STUDY ON FILLING PERFORMANCE OF HOLE FERTILIZATION DEVICE AND OPTIMIZATION OF CAVITY
/
穴施肥装置充肥性能研究及肥腔优化

Zhiqi Zheng[1], Tao Wang[1], Zhengdao Liu[*1], Qingjie Wang[2] Hongbo Zhao[1] Suyuan Liu[1]
[1] College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling 712100, China;
[2] College of Engineering, China Agricultural University, Beijing 100083, China;
Tel: +86029 87092064; E-mail: liuzd@nwafu.edu.cn
DOI: https://doi.org/10.35633/inmateh-64-13

Keywords: *hole fertilization, fertilizer filling, discrete element method, cavity, structure optimization*

ABSTRACT
Hole fertilization is an effective method to improve the utilization rate of chemical fertilizer. In order to improve the accuracy and stability of the amount of fertilizer discharging for the hole fertilization device, this paper proposed the method of rotary filling by notched disk, designed a hole fertilization device with notched disk, and completed the structure design of the device and cavity. Through the dynamic analysis of fertilizer particles in the process of fertilizer filling, this study found that the interface span of fertilizer cavity, the rotational speed of fertilizer disk, and the amount of fertilizer applied in each hole are the main factors affecting the performance of filling. Then, this study carried out the three-factor quadratic orthogonal rotation combination simulation test to optimize the structure of the cavity. The test used the discrete element method with interface span of fertilizer cavity, the rotational speed of fertilizer disk, and the amount of fertilizer applied in each hole as test factors and the accuracy and variation coefficient of filling amount as evaluation indexes. Results showed that the optimal performance was obtained when the cross section span of the cavity was 13.58°, the opening width was 29.56 mm, and the depth was 22.08 mm. The field validation showed that the average accuracy of filling amount per hole was 97.67%, and the average variation coefficient was 1.90%. The performance of fertilizer discharge satisfied the design requirements, and agreed with the law of the simulation results. The research results could provide a theoretical basis for the design of hole fertilization device and the improvement of filling performance.

摘要
穴施肥技术是提高化肥利用率的有效手段，为提高穴施肥装置排肥量准确性和稳定性，本文提出了腔盘回转取肥法，并设计了腔盘式穴施肥装置，完成了排肥盘及肥腔的结构设计。重点围绕取肥环节，通过对取肥过程肥料颗粒的动力学分析，明确了肥腔界面跨度，排肥盘转速和每穴施肥量是影响取肥性能的主要因素；采用离散元法，以上述因素为试验因素，以排肥量准确度和变异系数为评价指标，进行了三因素二次正交旋转组合仿真试验，完成了肥腔结构优化，当肥腔截面跨度为 13.58°，开口宽度为 29.56 mm，深度为 22.08 mm 时取肥性能最优。田间验证试验表明，每穴排肥量准确度平均为 97.67%，变异系数平均值为 1.90%，排肥性能满足设计要求，且与仿真结果规律相同。研究结果可为穴施肥装置的设计及取肥性能的提升提供理论依据。

INTRODUCTION
At present, grain fertilizer is the main source for corn fertilization. However, in the seedling stage, the area of maize root is still small. Thus, the fertilizer between adjacent plants is not easy to be absorbed, resulting in low fertilizer utilization rate (*Zhu et al., 2016; Liu et al., 2019*). The hole fertilization technology is an effective method to improve the utilization rate of corn fertilizer, because this technology directly applies a certain amount of chemical fertilizer nearby the seed and limits it in a certain length range according to the law of corn fertilizer needs. (*Jiang et al., 2018; Tang et al., 2019; Zhang et al., 2020*)

In order to achieve precision hole fertilization of corn, related scholars have carried out a series of studies on hole fertilization device. For instance, Great Plains Mfg. Inc. has developed the AccuShot Corn Liquid Fertilizer Precision Hole Planter for liquid fertilizer. Wang et al. (*2018a, 2018b*) adopted a planetary gear pot-tying and spraying mechanism to achieve the hole application of rice liquid fertilizer. However, granular fertilizer is still the main type of fertilizer in China and many other countries. Thus, it is necessary to develop fertilizer device to improve the utilization rate of granular fertilizer.

Around the particle fertilizer hole application device, *Hu et al.* (*2016*) adopted rotary retaining blocks to achieve intermittent fertilizer discharge, and the performance test met the design requirements at a forward speed of 2.88 km/h. *Wang et al.* (*2020*) implemented intermittent discharge of fertilizer by installing a stopper with a hole at the discharge opening, with a working speed ranging from 1.8 km/h to 3.6 km/h. *Zhang et al.* (*2018*) adopted the opening and closing of the turning plate to achieve intermittent fertilization. The variation coefficient of fertilizer application amount per hole was 0.09 in their study. *Yuan et al.* (*2018*) designed a spoon-wheel hole fertilizer discharge device, with an experimental advance speed of 1.8 km/h. *Li et al.* (*2018*) designed an electrically driven external groove-wheel hole fertilizer discharge device, and the average pass rate of hole fertilizer application was 87.49% when the advancing speed was 2.48 km/h. Fertilizer quantitative distribution was achieved through different structures in the above studies, but the operating speed was all at 4 km/h.

Therefore, in order to ensure the fertilizer filling performance of the hole fertilization device at different operating speeds, this study aimed to propose the cavity and disc rotation fertilizer filling method to ensure the fertilizer filling performance of the hole fertilization device at different operating speeds. The following steps were carried out to achieve the main purpose of this study. First, we designed the cavity and disc type hole fertilization device and the structure of fertilizer discharging disk and fertilizer cavity. Then, this study optimized the fertilizer cavity structure through theoretical analysis and simulation calculation to improve the accuracy and stability of the amount of fertilizer discharging for hole fertilization device. We believed the study could provide theoretical basis for the design of hole fertilization device and the improvement of fertilizer filling performance.

MATERIALS AND METHODS

Structure and working principle of corn hole fertilization device

The structure of corn hole fertilization device is shown in Fig.1. The hole fertilization device is fixed on the front beam of the corn fertilization seeder and used with the sowing monomer. It is mainly composed of frame, colter, secondary fertilizer box, fertilizer discharging disk, cleaning mechanism, protecting chamber, pneumatic delivery mechanism, regulating mechanism fertilization amount, and transmission mechanism.

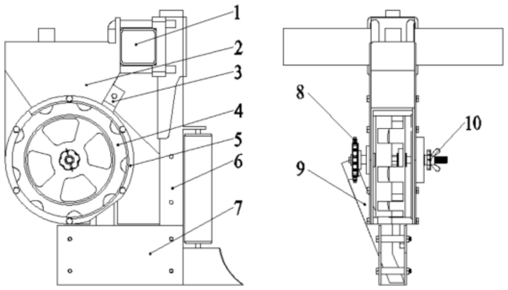


Fig. 1 - Overall structure of hole fertilization device

1) Front beam; 2) Secondary fertilizer box; 3) Fertilizer cleaning mechanism; 4) Fertilizer discharging disk; 5) Fertilizer protecting chamber; 6) Colter; 7) Soil retaining plate; 8) Drive sprocket; 9) Pneumatic delivery mechanism; 10) Regulating mechanism fertilization amount

The colter of the hole fertilization device adopts the no-tillage colter to prevent blockage, and the fertilizer bed is opened in the soil. The colter was designed with a soil retaining plate, so that the back end of the colter can maintain a complete trench type within a certain distance. The process of fertilizer from the box into the bed can be divided into four stages of filling, cleaning, transport and delivery. Driven by the driving force, the fertilizer discharge disk rotates around the central axis in the fertilizer protecting chamber and the secondary fertilizer box. When the fertilizer cavity passes through the secondary fertilizer box, it is filled with fertilizer. When the fertilizer cavity leaves the secondary fertilizer box with the fertilizer, the excess fertilizer is cleared out by the fertilizer cleaning mechanism and enters the fertilizer protecting chamber. The gap between the plate of the fertilizer protecting chamber and the fertilization cavity is less than the diameter of fertilizer particles. Fertilizers are always kept in the cavity in a lump-like form and transported to the fertilizer delivery mechanism at the bottom of the fertilizer care chamber with the rotation of the fertilizer discharge chamber and plate. Fertilizer delivery mechanism is connected with the fan, the lump-like fertilizer in the fertilizer cavity is discharged out of the fertilizer cavity and quickly delivered to the fertilizer ditch under the action of air flow and dead weight, and the hole type fertilizer discharge is completed.

Structure design of fertilizer discharge disk and cavity

Fertilizer discharging disk is the main carrier for carrying fertilizer. It is mainly composed of the main disk of fertilizer discharging, the auxiliary disk of fertilizer discharging, the main shaft of fertilizer discharging disk and the auxiliary shaft of fertilizer discharging disk. Fertilizer discharging disk is installed in the fertilizer protecting cavity. Its structure and installation method are shown in Fig. 2. A number of notches are distributed around the main plate, and the same number of matching bulges are distributed around the auxiliary plate. There is a hexagonal hole at the end of the main shaft, and the hexagonal shaft at the end of the auxiliary shaft is matched with the hexagonal hole. The main disk is fixed on the main shaft by a flat key and a clamp spring, and the secondary disc is installed on the secondary shaft in the same way. The main shaft and the auxiliary shaft are respectively installed on the wall of the fertilizer cavity and the side cover of the fertilizer cavity, so that the fertilizer discharge disk rotates in the fertilizer cavity. Main plate and auxiliary plate through the six-party axis and six square hole together, the disc gap and pair of disc bulge formed by the area is the fat cavity, deputy plate in fertilizer consumption by adjusting mechanism can be the main shaft of the six-party hole axial movement, change the raised amount of overlap and gap can adjust the cavity volume, and then adjust the single cavity fertilizer consumption.

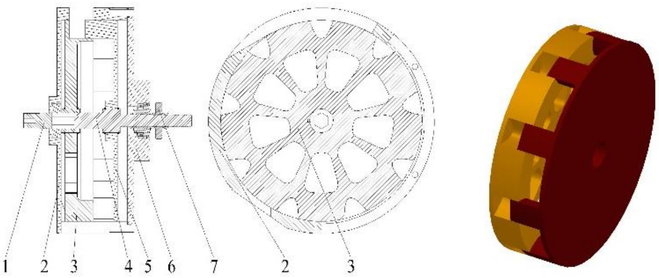


Fig. 2 - Structure diagram and three-dimensional shape of discharging fertilizer disk

1) Main shaft; 2) Wall of protecting chamber; 3) Main disk; 4) Auxiliary shaft; 5) Auxiliary disk; 6) Side cover; 7) Regulating mechanism of fertilization amount

Fertilizer cavity is the most important part of fertilizer disk, and its structural parameters will directly affect the movement of fertilizer group in the process of fertilizer discharging, especially in the stage of fertilizer collecting, the structure of fertilizer cavity has a great influence on the performance of fertilizer collecting disk. The cavity of the fertilizer discharging disk is surrounded by the notch of the main disk and the bulge of the auxiliary disk. In order to facilitate the filling and discharging of fertilizer, the cross section of the fertilizer chamber is generally curved and open-shaped. The shape of the fertilizer cavity was obtained by using the spline curve in Cro/E, as shown in Fig.3. The spline curve used in Cro/E is B-spline curve, and the cross section shape of the fertilizer cavity is determined by A, B and C, and its structural parameters include the cross section span and depth of the fertilizer cavity.

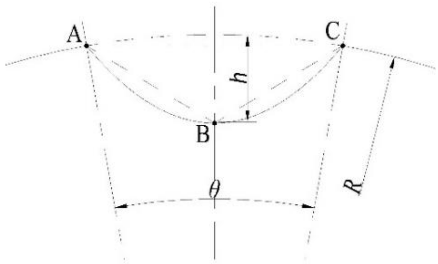


Fig. 3 - Structure drawing of fertilizer cavity

where: θ is the cross section span of fat cavity, (°);

R is the diameter of fertilizer discharging disk, mm;

h is the depth of cavity, mm.

In China, corn strip fertilization is generally applied in the range of 300 kg/hm^2 to 750 kg/hm^2 (*Rinnan et al., 2007; Cozzolino et al, 2006*). *Jiang et al.* (*2018*) showed that compared with strip fertilization, summer corn hole fertilization could improve nitrogen fertilizer performance use efficiency by 12.4% and phosphorus fertilizer performance use efficiency by 27.2%. Therefore, in this paper, when setting the maximum amount of fertilizer applied to each hole, the maximum amount of fertilizer applied by strip fertilization method was calculated as 80%. When the sowing row spacing of corn was generally 600 mm and the planting spacing was 250 mm, the maximum amount of fertilizer applied in each hole was calculated as 9 g. The measured bulk density of fertilizer particles is 8.3×10^{-4} g/mm^3, the maximum adjustment length of fertilizer chamber is 30 mm, and the calculated cross-section area of fertilizer chamber is 361.43 mm^2, rounded to 360 mm^2.

In the fertilizer filling stage, the fertilizer chamber rotates along with the discharge disk through the secondary fertilizer box, and the fertilizer in the secondary fertilizer box is filled into the fertilizer chamber under the disturbance of its own gravity and the fertilizer disk. The force and movement of fertilizer particles in the filling process are mainly affected by the rotating speed of fertilizer disk, the thickness of fertilizer in the secondary fertilizer box and the depth of fertilizer chamber. In the actual work process, the secondary fertilizer box is always full of fertilizer, and the accumulation thickness of fertilizer in the secondary fertilizer box is only used as the test condition, not as the test factor. Therefore, this paper will take the cross section span of the fertilizer chamber, the speed of the fertilizer disk and the thickness of the fertilizer chamber as the test factors to study the influence rules of the three factors on the performance of the fertilizer chamber.

Experiment design

In this paper, the discrete element method is used to simulate and analyze the process of fertilizer filling. Fertilizer plate simulation model and fertilizer simulation model were established by using Cro/E and EDEM software respectively. The fertilizer used in the experiment is a compound fertilizer commonly used in corn in North China, and the manufacturer is Hebei Zhongren Fertilizer Group Co., Ltd., with a moisture content of 4.37%. The particle shape is nearly spherical, the diameter distribution conforms to the normal distribution, the central value is 2.967 mm and the standard deviation is 0.25. The material contact and intrinsic parameters are shown in Table 1.

Table 1

Material contact and intrinsic parameters

Attribute	The fertilizer particle	Metal components
Poisson's ratio	0.25	0.269
Shear modulus (Pa)	0.29×10^{9}	8.12×10^{10}
density (kg/m^3)	1490	7890
Coefficient of restitution	0.40 (Fertilizer particle – Fertilizer particle)	0.50(Particle - metal construction)
Static friction coefficient	0.43 (Fertilizer particle – Fertilizer particle)	0.50(Particle - metal construction)
Rolling friction factor	0.05 (Fertilizer particle – Fertilizer particle)	0.01(Particle - metal construction)

This paper took the end span of fertilizer cavity, the speed of fertilizer disk and the amount of fertilizer applied in each hole as the test factors. Using the variation coefficient of the average amount of fertilizer applied and the amount of fertilizer applied per hole as the evaluation index, a three-factor quadratic orthogonal rotation combination test was carried out.

(1) Cross section span of fertilizer cavity

Since the cross section area of the cavity is determined to be 360 mm^2, the cross section span of the cavity determines the opening width and depth of the cavity section. In order to avoid too small opening width, which may affect fertilizer filling into the fertilizer chamber, the opening width and depth of the fertilizer chamber are equal, that is, the opening width of 23.3 mm is the minimum width, and the corresponding minimum cross section span of the fertilizer chamber is 10.70°. The minimum depth was 4 times the average particle diameter (2.967 mm), i.e., the maximum width was 40.1 mm, and the corresponding maximum span was 20.29 mm, in order to avoid the shallow cavity causing the particle size in the fertilizer cavity to be less than the theoretical application amount. Therefore, the cross section span of the fertilizer cavity in the test is 10° to 20°.

(2) Speed of fat plate

The rotating speed of fertilizer disk is determined by the advancing speed of the machine and tools, the spacing of sowing plants and the number of fertilizer cavities of fertilizer disk etc., and its calculation formula is:

$$n_p = \frac{v}{60\ l_p N} \times 10^6 \tag{1}$$

Where:

n_p is the speed of fertilizer discharging disk, r/min; l_p is the spacing of sowing plants, mm; v is the forward speed of the machine and tools, km/h; N is the number of fertilizer cavities in the fertilizer discharging disk.

The maximum cross section span of fertilizer chamber is 20°. In order to ensure that the distribution length of fertilizer in each hole in the soil is not more than half of the planting distance, the interval Angle between each fertilizer chamber must be greater than 2 times of the cross section span of fertilizer chamber. If the interval between adjacent fertilizer chambers is 40°, the number of fertilizer cavities in fertilizer discharge disk is 9. The planting spacing of maize was 250 mm, the forward speed of the machine was 3~8 km/h, and the speed range of the fertilizer disk was 22.22 r/min to 59.26 r/min. Therefore, the speed range of compost plate in the test was 20 r/min to 60 r/min.

(3) The amount of fertilizer applied to each point

When the cross section area of the cavity is determined, the amount of fertilizer applied to each hole is determined by the thickness of the cavity. The maximum adjustment distance of the fertilizer chamber is 30 mm, corresponding to the maximum fertilization amount of each hole which is 9 g. Since the thickness of the fertilizer chamber must be greater than zero, the minimum value is 5 mm, corresponding to the minimum fertilization amount of each hole which is 1.5 g. Therefore, the range of fertilizer application per hole in the test was 1.5 g to 9 g.

According to the ternary quadratic orthogonal rotation test design method, the horizontal coding of test factors is obtained, as shown in Table 2.

Table 2

Factor level coding table

The level	factors		
	Fertilizer cavity section span X_1 (°)	Fertilizer discharging disk rotational speed X_2 (r/min)	Fertilization amount per hole X_3 (g)
γ	20	60	9
1	17.97	51.89	7.48
0	15	40	5.25
-1	12.03	32.16	3.02
-γ	10	20	1.5
Δ*j*	2.97	14.86	2.23

The test indexes include variation coefficient and accuracy of fertilization amount. The test method is shown in Fig. 4. In the post-treatment stage, a Mass flow sensor was added below the exit of the secondary fertilizer box. The area covered by the Mass flow sensor should be larger than the cross section area of the fertilizer chamber, and there could only be one fertilizer cavity in the area at the same time, so the diameter of the Mass flow sensor was 20 mm. The change of the total fertilizer particle mass in the sensor covered area with time was recorded during the process of each fertilizer cavity passing through the sensor.

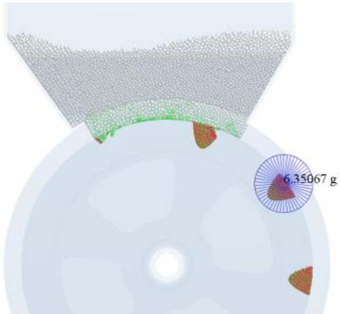


Fig. 4 - Grid bin group and mass flow sensor location

Calculation formula of each index:

(1) Variation coefficient of filling amount in each cavity

$$C_V = \frac{\sqrt{\frac{1}{n_1}\sum_{i=1}^{n_1}(m_{imax} - \overline{m}_{max}}}{\overline{m}_{max}} x100\ \% \qquad (2)$$

Where: n_1 is the number of fertilizer cavity passing through the mass flow sensor in the simulation period (excluding the first and last one); m_{imax} is the maximum mass in the sensor area during the process of the cavity passing through the mass flow sensor, g; m_{max} is the arithmetic mean of m_{imax}, g.

(2) Accuracy of filling amount in each cavity

$$\zeta = \frac{\sum_{i=1}^{n_1 \Sigma} m_{imax}}{n_1 M_h \%} \qquad (3)$$

Where:

M_h is the theoretical fertilizer application rate per hole, g.

In order to ensure continuous fertilizer supply throughout the whole simulation test process, and there is still enough residual fertilizer stored in the fertilizer box, the total mass of particles generated in the fertilizer box is set as 3 kg. The simulation time step was set as 15% Rayleigh time step, the output time step was 0.01 s, the grid size was 5.44 mm, and the total length of simulation time was 5 s.

RESULTS

Expert Design 8.0.6 software was used to design the experiment and record the test results. The test scheme and results are shown in Table 3. After the experiment, quadratic regression analysis was conducted on the test results and multiple regression fitting was performed to obtain the regression equations of the Variation coefficient of fertilizer discharge rate Y_1 and the accuracy of filling amount rate Y_2 at each hole.

Table 3

Test scheme and results

Test serial number	Fertilizer cavity section span X_1	Fat disk rotational speed X_2	Fertilization amount per hole X_3	Variation coefficient of filling amount Y_1 (%)	Accuracy of filling amount Y_2 (%)
1	-1	-1	-1	2.24	81.32
2	1	-1	-1	2.55	76.92
3	-1	1	-1	3.23	74.10
4	1	1	-1	4.00	70.24
5	-1	-1	1	1.67	87.60
6	1	-1	1	1.5	82.16
7	-1	1	1	1.27	84.22
8	1	1	1	2.24	77.92
9	-1.682	0	0	1.85	83.76
10	1.682	0	0	2.96	74.04
11	0	-1.682	0	1.63	85.19
12	0	1.682	0	2.32	79.87
13	0	0	-1.682	4.35	68.55
14	0	0	1.682	1.27	85.10
15	0	0	0	1.95	82.74
16	0	0	0	1.88	81.11
17	0	0	0	1.70	80.59
18	0	0	0	2.23	83.24
19	0	0	0	1.82	81.93
20	0	0	0	2.18	83.74
21	0	0	0	1.79	82.37
22	0	0	0	1.83	81.52
23	0	0	0	2.07	83.21

Significance analysis of variation coefficient of filling amount (Y_1)

The software Design Expert 8.0.6 was used to conduct variance analysis on the test results, and the results are shown in Table 4. As can be seen from Table 4, the test model is extremely significant ($P < 0.01$). Among the main factors, the section span of fertilizer cavity, the rotational speed of fertilizer disk and the amount of fertilizer application all had extremely significant effects on the variation coefficient of filling amount at each hole, and the order of influence of each factor on the variation coefficient of filling amount was $X_3>X_2>X_1$. Among the interaction terms, X_2X_3 has a very significant effect on the variation coefficient of filling amount, X_1X_2 has a significant effect, but X_1X_3 has no significant effect. In the quadratic term, X_3^2 has a very significant effect on the variation coefficient of filling amount, and X_1^2 has a significant effect. After incorporating the non-significant factors into the residual items, variance analysis was conducted again. The results are shown in Table 4. The regression equation between each factor and indicator is:

$$Y_1 = 8.056 - 0.632X_1 - 0.009X_2 - 0.562X_3 + 0.006X_1X_2 - 0.010X_2X_3 + 0.017{X_1}^2 + 0.058{X_3}^2 \quad (4)$$

Where: X_1 represents the cross section span of fertilizer cavity, X_2 represents the rotating speed of fertilizer plate, and X_3 represents the amount of fertilizer application.

The loss of fit test for the above regression equation shows that $P > 0.1$ is not significant, which proves that there is a significant quadratic relationship between the test index and the test factors.

Table 4

Variance analysis of variation coefficient of filling amount

Sources of variation	Sum of squares	Degrees of freedom	The mean square	*F*	*P*
Model	12.819/12.809	9/7	1.424/1.830	28.399/41.446	<0.0001***/<0.0001***
X_1	1.028/1.028	1/1	1.028/1.028	20.495/23.282	0.0006***/0.0002***
X_2	1.137/1.137	1/1	1.137/1.137	22.668/25.751	0.0004***/0.0001***
X_3	8.104/8.104	1/1	8.104/8.104	161.567/183.541	<0.0001***/<0.0001***
X_1X_2	0.320/0.320	1/1	0.320/0.320	6.380/7.248	0.0253**/0.0167**
X_1X_3	0.010	1	0.010	0.195	0.6657
X_2X_3	0.551/0.551	1/1	0.551/0.551	10.991/12.486	0.0056***/0.0030***

Table 4
(continuation)

Variance analysis of variation coefficient of filling amount

Sources of variation	Sum of squares	Degrees of freedom	The mean square	*F*	*P*
X_1^2	0.342/0.342	1/1	0.342/0.342	6.824/7.757	0.0215**/0.0139**
X_2^2	0.0004	1	0.0004	0.009	0.9268
X_3^2	1.336/1.336	1/1	1.336/1.336	26.635/30.267	0.0002***/< 0.0001***
Lost to poor	0.383/0.393	5/7	0.077/0.056	2.280/1.672	0.1437/0.2432
error	0.269/0.269	8/8	0.034/0.034		

notes：The figures under "/" are the results of ANOVA after excluding the insignificant factors："***" means extremely significant（*P* < 0.01）；"**" means significant（0.01 < *P* <0.05）；"*" means more significant（0.05 < *P* < 0.1），It is the same in the following.

Significance analysis of accuracy of filling amount (Y_2)

The results of variance analysis of Y_2 for fertilizer discharge accuracy are shown in Table 5. As can be seen from Table 5, the experimental model was significant (P < 0.01). Among the main factors, the cross section span of fertilizer cavity, the rotating speed of fertilizer disk and the fertilizing amount all had extremely significant effects on the accuracy of filling amount. Among the interaction terms, X_2X_3 had a significant effect on the accuracy of filling amount, while the other interaction terms had no significant effect. In the quadratic term, both X_1^2 and X_3^2 have extremely significant effects on the Variation coefficient of fertilizer discharge, while X_2^2 has no significant effects. After incorporating the non-significant factors into the residual items, variance analysis was conducted again. The results are shown in Table 5, and the regression equation between each factor and indicator is

$$Y_2 = 82.33 - 2.66X_1 - 2.23X_2 + 4.18X_3 + 0.79X_2X_3 - 1.18{X_1}^2 - 1.91{X_3}^2 \quad (5)$$

The loss of fit test for the above regression equation shows that P > 0.1 is not significant, which proves that there is a significant quadratic relationship between the test index and the test factors.

Table 5

Variance analysis of accuracy of filling amount

Sources of variation	Sum of squares	Degrees of freedom	The mean square	*F*	*P*
Model	490.304/488.603	9/6	54.478/81.434	37.046/62.589	<0.0001***/<0.0001***
X_1	96.736/96.736	1/1	96.736/96.736	65.783/74.350	<0.0001***/<0.0001***
X_2	67.969/67.969	1/1	67.969/67.969	46.221/52.241	<0.0001***/<0.0001***
X_3	239.187/239.187	1/1	239.187/239.187	162.653/183.837	<0.0001***/<0.0001***
X_1X_2	0.013	1	0.013	0.009	0.9271
X_1X_3	1.514	1	1.514	1.029	0.3288
X_2X_3	4.930/4.930	1/1	4.930/4.930	3.352/3.789	0.0901*/0.0694*
X_1^2	22.080/22.109	1/1	22.080/22.109	15.015/16.992	0.0019***/0.0008***
X_2^2	0.174	1	0.174	0.118	0.7365
X_3^2	58.115/58.162	1	58.115/58.162	39.520/44.702	<0.0001***/<0.0001***
Lost to poor	10.055/11.755	5/8	2.011/1.469	1.775/1.297	0.2241/0.3609
error	9.062/9.062	8/8	1.133/1.133		

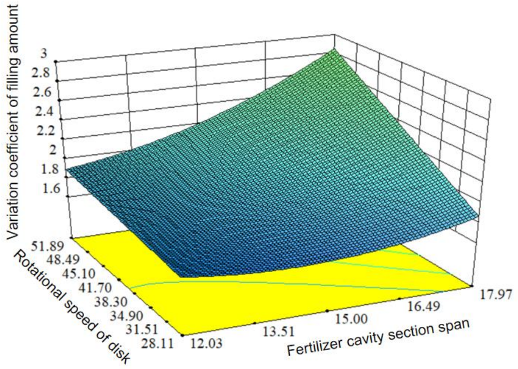
According to the significance analysis, X_1X_2 and X_2X_3 had significant effects on the variation coefficient of fertilization rate, and X_2X_3 had significant effects on the accuracy of fertilization rate. Through data processing with Desk-Expert 8.0.6, the response surface of interaction effect on the variation coefficient and accuracy of fertilizer filling was obtained.

As for the variation coefficient of fertilizer quantity, the interaction between the speed of fertilizer plate and the section span of fertilizer cavity is shown in Fig. 5a. When the rotational speed of each fertilizer cavity is fixed, the variation coefficient of fertilizer quantity decreases first and then increases with the cross section span of the fertilizer cavity, and the optimal cross section span of the fertilizer cavity is 12° to 15°. When the cross section span of the fertilizer cavity is fixed, the variation coefficient of fertilizer quantity increases with the increase of the speed of the fertilizer disk, and the optimal speed range of the fertilizer disk is 40 r/min to 55 r/min.

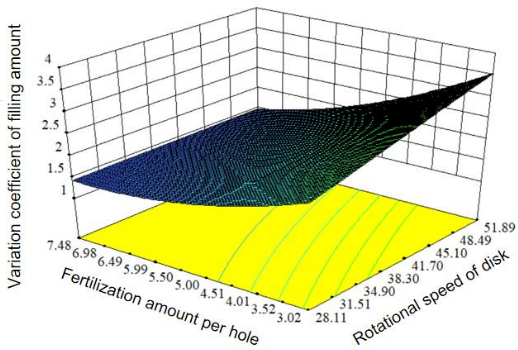
For the variation coefficient of fertilization amount, the interaction between the speed of fertilizer plate and the amount of fertilizer applied in each hole is shown in Fig. 5b. When the amount of fertilizer was fixed in each hole, the variation coefficient of fertilization amount increased with the increase of the speed of fertilizer disk, and the optimal range of the speed of fertilizer disk was 40 r/min to 60 r/min.

When the rotational speed of fertilizer plate was fixed, the variation coefficient of fertilization amount decreased with the increase of fertilization amount in each hole, and the optimal range of fertilization amount in each hole was 7 g to 8 g.

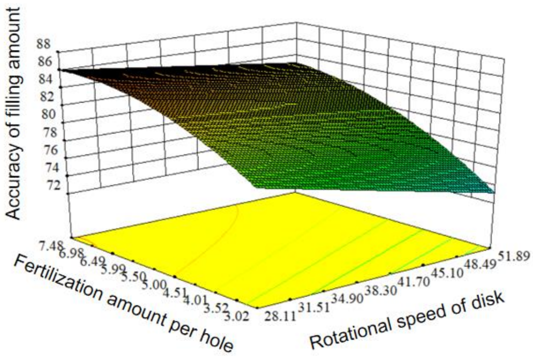
As for the accuracy of fertilizer filling, the interaction between the speed of fertilizer plate and the amount of fertilizer applied in each hole is shown in Fig. 5c. When the amount of fertilizer was fixed in each hole, the accuracy of fertilization amount decreased with the increase of the speed of fertilizer disk, and the optimal range of the speed of fertilizer disk was 40 r/min to 60 r/min. When the rotational speed of the fertilizer disk was fixed, the accuracy of fertilizer filling increased with the increase of fertilization amount in each hole, and the optimal range of fertilization amount in each hole was 6 g to 8 g.



(a) Variation coefficient of filling amount influenced by X_1X_2



(b) Variation coefficient of filling amount influenced by X_2X_3



(c) Accuracy of filling amount influenced by X_2X_3

Fig. 5 - Response surface of interaction to test index

In order to obtain the optimal structural parameters of the fat cavity, the optimization module of Design Expert 8.0.6 software was used to solve the constraint objective optimization of the above two regression models. In order to make the fertilizer disk meet the requirements of various forward speeds and fertilization amount, the difference values of the speed of fertilizer disk and fertilization amount of each hole were taken when selecting the optimal constraint conditions, objectives and constraint functions. That is, the rotational speed of the fertilizer disk is 50 r/min, and the fertilization amount per hole is 3 g.

The final objective function is:

$$\begin{cases} \min Y_1(X_1, X_2, X_3) \\ \max Y_2(X_1, X_2, X_3) \\ \text{s.t.} \begin{cases} 12 \le X_1 \le 15 \\ X_2 = 50 \\ X_3 = 3 \end{cases} \end{cases} \tag{6}$$

The objective function was optimized and solved. The results were as follows: when the cross section span of the fertilizer cavity was 12.35°, the rotational speed of the fertilizer disk was 50 r/min, and the fertilization amount per hole was 3 g, the variation coefficient of fertilization amount was 3.20%, and the accuracy of fertilization amount was 75.05%. Fertilizer application rate in each hole and fertilizer disk speed were changed to the optimal values under operating conditions, that is, fertilizer discharge disk speed was 20 r/min, fertilizer application rate in each hole was 9 g, the variation coefficient of fertilization amount was 1.89%, and the accuracy of fertilization amount was 86.93%.

When the cross section span of the fertilizer cavity is 12.35°, the accuracy of fertilizer filling varies from 75.05% to 86.93% with the change of the rotational speed of the fertilizer disk (the moving speed of the machine) and the fertilizer application amount per hole. In order to keep the accuracy of the fertilizer disk near 100% and the diameter of the fertilizer disk unchanged, the opening width and depth of the section of the fertilizer cavity are increased to 1.23 times of the original. That is, after the final optimization, the cross section span of the cavity is 13.58°, the opening width of the cavity is 29.56 mm, and the depth of the cavity is 22.08 mm.

The verification test was carried out under the operating conditions of the central group, namely, the rotational speed of the fertilizer disk was 40 r/min, and the fertilization amount applied to each hole was 5.25g. The test results showed that the average fertilization amount was 5.221 g, the accuracy of fertilization amount was 98.45%, and the variation coefficient of fertilization amount was 1.74%, which met the design requirements.

Verification test

The field performance test was carried out in April 2019. The experimental site was selected at the Cultivated Land Conservation Observation and Experiment Station in North Hebei, China Agricultural University, located in Dongchengfang Town, Zhuozhou City, Hebei Province (115° 56'E, 39° 28'N). In order to test the operating performance of the machine under different operating conditions, the forward speed of the machine was selected as the test factor for single factor test. Fertilizer application rate was set at 6 g/plant, the advancing speed of the machine was 3, 4, 5 and 6 km/h, respectively. The operating length of each group was 100 m, among which the middle 60 m was the stable operation area. During the test, the seeding depth and fertilization depth were measured after the normal operation of the seeder. Since it is difficult to observe and sample after the fertilizer is placed in the soil, the depth of sowing fertilization is adjusted to 0 during the test to make the seeds and fertilizer fall on the surface, as shown in Fig. 6.

Fig. 6 - Seed and fertilizer distribution

The experimental results showed that when the application amount was 6 g per hole and the moving speed of the machine was 3, 4, 5 and 6 km/h, the actual fertilizer discharge amount per hole was 5.88, 5.79, 5.91 and 5.86 g, respectively. The variation coefficients of the application amount per hole were 2.39%, 1.78% and 1.52%, respectively, which did not show significant difference. The average amount of fertilizer applied in each hole was 5.86 g, the average accuracy of filling amount was 97.67%, and the average variation coefficient of fertilizer application in each hole was 1.90%. The performance of fertilizer discharge met the design requirements, and the law was the same with the simulation results, which verified the accuracy of the simulation test.

CONCLUSIONS

(1) This study put forward the rotation of cavity and plate for fertilizer extraction according to the agronomic requirements of corn hole fertilization and sowing. Meanwhile, this study designed the overall structure of the cavity fertilization device, the fertilizer discharging plate, and fertilizer cavity. Through the dynamic analysis of fertilizer particles in the process of fertilizer filling, we found that the main factors affecting the performance of fertilizer filling were the cross section span of fertilizer cavity, the rotational speed of fertilizer disk, and the amount of fertilizer applied in each hole.

(2) The discrete element method was used to carry out the three-factor quadratic orthogonal rotation combination test. The effects of the cross section span of the fertilizer cavity, the speed of the fertilizer disk, and the application rate of fertilizer per hole on the variation coefficient and accuracy of fertilizer filling were

studied. The structure of the fertilizer cavity was optimized. The cavity performed the best when the cross section span of the cavity is 13.58°, the opening width of the cavity is 29.56 mm, and the depth of the cavity is 22.08 mm.

(3) The verification test in the corn field showed that the average accuracy of filling amount in each hole was 97.67%, and the average variation coefficient of fertilizer application in each hole was 1.90%. The fertilizer discharge performance satisfied the design requirements, and agreed with the law in the simulation results, which verified the accuracy of the simulation test.

ACKNOWLEDGEMENT

This work was supported by the National Key R & D Program - Key Techniques and Equipment for Precision Sowing and Precision-deep Fertilization in Northern China (Grant No. 2016YFD0200600).

REFERENCES

[1] Cozzolino D., Morón A., (2006), Potential of near-infrared reflectance spectroscopy and Chemometrics to predict soil carbon fractions. *Soil & Tillage Research*, vol. 85, issue 1, pp. 78-85.
[2] Hu H., Li H., Wang Q. et al., (2016), Design and experiment of a topdressing machine for deep application of maize at fixed point between rows. *Transactions of the Chinese Society of Agricultural Engineering*, vol. 32, issue 24, pp. 26-35.
[3] Jiang C., Wang H., Lu D. et al., (2018), The yield and nutrient absorption and utilization efficiency of summer maize were improved by one-time application of urea in root zone. *Transactions of the Chinese Society of Agricultural Engineering*, vol. 34, issue 12, pp. 146-153.
[4] Li S., (2018), Design and experiment of side deep burrow fertilization device with electromechanical drive for precision burrow direct seeding of rice, *Northeast Agricultural University*.
[5] Liu Z., Zhao Y., Guo S. et al., (2019), Enhanced crown root number and length confers potential for yield improvement and fertilizer reduction in nitrogen-efficient maize cultivars, *Field Crops Research*, vol. 241, pp. 107562.
[6] Luo X., Liao J., Hu L., et al., (2016), Raise agricultural mechanization level to promote agricultural sustainable development. *Transactions of the Chinese Society of Agricultural Engineering*, vol. 32, issue 01, pp. 1-11.
[7] Rinnan R., Rinnan S., (2007), Application of near infrared reflectance (NIR) and fluorescence spectroscopy to analysis of microbiological and chemical properties of arctic soil. *Soil Biology & Biochemistry*, vol. 39, issue 07, pp. 1664-1673.
[8] Tang H., Wang J., Xu C., et al., (2019), Research progress analysis on key technology of chemical fertilizer reduction and efficiency increase, *Transactions of the Chinese Society for Agricultural Machinery*, vol. 50, issue 4, pp. 1-19.
[9] Wang J., Li S., Z. Z., (2018a), Design and experiment of side deep burrow fertilization system with electromechanical drive for precision burrow direct seeding of rice (English). *Transactions of the Chinese Society of Agricultural Engineering*, vol. 34, issue 08, pp. 43-54.
[10] Wang J., Zhou W., Bai H., (2018b), Design and Test of Differential Bidirectional Fertilizer Supply and Distribution Device for Liquid Fertilizer Deep applicator. *Transactions of the Chinese Society for Agricultural Machinery*, vol. 49, issue 06, pp. 105-111.
[11] Wang Z., Liang C., Wang H., (2020), Design and experiment of corn variable hole fertilization test bed. *Mechanization research*, vol. 42, issue 04, pp. 166-169.
[12] Yuan W., Li K., Jing C., (2018), Design and test of hole fertilizer dispenser. *Mechanization research*, vol. 40, issue 1, pp. 145-149.
[13] Zhang L., Song H., Chen X., et al., (2020), Primary study on nutrient migration under hole fertilization in soils, *Soils*, vol. 52, issue 6, pp. 1145-1151.
[14] Zhang J., Liu H., Gao J., (2018), SPH simulation and experiment of maize delamination positive hole fertilization and precision seeder. *Transactions of the Chinese Society for Agricultural Machinery*, vol. 49, issue 9, pp. 66-72.
[15] Zhou W., Sun X., Liu Z., et al., (2020), Simulation analysis and test of interaction between needle body and soil of liquid fertilizer hole applicator. *Transactions of the Chinese Society for Agricultural Machinery*, vol. 51, issue 4, pp. 87-94.
[16] Zhu S., Jorge M. V., Daniel K. M., (2016), Nitrogen fertilizer rate affects root exudation, the rhizosphere microbiome and nitrogen-use-efficiency of maize, *Applied Soil Ecology*, vol. 107, pp. 324-333.