, the ratio between the length of stirring paddle and the diameter of seed box of 0.69, and distance between the pump tube and the stirring paddle of 0.11 cm. The verification test was conducted under these parameters, and the right rate of hill distance, right rate of seeds per hill and rate of no seed hill were 94.14%, 84.24%, and 2.21%, respectively, and the error from the predicted values was less than 4%. The performance indexes of fluid seed metering were improved compared with the fluid seed metering device without stirring device, indicating that the optimized stirring parameters can improve the performance indexes of millet fluid seed metering. This study can provide a reference for the research and development of key technologies and equipment for precision fluid seed metering of millet.

摘要

流体播种是现代农业抗旱、节水和增产的一种新技术。为提高谷子流体排种均匀性，在现有输送泵式谷子流体排种器的基础上增设了机械搅拌装置，对泵管尺寸参数、安装位置及搅拌技术参数进行了单因素试验。选取搅拌速率、搅拌桨-种箱直径比和泵管-搅拌桨垂直距离为自变量，以穴距合格率、穴粒数合格率和空穴率为响应值，按照Central Composite Design 试验设计原理，采用三因素五水平响应面分析方法建立了各试验因素与性能指标之间的数学模型，并对各因素进行分析。单因素试验结果表明：当泵管安装于种箱侧面，其内径和壁厚分别为 4.8 mm、1.6 mm 时，排种性能较优。响应面试验结果表明：搅拌速率、搅拌桨-种箱直径比和泵管-搅拌桨垂直距离均对谷子流体排种性能有一定影响，且流体排种器最佳搅拌参数为搅拌速率 30 r/s、搅拌桨-种箱直径比 0.69、泵管-搅拌桨垂直距离 0.11cm。该参数下进行验证试验得到谷子流体排种穴距合格率、穴粒数合格率和空穴率分别为 94.14%、84.24%、2.21%，与预测值误差小于 4%。通过与未加搅拌装置的流体排种器进行对比试验，流体排种性能指标均有明显改善，说明增设的搅拌装置及其最优技术参数可提高谷子流体排种性能指标。该研究可为谷子精量流体排种关键技术与装备的研发提供参考。

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INTRODUCTION

Millet is a coarse grain crop grown in arid regions of northern China. In recent years, the realization of precise mechanized sowing of millet has been one of the problems to be solved urgently with the gradual development of the millet industry *(Du et al., 2015; Li et al., 2014).* Millet is often sown in dry land with little rain, and it is difficult to germinate after sowing in the hilly and mountainous areas of northern China *(Tian et al., 2013)*. At the same time, the traditional mechanical sowing technology and equipment were used by most farmers to sow millet, which resulted in poor uniformity of sowing, large sowing amount, irregular seedling emergence, heavy thinning workload, and even the phenomenon of seedling shortage *(Zhang et al., 2017)*. Fluid seeding is a new technology for modern agriculture to resist drought, save water and increase production, that is to say, a method of quantitative machine seeding by evenly distributing seeds in a water solution with the water retaining agent *(Pill, 1991)*. The water retaining agent has a high viscosity, water absorption and water retention. It can slowly release water for crop absorption and utilization. In the case of drought, the purpose of seedling growth and stable yield can be achieved *(Chen et al., 2010; Hayes et al., 2010).* Therefore, using the fluid seeding method can not only improve the uniformity of seeding, but also promote the growth of millet in dry land.

At present, spray seeding is mainly used for fluid seeding of small seeds, such as pneumatic fluid seeder, *KangdaCPB8* spray seeder and *SL-PBJ* spray seeder, which are mainly applied to the drill and broadcast sowing for forage grass and flower seeds *(Currah et al., 2010).* A precise fluid seeding device controlled by a microcomputer has been developed in America and Japan, but it is still in the stage of experimental research and has not been popularized yet *(Wu, 1995)*. A study showed that the structure of the seed box was optimized by the stirring system of pressurized air, and the corn seeds tended to be uniformly suspended by air stirring of high pressure *(Xin et al., 2008).* The Scholars analyzed the interaction mechanism of seeds, water retaining agent and bubbles in the multiphase flow, revealed the theory of uniform suspension of seeds in the multiphase flow and invented three kinds of fluid seeding device, such as roller type, groove type, cable tray type, which provides a key technology for quantitative sowing of large seeds *(Xin et al., 2016a; Xin et al., 2016b)*. Millet seeds are small in size and light in weight, belonging to small seeds *(Sun et al., 2021)*, and there are still problems such as a large amount of sowing and poor uniformity in the field. So it is necessary to develop the fluid seeding equipment which should meet the requirements of precision seeding.

The seed metering device is the core component of the seeder. Our project initially developed a fluid metering device of the delivery pump for millet seeds, but it has the problem of uneven seed metering. Mechanical stirring is an important method to promote the uniformity of solid-liquid mixture *(Li et al., 2021)*. In this study, a mechanical stirring device was added to the seed box, the effects of the size parameters of the pump tube, installation position and stirring technical parameters on the seed metering performance were analyzed, and the optimal stirring parameters were obtained. The performance of the fluid seed metering device was improved through mechanical stirring, providing a reference for the development of fluid seed metering technology for millet seeds.

MATERIALS AND METHODS

Materials and equipment

Jingu No. 21 millet seed were selected, which is widely grown locally. The 1000-grain weight of millet seed was 3.31 g (13.2%, w.b.), and its average length, width and thickness were 3.14 mm ,1.92 mm and 1.50 mm, respectively. *Anxin* water retaining agent was used to prepare solid-liquid mixture, and the rate of water absorption was 450-500. The mass ratio of water retaining agent, millet seeds and water in a solid-liquid mixture was 1.1:10:200, and the viscosity of the solid-liquid mixture was 1.62 Pa·s *(Zhang et al., 2017).*

The self-made test bench, fluid seed metering device, had been adopted to the performance test, and its structure is shown in Fig.1. Its operation process is that negative pressure was generated inside the pump tube and the solid-liquid mixture was extracted from the seed box under the extrusion pressure of the delivery pump. The seeds passed through pump tube, three-way tube, long bent tube and short bent tube, and were finally discharged from the end drainage tube. The delivery pump provided power for the seed delivery, and the amount of seed metering could be adjusted by changing the speed of the delivery pump. The combination of the three-way tube, long bent tube and short bent tube can improve the uniformity of the seed metering, and the limiting clip was used to prevent the pump tube from moving *(Zhang et al., 2017).*

In order to improve the performance of the fluid seed metering device, a cylindrical barrel was used as a seed box, and a mechanical stirring device was added in this study, as shown in Fig.2. The speed of the mechanical stirring device *R* can be adjusted by the motor controller, and its adjustment range is 0-3000 r/min. The stirring paddle can be replaced in different tests, and the ratio of the stirring paddle length *t* to the diameter of the seed box *T* was 0.5-0.9. The width of the stirring paddle *d* and its distance from the bottom of the seed box *h* were 10 mm and 45 mm, respectively. The pump tube could be installed at the bottom, top and side of the seed box, so as to facilitate seed metering performance tests at different installation positions of the pump tube. Meanwhile, the position of the pump tube on the side of the seed box can be adjusted, and its vertical distance from the stirring paddle *D* was -4 - +4 cm ('-' represents the position below the stirring paddle, and '+' represents the position above the stirring paddle). All fluid metering performance tests were carried out on a mobile platform with a speed adjustment range of 0.5 – 1 m/s. *(Zhang et al., 2017).* The other test tools were mass balance (500 g, 0.01 g), rulers (500 cm, 0.1 cm), and the pump tubes with different size parameters. In this study, the speed of the delivery pump and mobile platform were 40 r/min and 0.5 m/s, respectively.

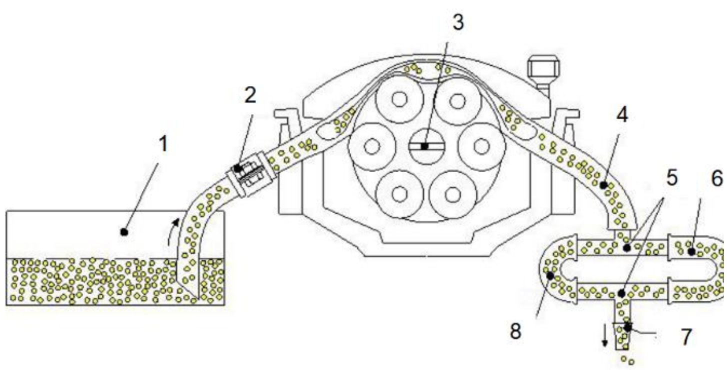

Fig. 1 - Fluid seed metering device

1.Seed box; 2.Limiting clip; 3.Delivery pump; 4.Pump tube; 5.Three-way tube; 6.Long bent tube; 7.End drainage tube; 8.Short bent tube

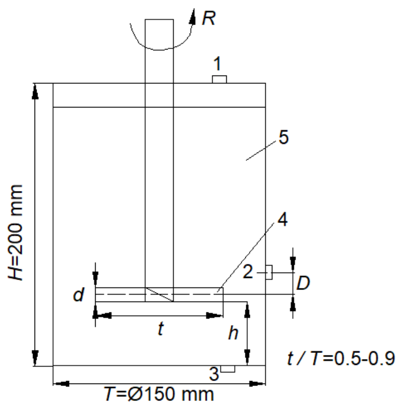

Fig. 2 - Mechanical stirring device

1.Top entrance of pump tube; 2.Side entrance of pump tube; 3. Bottom entrance of pump tube; 4. Stirring paddle; 5. Seed box

Test evaluation index

The NY/T 987-2006 "Operating quality grains film-covering hill-drop drill" was referenced for fluid seeding performance tests *(China Agriculture Press, 2006)*. The seed number of 51 holes was recorded in each experiment, and the distance between 50 holes was measured continuously. According to the agronomic requirements of millet sowing, the theoretical hill distance value ± 1.5cm was the qualified hill distance, and the reasonable seed number per hill was 2-4 *(Cui et al., 2017; Ren et al., 2014)*. The experiment was repeated for 3 times, and the evaluation indexes of the right rate of hill distance Y_1, right rate of seeds per hill Y_2 and rate of no seed hill Y_3 were calculated as follows:

$$Y_1 = \frac{P}{e-1} \times 100\% \tag{1}$$

$$Y_2 = \frac{Q}{e} \times 100\% \tag{2}$$

$$Y_3 = \frac{W}{e} \times 100\% \tag{3}$$

Where: *P* is the number of qualified hill distances, *Q* is the number of right seeds range, *W* is the number of no seeds per hill, *e* is the total number of hills determined in the test.

The undamaged millet seeds were selected for static tests of fluid seed metering, and 200 mL solid-liquid mixture was collected to calculate the rate of seed breakage *Z*.

The experiment was repeated for 3 times, and the formula of *Z* is as follows:

$$Z = \frac{M}{N} \times 100\% \tag{4}$$

Where: *Z* is the rate of seed breakage, *M* is the number of damaged seeds, *N* is the total number of seeds.

Test design

The test device is shown in Fig.3. The single-factor performance tests of fluid seeding were carried out by selecting the different size parameters of the pump tube, installation position of the pump tube, stirring speed and ratio between the length of stirring paddle and the diameter of seed box as the factors. The vertical distance between the pump tube and the stirring paddle was selected as a factor to carry out the fluid seeding performance test after the installation position of the pump tube was determined, and test factors and levels are shown in Table 1.

In order to further study the influence factors on the performance of fluid seeding and optimize technical parameters of mechanical stirring, Central Composite Design (CCD) was used for response surface test design based on the single-factor tests, and the relation of practical and coding values with CCD is shown in Table 2.

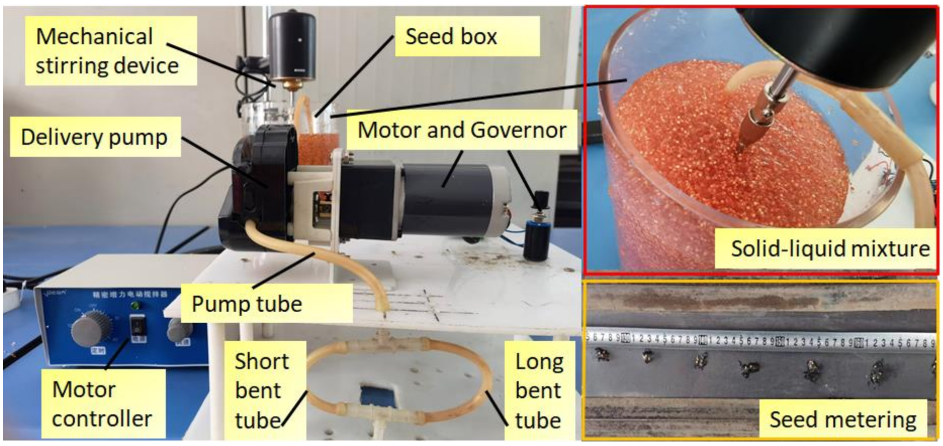

Fig. 3 - Test of fluid seed metering

Table 1

Factors and levels of single-factor tests

Levels	Inner diameter (thickness) of pump tube / mm	Stirring speed *R* / (r/s)	Ratio between the length of stirring paddle and the diameter of seed box *A*	Installation position	Distance between the pump tube and the stirring paddle *D* / cm
1	4 (1)	20	0.5	/	-4
2	4 (2)	25	0.6	Top	-2
3	4.8 (1.6)	30	0.7	Side	0
4	6 (1)	35	0.8	Bottom	+2
5	6 (2)	40	0.9	/	+4

Table 2

Relation of practical and coding values with CCD

Coding values	Practical values		
	Stirring speed *R* / (r/s)	Ratio between the length of stirring paddle and the diameter of seed box *A*	Distance between the pump tube and the stirring paddle *D* / cm
-1.682	21.59	0.53	-3.36
-1	25	0.6	-2
0	30	0.7	0
+1	35	0.8	+2
+1.682	38.41	0.87	+3.36

RESULTS

Results of single-factor test

The performance tests of fluid seed metering were carried out by replacing the pump tube of different size parameters when the seeds were discharged from the side of the seed box and the *R, A* and *D* were determined as 30 r/s, 0.7 and 0 cm, respectively.

Exploring the effect of the installation position, the inner diameter and wall thickness of the pump tube were 4.8 mm and 1.6 mm, respectively. As shown in Table 3, the seeds could not move smoothly in the pump tube, and the pump tube was clogged when the inner diameter of the pump tube was 4 mm. It was related to the size of the millet seed, and the agglomeration of multiple seeds caused the clogging and seed breakage in the pump tube. The right rate of hill distance, right rate of seeds per hill and rate of seed breakage improved obviously when the inner diameter of the pump tube increased to 4.8 – 6 mm, but the rate of no seed hill of the pump tube with a 6 mm inner diameter was higher than that of the pump tube with a 4.8 mm inner diameter. This is mainly because in the process of seed filling, more liquid was pumped and the seeds were not extracted proportionally.

In the case of the installation position of the pump tube, all the values of the evaluation indexes showed that the pump tube could be installed on the side of the seed box. Therefore, the pump tube with a 4.8 mm inner diameter was selected and installed on the side of the seed box for the best performance of the millet fluid seed metering.

In this study, the performance tests of fluid seed metering under different stirring speeds were conducted when *A* and *D* were 0.7 and 0 cm, respectively. It can be obtained from Table 4 that the right rate of hill distance Y_1 and right rate of seeds per hill Y_2 generally increased first and then decreased with the increase of the stirring speed, and the rate of no seed hill Y_3 first decreased and then increased. This reason may be that the viscosity of the solid-liquid mixture is relatively high, and a slow stirring speed cannot promote the uniform flow of the seeds. Similarly, the larger stirring speed causes the liquid flow to be accelerated in the solid-liquid mixture, resulting in an increase of the rate of no seed hill and a decrease of the right rate of seeds per hill.

Table 3

Effects of the size parameters and installation position of pump tube on fluid seed metering

Factor	Value	Y_1 / %	Y_2 / %	Y_3 / %	*Z* / %	Whether the clogging
Inner diameter (thickness) of pump tube / mm	4 (1)	85.72	80.58	3.89	0.01	Yes
	4 (2)	87.14	81.30	3.14	0.005	Yes
	4.8 (1.6)	95.12	86.23	2.38	0	No
	6 (1)	94.13	85.44	3.53	0	No
	6 (2)	95.33	86.14	3.47	0	No
Installation position	Top	93.55	83.12	3.14	0	No
	Side	95.12	86.23	2.38	0	No
	Bottom	93.71	84.54	3.22	0	No

Under the condition that the *R* and *D* were 30 r/s and 0 cm, respectively, the *A* was changed by installing different stirring paddles to conduct the fluid seed metering tests. The evaluation indexes were the optimum when the ratio between the length of the stirring paddle and the diameter of seed box *A* was 0.7. The main reason is that the high-viscosity mixture and the short stirring paddle could not make the seeds flow faster on the side of the seed box, and the long stirring paddle made the centrifugal force of millet seed increase, causing a large amount of liquid without seeds to be discharged.

Table 4

Effects of the stirring parameters on fluid seed metering of millet

Factor	Value	Y_1 / %	Y_2 / %	Y_3 / %	*Z* / %
Stirring speed *R* / (r/s)	20	90.35	80.54	3.04	0
	25	92.14	83.21	2.54	0
	30	95.33	86.78	2.15	0
	35	95.12	81.24	2.28	0
	40	95.20	78.25	2.33	0
Ratio between the length of stirring paddle and the diameter of seed box *A*	0.5	89.23	79.55	2.89	0
	0.6	93.00	81.23	2.54	0
	0.7	95.13	86.74	2.21	0
	0.8	91.23	86.41	2.23	0
	0.9	88.26	87.55	2.34	0

Table 4
(continuation)

Factor	Value	Y1 / %	Y2 / %	Y3 / %	Z / %
Distance between the pump tube and the stirring paddle *D* / cm	-4	91.23	81.53	2.74	0
	-2	94.12	84.35	2.39	0
	0	95.66	86.87	2.15	0
	+2	91.03	84.47	2.29	0
	+4	88.76	80.65	2.36	0

The performance tests of fluid seed metering under the different distances between the pump tube and the stirring paddle were conducted when *R* and *A* were 30 r/s and 0.7, respectively. We can see from Table 4 that these indexes were optimal when the pump tube was installed on the side of the seed box and the closer the pump tube was to the stirring paddle. During the stirring process of the solid-liquid mixture, the main flow modes are circulating flow and turbulent flow, and the latter can promote the seeds to mix evenly in the liquid *(Blais B.et al., 2017; Xin et al., 2008)*. At the same time, we observed that millet seeds were not broken at a rapid stirring speed, and this is mainly due to the high viscosity of the solid-liquid mixture resulted in a faster stirring speed that does not cause the seeds to be broken.

Results of response surface test

In order to obtain the optimal stirring parameters for fluid seed metering of millet, a response surface test was carried out after determining the size parameters and installation position of the pump tube, and Table 5 shows the results of the response surface test.

Table 5

Response surface analysis data of fluid seed metering test

Testing number	Factor levels			Y_1 / %	Y_2 / %	Y_3 / %
	R	*A*	*D*			
1	–1	–1	–1	92.28	80.28	2.24
2	–1	–1	1	96.01	86.79	2.18
3	–1	1	–1	95.65	86.54	2.14
4	–1	1	1	91.43	84.70	2.45
5	1	–1	–1	92.06	82.97	2.36
6	1	–1	1	94.08	82.27	2.40
7	1	1	–1	93.53	83.85	2.43
8	1	1	1	96.39	86.11	2.16
9	–1.682	0	0	95.78	87.78	2.07
10	1.682	0	0	94.16	83.22	2.50
11	0	–1.682	0	91.25	81.04	2.27
12	0	+1.682	0	91.64	81.92	2.42
13	0	0	–1.682	93.46	82.00	2.30
14	0	0	+1.682	95.23	86.82	2.14
15	0	0	0	92.45	81.31	2.37
16	0	0	0	95.37	86.80	2.17
17	0	0	0	93.09	82.93	2.39
18	0	0	0	92.46	82.66	2.39
19	0	0	0	93.07	84.26	2.17
20	0	0	0	94.11	81.93	2.35

Design Expert 11.0 was conducted to analyze the test results to reveal the relationships between the factors and the evaluation indexes of fluid seed metering, and the regression equations were determined as follows:

$$Y_1 = -0.06R^2 - 85.21A^2 - 0.19D^2 + 3.38R + 118.63A - 0.16D + 0.14RA + 0.02RD - 0.36AD + 1.60 \quad (5)$$

$$Y_2 = -0.08R^2 - 127.75A^2 - 0.28D^2 + 4.27R + 160.30A - 2.42D + 0.5RA + 0.05RD - 1.25AD - 30.07 \quad (6)$$

$$Y_3 = 0.0027R^2 + 4.17A^2 + 0.029D^2 - 0.22R - 7.70A - 0.07D + 0.07RA + 0.001RD + 0.06AD + 8.13 \quad (7)$$

Table 6

Regression equation analysis of variance results

Source of variation	Right rate of hill distance Y_1 / %			Right rate of seeds per hill Y_2 / %			Rate of no seed hill Y_3 / %		
	DOF	F-Value	p-Value	DOF	F-Value	p-Value	DOF	F-Value	p-Value
Model	9	20.39	<0.0001**	9	10.55	<0.0001**	9	19.43	<0.0001**
R-R	1	3.02	0.11	1	17.58	0.0018**	1	13.47	0.0043**
A-A	1	6.56	0.03*	1	4.66	0.0562	1	7.51	0.02*
D-D	1	13.62	0.004**	1	0.30	0.60	1	0.96	0.35
RA	1	0.15	0.71	1	1.36	0.27	1	6.33	0.03*
RD	1	1.52	0.25	1	5.44	0.04*	1	0.61	0.45
AD	1	0.16	0.70	1	1.36	0.27	1	0.61	0.45
R^2	1	112.90	<0.0001**	1	154.03	<0.0001**	1	38.27	0.0001**
A^2	1	40.18	<0.0001**	1	63.93	<0.0001**	1	15.06	0.0031**
D^2	1	32.13	0.0002**	1	49.31	<0.0001**	1	113.06	<0.0001**
Residual	10			10			10		
Lack of fit	5	1.89	0.25	5	1.45	0.35	5	1.15	0.44
Error	5	R^2=0.9483		5	R^2=0.9627		5	R^2=0.9459	
Total	19			19			19		

*Note: * represents significant (p<0.05), ** represents highly significant (p<0.01).*

Table 6 shows the variance analysis of regression models of the right rate of hill distance, right rate of seeds per hill and rate of no seed hill. The response surface models of these evaluation indexes were significant (p<0.01). The lack of fit F-value was not significant (p>0.05) and the fitting degrees R^2 were larger than 0.94, indicating that the regression models were valid.

The significance of the influence of each factor on the evaluation indexes in the regression equation was determined by the F test. The evaluation index of the right rate of hill distance showed that the quadratic terms of R, A and D and the linear term of D were highly significant (p<0.01), and the linear term of A was significant (p< 0.05), but the linear term of R had no significant effect on the right rate of hill distance (p>0.05). The primary and secondary orders of each factor that affected the right rate of hill distance were D, A and R. The evaluation index of the right rate of seeds per hill showed that the quadratic terms of R, A and D were extremely significant (p<0.01), and the linear term of R was highly significant (p<0.01), and the interaction term between R and D were significant (p<0.05). The primary and secondary orders of each factor that affected the right rate of seeds per hill were R, A and D.

The evaluation index of the rate of no seed hill showed that the quadratic terms of R, A and D and the linear term of R were extremely significant (p<0.01), and the linear term of A and the interaction term between R and A were significant (p<0.05). The primary and secondary orders of each factor that affected the rate of no seed hill were R, A and D.

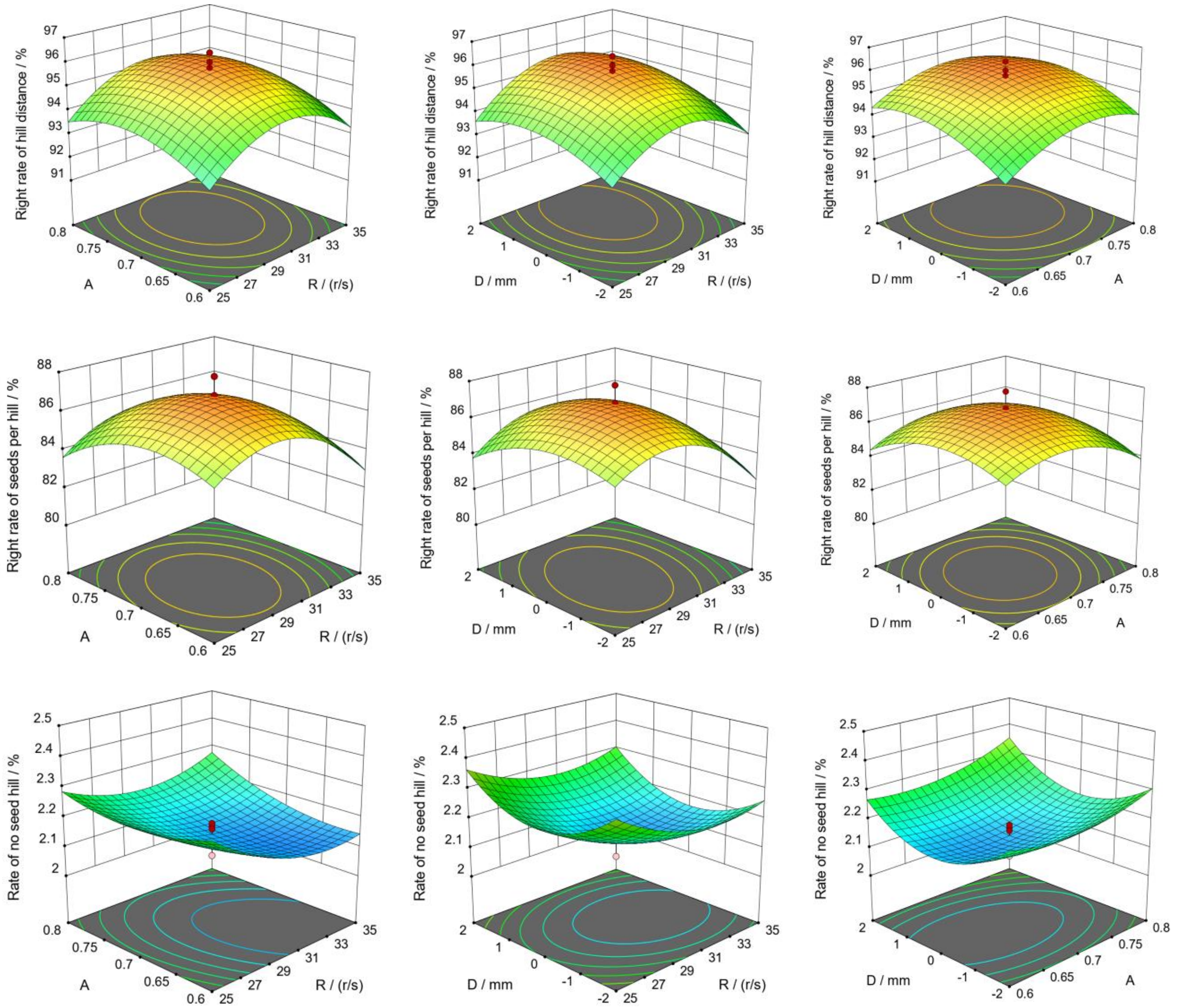

Fig. 4 - Response surface of various factors on the evaluation indexes of fluid seed metering test

Any two factors were fixed to 0 level, and the response surface was obtained according to regression equations (5), (6) and (7), respectively (Fig. 4).

The response surface figures showed that the change of the fluid seeding performance indexes were consistent with the single-factor experiment, and the interaction terms *R* and *D* was significant for Y_2, which indicated that the combined effect of stirring speed and the ratio between the length of stirring paddle and the diameter of seed box could improve the right rate of seeds per hill. Meanwhile, the interaction terms *R* and *A* were significant for Y_3, which indicated that the combined effect of the stirring speed and the distance between the pump tube and the stirring paddle could decrease the rate of no seed hill.

The Design expert 11.0 was adopted to the optimization of the fluid seed metering performance indexes to get the technical parameters of stirring, and the optimization equation is as follows：

$$\begin{cases} \max Y_1(R,A,D) \\ \max Y_2(R,A,D) \\ \min Y_3(R,A,D) \\ -1.682 \le R \le 1.682 \\ -1.682 \le A \le 1.682 \\ -1.682 \le D \le 1.682 \end{cases} \tag{8}$$

The stirring parameters (*R*, *A* and *D*) for the maximization of Y_1 and Y_2, and the minimization of Y_3 predicted from the response surface models were as follows: the stirring speed of 30.21 r/s, the ratio between the length of stirring paddle and the diameter of seed box of 0.69, and the distance between the pump tube and the stirring paddle of 0.11 cm. Under these parameters, the predicted values of the right rate of hill distance, right rate of seeds per hill and rate of no seed hill were 95.76%, 86.77% and 2.14%, respectively. The feasibility of the optimization results was validated through a verifying test. The test results are shown in Table 7. The error of Y_1, Y_2 and Y_3 between the actual results and the predicted values were less than 4%, indicating that the response surface model determined in this research was reliable. It can also be seen from Table 7 that the performance indexes of fluid seed metering have been improved after adding the stirring device, which has a reference value for improving the performance of millet fluid seeding.

Table 7

Results of verifying tests

Testing	**Results**			**Error of Y_1 / %**	**Error of Y_2 / %**	**Error of Y_3 / %**
	Y_1 / %	**Y_2 / %**	**Y_3 / %**			
Predicted values with stirring device	95.76	86.77	2.14	1.69	2.92	3.27
Measured values with stirring device	94.14	84.24	2.21			
Measured values without stirring device	90.02	80.55	3.19	/	/	/

CONCLUSIONS

The mechanical stirring device was added to the performance test of millet fluid seed metering, and the optimal stirring parameters of fluid seed metering were obtained based on the response surface test method, and the following conclusions were drawn:

(1) The inner diameter (thickness) of the pump tube suitable for millet fluid seed metering was 4.8 (1.6) mm, and the seeding performance indexes were the best when it was installed on the side of the seed box.

(2) According to the response surface test, the stirring speed, ratio between the length of stirring paddle and the diameter of seed box and distance between the pump tube and the stirring paddle have an influence on the seeding performance indexes of the right rate of hill distance, right rate of seeds per hill and rate of no seed hill.

(3) The optimal stirring parameters predicted from the response surface model were the stirring speed of 30.21 r/s, the ratio between the length of stirring paddle and the seed box diameter of 0.69 and the distance between the pump tube and the stirring paddle of 0.11 cm. The right rate of hill distance, right rate of seeds per hill and rate of no seed hill were 95.76%, 86.77% and 2.14%, respectively, and the error of these evaluation indexes from the actual results were less than 4%.

(4) Compared with the seed metering performance without the stirring device, the uniformity of the indexes with the addition of the stirring device were improved, which can provide references for improving the uniformity of the millet fluid seeding.

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