DESIGN OF SHAPED-HOLE VOLUME-VARIABLE PRECISION SEEDER
/
变容量型孔轮式排种器设计

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ABSTRACT

To improve the seed spacing consistency of vertical-disc seeders and starting from the mechanical compulsory seed metering, we designed a variable-volume hole precision seeder that adopts a cam push-rod structure to realize the compulsory seed metering. We studied the overall design of this new seeder. The optimal hole parameters were determined. Response surface method (RSM) was used in trial design, and this scheme was implemented on the discrete element software EDEM. RSM regression and prediction optimization show the optimal hole parameters are hole diameter 10 mm, depth 6.5 mm, and chamfer 2 mm. Comparative tests on the bench show that the new seeder is over the vertical-disc device showing 14%-21% higher longitudinal consistency and 18%-26% higher transversal consistency. The hole-typed volume-variable precision seeder with a cam push-rod structure would significantly improve the seed spacing consistency.

摘要

本文提出提高排种器的粒距一致性需具备的“两个条件”，并由机械式强制排种入手，设计出采用凸轮推杆机构实现定点强制排种的型孔容积可变式精密排种器，对该排种器进行了整体设计。为求出型孔参数的最优解，利用响应曲面方法进行试验设计，并在离散元软件 EDEM 中实施试验方案；经响应曲面回归分析和预测寻优，得出型孔参数最优解为，直径 10mm、深度 6.5mm、倒角 2mm。为验证仿真试验的准确性，又进行了离散元和 JPS-12 排种器试验台对比试验，试验结果相近，表明离散元仿真试验得出的结果是准确的，型孔参数的最优解可信。经与普通垂直圆盘排种器精播大豆粒距分布台架对比试验，得出型孔容积可变式精密排种器的合格粒距一致性可提高14%～26%。

INTRODUCTION

During precision seeding, the number (single-seed or multi-seed), space and depth of seeds are precisely controlled as per the agronomic requirements and plowed into soils. As a result, the seed spacing consistency is improved, which facilitate the growth, development of seeds and finally improve the crop yield (*Zheng, 2017*).

The premise of precision seeding is precise seed metering of the seeder. Precision seeders can be divided by the working principle into mechanical and pneumatic ones. Precision seeders are limited in maintaining the consistency of seed spacing. 1) As for mechanical devices, due to the difference in seed sizes *(Arzu and Adnan, 2014)* and the impacts of metering structures, three seed dropping methods (prompt dropping, delayed dropping and compulsory dropping) coexist. As a result, the seeds are not dropped from the same position of the seeder and at the same start speed at a constant time interval. 2) As for pneumatic devices, the consistency of seed spacing is impacted by the air pressure, rotating speed of seeder and the number and size of suction holes. Due to the difference in seed sizes, the pneumatic device is not as stable or reliable as the mechanical one. Even though the suction holes on the suction cup can precisely fill seeds, the departing speeds of seeds from the metering device would differ, which leads to the differences in seed spacing *(Zdzislaw et al., 2015; Fang et al., 2018; Rasool and Qayoum, 2018)*.

Two commonly-used precision machinery seeders are vertical-disc and horizontal-disc devices. The seed spacing consistency can be improved if the seed dropping methods of these two devices are restricted to one method such as compulsory seed dropping, so that the seeds would be ejected from the same position of the metering device.

There is rare research on the seed spacing consistency from the perspective of compulsory seed metering. For instance, the addition of a vertical disc or a ball-roll pusher seed planter significantly improves the seed spacing consistency of horizontal-disc seeders.

Compared with the pneumatic one, the precision mechanical metering device is superior with simple structure, low machining cost, working stability and reliability, and ability in improving the seed spacing consistency *(Ike, 2018*). Among the mechanical seeders, the vertical-disc device is more able to maintain the seed spacing consistency due to the height and direction of seed dropping. Thus, we selected the vertical-disc seeder and made the research from the perspective of mechanical compulsory seed metering. We aim to establish a shaped-hole volume-variable soybean precision seeder with point-fixed compulsory seed metering (*Yao, 2018*).

MATERIALS AND METHODS

Experiment part

Design of a Novel Seeder

This seeder was built by adding a cam push rod structure into the traditional vertical-disc seeder. This cam push rod structure had a fixed cam and was driven by the hole disc to rotate around the cam. The push rod was controlled by the cam outline curve to regularly shrink in the hole, which thereby changes the hole volume, so that the compulsory seed metering is adopted when the hole shrinks.

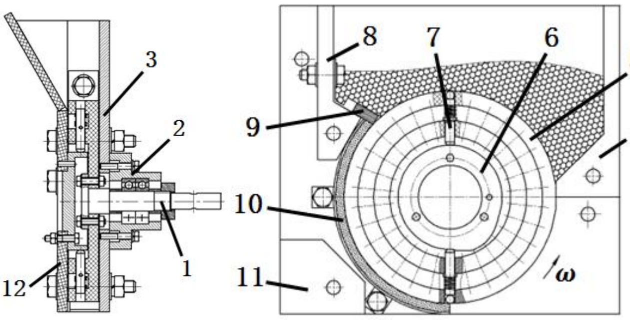
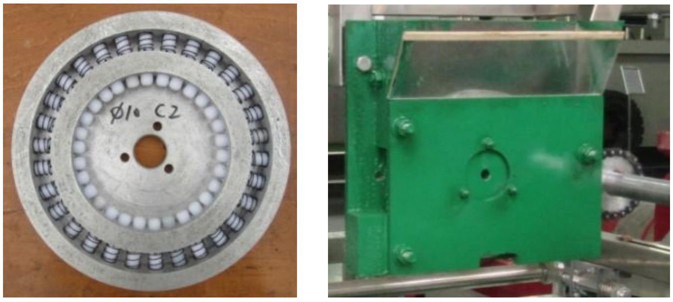


Fig. 1 - The structure of volume-variable hole precision seeder

1. Transmission shaft; 2. Bearing seat; 3. Front lid of seed box; 4. Upper right support; 5. Hole disc; 6. Cam; 7. Push rod; 8. Upper left support; 9. Seed brush; 10. Protection board; 11. Lower left support; 12. Rear lid of seed box;



(a) Hole disc assembly *(b) Back of the seeder*

Fig. 2 - The shaped-hole volume-variable soybean precision seeder

Soybean used in the Experiment

The properties of the soybean (*Hefeng 50*) used here are listed in Table 1. The equivalent diameter of soybean approximately obeys the normal distribution with a mean of 6.52 mm and standard deviation (SD) of 0.31 mm. The beans with equivalent diameter within 6.00-7.20 mm account for 88.7%.

Table 1

Properties of soybean

Water content	**Density**	**Poisson's ratio**	**Shear modulus**
9.4 %	1.27 g/cm^3	0.413[34]	45.56 MPa[34]

Table 2

Properties of materials that get in contact with soybeans

	Al	**Rubber**	**Q235**	**PMMA**
Poisson's ratio	0.334	0.49	0.26	0.33
Shear modulus (GPa)	25.5	0.006	81.34	0.08
Density(g/cm^3)	2.7	1.52	7.85	1.19

Table 3

Mechanical parameters between soybeans and contact materials

	Seed&Seed	Seed&Q235	Seed&PMMA	Seed&Rubber	Seed&Al
Recovery coefficient	0.47 [29]	0.6 [34]	0.58 [29]	0.60 [34,38]	0.6 [34]
Static friction coefficient	0.27 [35]	0.23 [36]	0.32 [37]	0.34 [26]	0.25 [39]
Rolling friction coefficient	0.05 [34]	0.20 [29]	0.1 [29]	0.26 [27]	0.19

Parameter setting on EDEM software

The use of EDEM software into design of seeders helps to improve the research and design levels, shorten the development period and increase the performance.

The use of DEM (Discrete Element Modeling) into simulation of seeders necessitates the provision of multiple physico-mechanical parameters such as water content, density, three-axis dimensions, and static rolling friction coefficient.

The fault Hertz-Mindlin (No Slip) model was selected as the between-seed and seed-boundary contact physical model. The physical properties of the seeds and boundary were set as per Tables 1 and 2. The contact parameters between the seeds and the components of the seeder were set as per Table 3. The simplified seeder model was introduced. The material properties of all components were added as per Table 3. The seed spacing was set as 50 mm, when the seeder worked at the limit speed 2.57 km/h. After simulation tests with different speeds, we determined the final rotating speed to be 25.56 rpm (at the real working speed of 2.3 km/h). A spherical model was used to simulate beans. Their diameters within 6.00-7.20 mm obeyed the normal distribution with mean of 6.52 mm and SD of 0.31. During the simulations, totally 1500 seeds were generated, and their sizes and positions were randomly formed *(Bilonoga Y., Maksysko O., 2018)*. The time step length was 9.79×10^{-6}s, about 20% of Rayleigh time step. The simulation duration was 22 s, data collection interval was 0.01 s and mesh size was 2R.

Description of test Equipment

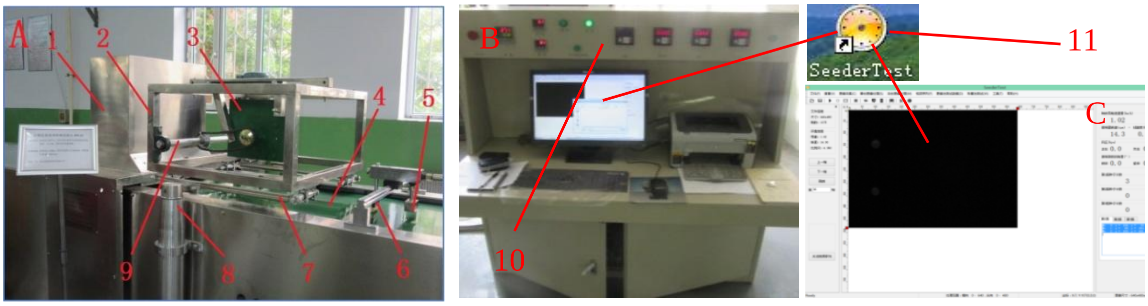
We conducted verification tests with this seeder on a JPS-12 seeder bench. The trial scheme was that trials were conducted on EDEM and the test bench separately. The working speeds (seed spacing =5cm) and the rotating speeds of the seeder are listed in Table 4.

Table 4

The working speeds and the rotating speeds of the seeder

Working speed (km/h)	1	1.5	2	2.5	3	3.5
Rotating speed (rpm)	11.1	16.7	22.2	27.8	33.3	38.9

The bench trials were conducted on a JPS-12 seeder performance test bench (Jointly developed by Heilongjiang Institute of Agricultural Machinery Engineering Science and Harbin Bona Technology Co. Ltd).



(A) mechanical structure unit *(B) control unit* *(C) seed metering performance test unit.*

Fig. 3 - Overall composition of the seeder test bench

1. Industrial camera 2. Metering device universal mounting bracket 3. Variable-volume hole precision seeder. 4. Oil zone 5. Nozzle 6. Oil brush 7. Mounting bracket front and rear inclining angle adjusting device 8. Mounting bracket height and left/right inclining angle adjusting device 9. seed metering shaft 10. bench operation control plane 11. metering performance test software

Research Method

The parameters of hole structure are all continuous, so the significant ones should be selected as per regression fitting, factor analysis and interactions. Finally, the parameters are optimized (*Liu, 2018*). The response surface method (RSM) is more suitable for optimization of hole structure parameters of seeders. Here the Box-Behnken RSM trial design from Design-Expert was used to optimize hole structure parameters.

Simulation experiment: There were totally 17 trials including 12 trials of factor analysis, 5 trials of zero tests. Each trial was conducted in triplicate.

The factor levels and trial design are showed in Table 5.

Table 5

Factor levels

Level	**Factor/mm**		
	diameter(A)	**depth(B)**	**chamfer(C)**
1	10	7	3
0	9	6.7	2
-1	8	6.4	1

Contrast experiment: Like the simulations, with reference to the results of simulation processing and manufacturing material, the new seeder and a vertical-disc seeder (a bristle brush wheel seeder) were sent into seed spacing consistency comparative test on the JPS-12 test bench, so as to validate whether the new device can improve the seed spacing consistency.

To more precisely study the consistency of qualified seed spacings, we used longitudinal consistency (longitudinal seed spacing consistency) and transversal consistency (transversal seed spacing consistency) to measure qualified grain interval consistency. Specifically, the longitudinal seed spacing consistency was reflected by the seed spacing SD (σ_Z), while the transversal seed spacing consistency was measured by the SD away from the centreline (σ_H).

RESULTS

Hole parameter optimization with the seeder.

Regression analysis

Table 6

Final analysis of variance (ANOVA) of single-seed rate

Source	**Sum of squares**	df	**Mean Square**	**F Value**	**p-value**
Model	6892.60	5	1378.52	161.18	<0.0001
A	2733.19	1	2733.19	319.57	<0.0001
C	2831.66	1	2831.66	331.09	<0.0001
AC	991.62	1	991.62	115.94	<0.0001
A^2	89.17	1	89.17	10.43	0.0080
C^2	230.00	1	230.00	26.89	0.0003
Residual	94.08	11	8.55		
Lack of fit	64.46	7	9.21	1.24	0.4403
Pure Error	29.62	4	7.40		
Total	6986.67	16			
Std.Dev	2.92		R^2	0.9865	
Mean	80.63		**Adj** R^2	0.9804	
C.V.%	3.63		**Pred** R^2	0.9676	
PRESS	226.66		**Adeq Precision**	45.416	

1) At the significance level p<0.05, the significant items are A, C, AC, A^2, C^2, at the insignificance level p>0.1, there is no insignificant item.

2) The F-value of the regression equation is 161.18, indicating significant (p<0.01).

3) The regression equation shows no lack-of-fit (p<0.05). The coefficient of determination (R^2=0.9865) and adjusted R square (*Adj* R^2=0.9804 are both close to 1, indicating this regression equation is precise and effective significantly.

The predicted R^2 (*Pred* R^2=0.9676) and precision value (*Adeq Precision*=45.416>4) suggest this regression equation predicts well within the preset range.

Moreover, the significance levels of all factors rank as follows: chamfer > diameter > depth.

After substitution into the coding equation, we get the regression equation of single-seed rate against the real factors:

$$\text{Single-seed Rate}=-802.90+132.70d+190.04\delta-15.75d\delta-4.60d^2-7.38\delta^2 \qquad (1)$$

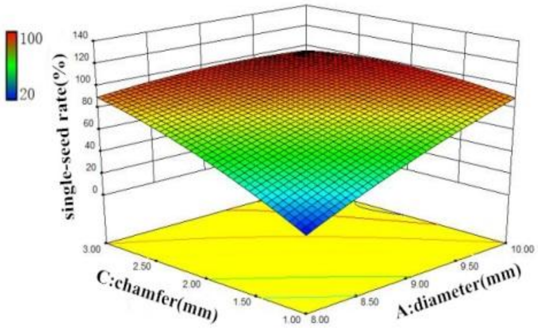


Fig. 4 - Contours of diameter (A) and chamfer (C) against single-seed rate (R1)

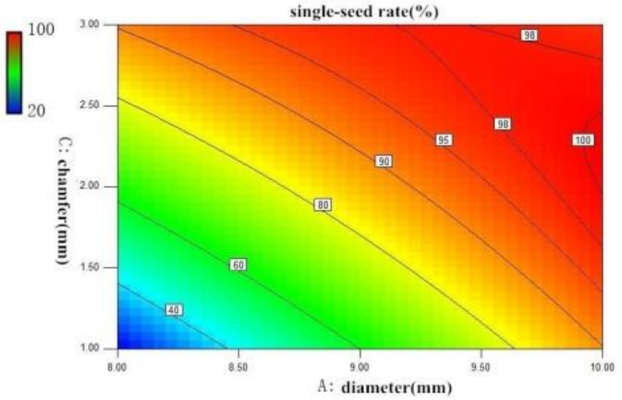


Fig. 5 - Response surfaces of diameter (A) and chamfer (C) against single-seed rate (R1)

The contours and response surfaces can be used to determine whether the impact of a factor on the effect is significant, the changing trend of effect against the factor and the area of the optimal value. The contours (Fig. 4) and response surface (Fig. 5) of hole diameter (*A*) and chamfer (*C*) against single-seed ratio (R_1) were plotted on Design-Expert. The contours show that the single-seed rate (R_1) is significantly affected by the hole diameter (*A*) and chamfer (*C*). The single-seed rate increases from 20% at *A*=8 mm to 100% at *A*=10 mm. The single-seed rate rises from 20% at *C*=1 mm to 100% at *C*= 3 mm and then declines. The interactive effect between *A* and *C* on single-seed rate is very significant. The maximum of single-seed rate is obtained at *A*=10 mm and within *C*= 2-3 mm. This phenomenon is also revealed on the response surface. Similarly, the final ANOVA of cavity rate is showed in Table 7.

Table 7

Final ANOVA of cavity rate

Source	Sum of squares	df	Mean Square	F Value	p-value
Model	6676.60	5	1335.32	146.03	<0.0001
A	2665.23	1	2665.23	291.47	<0.0001
C	2601.73	1	2601.73	284.52	<0.0001
AC	1036.84	1	1036.84	113.39	<0.0001
A^2	76.35	1	76.35	8.35	0.0147
C^2	279.08	1	279.08	30.52	0.0002
Residual	100.59	11	9.14		
Lack of fit	70.97	7	10.14	1.37	0.4009
Pure Error	29.62	4	7.40		
Total	6777.18	16			
Std.Dev	3.02		R^2	0.9852	
Mean	19.77		*Adj* R^2	0.9784	
C.V.%	15.30		*Pred* R^2	0.9629	
PRESS	251.17		***Adeq Precision***	43.846	

1) The significant items are *A*, *C*, *AC*, A^2, C^2; there is no insignificant item.

2) The F-value of the regression equation is 146.03, indicating significant ($p<0.01$).

3) The regression equation shows no lack-of-fit ($p=0.4009<0.05$).

The coefficient of determination ($R^2=0.9852$) and adjusted *R* square (*Adj* $R^2=0.9784$) are both close to 1, indicating this regression equation is precise and effective significantly.

The predicted R^2 (*Pred* $R^2=0.9629$) and precision value (*Adeq Precision*=43.846>4) suggest this regression equation predicts well within the preset range. Moreover, the significance levels of all factors rank as follows: diameter > chamfer > depth.

After substitution into the coding equation, we get the regression equation of cavity rate against the real factors:

$$\text{Cavity Rate}=881.05-127d-195.45\delta+16.1d\delta+4.25d^2+8.13\delta^2 \tag{2}$$

The contours and response surface of hole diameter *(A*) and chamfer (*C*) against cavity rate (R^2) were plotted on Design-Expert. The contours show that the cavity ratio (R^2) is significantly affected by the hole diameter (*A*) and chamfer (*C*). The cavity rate increases from 80% at *A*=8 mm to 0 at *A*=10 mm. The cavity rate first declines and then rises with the increase of *C* from 1 to 3 mm. The interactive effect between *A* and *C* on cavity rate is very significant. The minimum of cavity rate is obtained at *A*=10 mm and within *C*= 2-3 mm. This phenomenon is also revealed on the response surface.

The working performance of the seeder is jointly reflected by the single-seed rate, cavity rate, and double-seed rate. During the simulations, nearly no double-seed in one hole was found. The data obtained during the trials were insufficient to build a regression equation of diameter (*A*), depth (*B*) or chamfer (*C*) against double-seed rate. According to experiences, when the hole chamfer and diameter are very large, the seeds are more likely to fall into holes, but if the depth only accommodates one seed, other seeds will be cleaned outside anyway.

Prediction optimization

The RSM is feasible for prediction optimization. In the design domain, we provided the maximum of single-seed rate, the minimum of cavity rate, and obtained the contours and response surface of fitness.

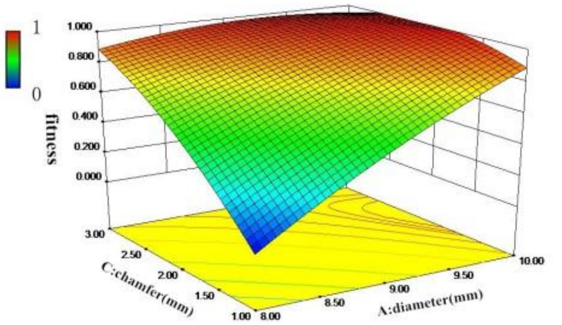


Fig. 6 - Contour of fitness

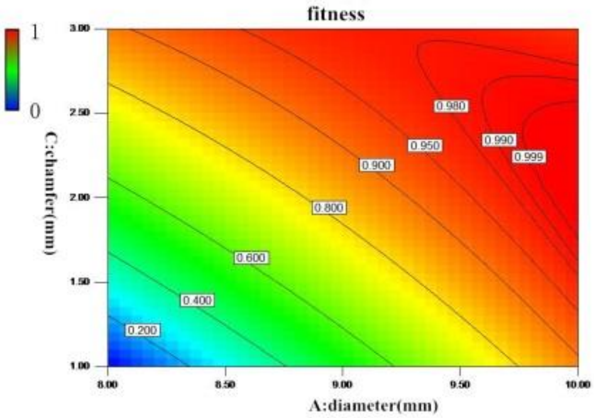


Fig. 7 - Response surface of fitness

As showed in Fig. 7, in the area with the fitness close to 1, we obtain the optimal solution. The optimal solution is found at hole diameter of 10 mm and chamfer of 2 mm. When the diameter and chamfer were assigned with integers, it facilitated the hole machining. Thus, we set hole diameter = 10 mm and chamfer = 2 mm. The hole depth has no significant effect on single-seed rate or cavity rate, but at large depth, the hole accommodates two seeds. The equivalent diameters of the seeds are 5.45-7.46 mm (mean 6.52), so the hole depth was set at 6.5 mm. Finally, the optimal combination of hole parameters is listed in Table 8.

Table 8

Optimal combination of hole parameters (mm)

Diameter *d*	Depth *h*	Chamfer *δ*
10	6.5	2

Contrast experiment

In this section, the new seeder and a vertical-disc seeder (a bristle brush wheel seeder) were sent into seed spacing consistency comparative test, so as to validate whether the new device can improve the seed spacing consistency.

(a) volume-variable hole precision seeder; (b) bristle brush wheel seeder.

Fig. 8 - Comparative test of seeders

To more precisely study the consistency of qualified seed spacings, we used longitudinal consistency (longitudinal seed spacing consistency) and transversal consistency (transversal seed spacing consistency) to measure qualified grain interval consistency. Specifically, the longitudinal seed spacing consistency was reflected by the seed spacing SD (σ_Z), while the transversal seed spacing consistency was measured by the SD away from the centreline (σ_H).

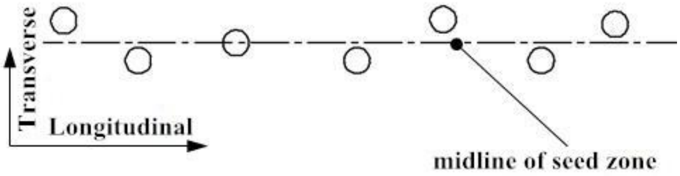
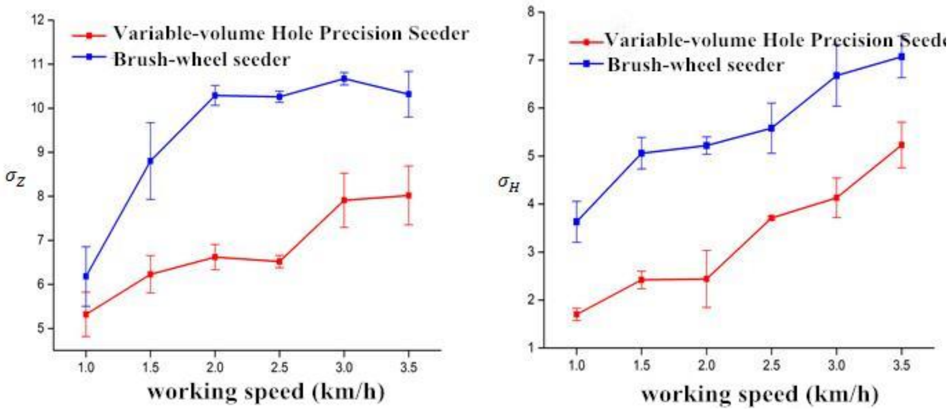


Fig. 9 - Seed zone transversal and longitudinal schematic diagrams



(a) (b)

Fig. 10 - σ_Z σ_H of two seeders

Note: A-σ_Z changes with velocity; B-σ_H changes with velocity

Comparative tests on the JPS-12 test bench show that the new seeder is superior over the vertical-disc seeder in terms of 14%-21% higher longitudinal consistency and 18%-26% higher transversal consistency. The variable-volume hole precision seeder with a cam push-rod structure would significantly improve the seed spacing consistency.

CONCLUSIONS

1) To improve the seed spacing consistency of vertical-disc seeders, we, starting from the mechanical compulsory seed metering, designed a variable-volume hole precision seeder that adopts a cam push rod structure to realize the compulsory seed metering. We studied the overall design of this new seeder.

2) The hole parameters of the new seeder were optimized via Box-Behnken trials. The trial scheme was implemented on the discrete software EDEM. Response surface regression and prediction optimization were conducted on Design-Expert. The single-seed rate and cavity rate were significantly affected by both hole diameter and chamfer. The regression equations of hole diameter, depth and chamfer against the single-seed rate or cavity rate were determined separately. The optimal solution of hole parameters is: diameter 10 mm, depth 6.5 mm and chamfer 2 mm.

3) Comparative tests on the bench show that the new seeder is superior to the vertical-disc device in terms of 14%-21% higher longitudinal consistency and 18%-26% higher transversal consistency. The shaped-hole volume-variable precision seeder with a cam push-rod structure would significantly improve the seed spacing consistency.

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