DESIGN AND EXPERIMENTS OF A LAYERED FERTILIZER SHOVEL FOR MAIZE
/
玉米分层施肥铲设计与试验

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ABSTRACT
A layered fertilizer shovel is designed to achieve double layer fertilization in response to the current problem of large fertilizer efficiency loss in one-time banding application. The key structural parameters of the layered shovel were designed and the working speed V, the distance L_1 between the banding fertilizer discharging pipe and the point-applied fertilizer discharging device and the distance L_2 between the fertilizer distribution plate and the point-applied fertilizer discharging device were determined as the main factors affecting the layered distance h. A quadratic regression model between factors and indicators was established by single-factor test and response surface analysis. With the layered distance h=10 cm as the optimization target, the predicted value of layered distance h is 10 cm when V, L_1 and L_2 are 2.7 km/h, 15.3 cm and 18.2 cm, respectively, and the simulation test is conducted to verify the combination of the parameters obtained from the optimization solution, and the simulated value of layered distance h is 9.9 cm, which is a small error compared with the predicted value. The field test was conducted under the optimal combination of parameters, and the results showed that the layered distance h was 9.1 cm at the working speed V of 2.7 km/h, and the relative error was 8.1% compared with the simulation value, which can be considered as a high reliability of the simulation test, and the simulation test can accurately simulate the distribution of fertilizer particles in the real environment in the field. When the working speed V is 1.8-5.4 km/h, the distribution range of layered distance h is 8.0-9.5 cm, which can meet the agronomic requirements of fertilizer layered application.

摘要
针对目前肥料一次性条施存在肥效损失大的问题，设计了一种分层施肥铲，实现双层施肥。对分层施肥铲的关键结构参数进行了设计，确定作业速度 V、条施肥排肥管与穴施肥排肥器间距离 L_1 和分肥板与穴施肥排肥器间距离 L_2 为影响分层距离 h 的主要因素。通过单因素试验和响应面分析建立因素和指标间的二次回归模型。以分层距离 h=10 cm 为优化目标，得到作业速度 V、条施肥排肥管与穴施肥排肥器间距离 L_1 和分肥板与穴施肥排肥器间距离 L_2 分别为 2.7 km/h、 15.3 cm 和 18.2 cm 时，分层距离 h 预测值为 10 cm，对优化求解得到的参数组合进行仿真试验验证，得到分层距离 h 仿真值为 9.9 cm，与预测值相比误差较小。在最优参数组合下进行田间试验，结果表明作业速度 V 为 2.7 km/h 时，分层距离 h 为 9.1 cm，与仿真值相比相对误差为 8.1%，可认为仿真试验可信度高，仿真试验可准确模拟肥料颗粒在田间真实环境下的分布情况。当作业速度 V 为 1.8-5.4 km/h 时，分层距离 h 的分布范围为 8.0-9.5 cm，可满足肥料分层施用的农艺要求。

INTRODUCTION
Maize is the largest and most productive food crop in China, and plays a leading role in the country's food production and food security (*Li et al.*, *2017*). As China's per capita arable land continues to decrease, increasing yields has become the only way to ensure food security and people's livelihood (*Liu et al.*, *2018*). In order to ensure high crop yields, farmers apply chemical fertilizers in large quantities while causing serious surface pollution and fertilizer waste, which restricts the sustainable development of agricultural production Zhang *et al.*, *2021*). In order to improve crop yield and fertilizer use efficiency, a lot of research has been carried out by scholars at home and abroad (*He et al.*, *2014*).

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Farmers used to apply fertilizer in a one-time banding fertilization at a distance of 5-10cm from the seed row and 10cm deep when sowing maize (as shown in Figure 1), some of the fertilizer is in the soil far from the roots and the root system is very inefficient, the released nutrients are not absorbed and used in time, the excess fertilizer nutrients leave the cultivated soil due to runoff, leaching or gaseous loss, thus causing groundwater or atmospheric pollution (*Ye et al.*, *2010; Zhu et al., 2013; Chen et al., 1995*). In recent years, there has been widespread interest in the root zone application pattern (as shown in Figure 1). It has been found that when fertilizer is point-applied in a single burrow 5-10 cm away from the plant and 10 cm deep at the time of sowing, ammonia volatilization and run-off losses from urea granules are significantly reduced, thus greatly improving the utilization of nitrogen fertilizer (*Cao et al.*, *1984; Savan et al., 1980*). Zhou et al. found that a single root-zone point application under monopoly furrow with full film cover was beneficial to the concentration of nitrogen in the soil tillage layer, improving the efficiency of nitrogen use by summer maize and promoting the accumulation of dry matter and yield of summer maize (*Zhou et al.*, *2020*). Jiang et al. found that a one-time root zone point application of urea increased yield by 9.8% and 8.8%, respectively, and the apparent nitrogen fertilizer utilization rate increased by 12.4% and 8.3%, respectively, compared with a one-time banding application of urea and farmers' customary split application of nitrogen, so a one-time root zone point application of urea can achieve the effect of slow-release fertilizer and improve the utilization rate of nitrogen fertilizer (*Jiang et al., 2018*; *Jiang et al.*, *2019; Jiang et al., 2018; Jiang et al., 2018*). Zhang et al. used indoor simulations to investigate the nutrient transport patterns of nitrogen, phosphorus and potassium under the point application conditions of urea, ammonium polyphosphate and potassium chloride compound fertilizers (*Zhang et al.*, *2020*). He found that the nitrification of ammonium nitrogen under fertilizer cavity application conditions was inhibited by the high concentration of nutrients in the fertilizer interval, thus delaying the conversion of ammonium nitrogen to nitrate nitrogen, which is an important reason for the sustained and efficient supply of nitrogen in the root zone primary application technique. Guo et al. showed that full inter-plant point application increased plant yield by 3.70%, above-ground biomass by 3.56% and N and P nutrient accumulation by 11.24% and 19.44% compared with open-row strip application (*Guo et al.*, *2020*). Wang et al. believes that most crops have a low proportion of inter-root soil in the total volume of farm soil, and the nutrients absorbed by the root system mainly come from the soil around the root zone (*Wang et al.*, *2013*). Fertilizer application in the root zone is the best way to match the dynamic range of fertilizer nutrient diffusion with the dynamic range of root extension, which has a significant effect on weight loss and efficiency.

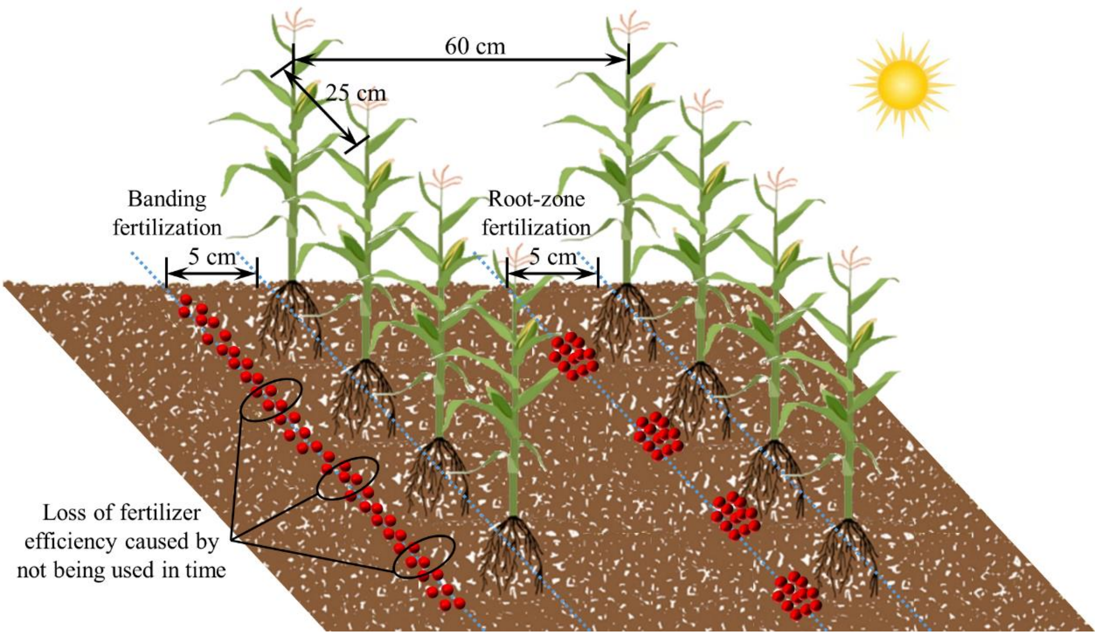

Fig. 1 – Agronomic diagram of banding and root zone fertilizer application

Studies have shown that the most active root system of maize plants is at 10 cm before and after the pulling stage, the most active root system is at 20 cm before and after the spitting stage, and the dry weight of the root system in the depth range of 0-20 cm accounts for more than 80% of the total dry weight of the root system from the trumpet stage to the finishing stage (*Guan et al.*, *2006*). The root system is most active within 20 cm of the horizontal distribution.

At present, a single application of fertilizer at a depth of 10 cm only ensures efficient uptake of fertilizer by the maize plant around the time of nodulation. In order to ensure an efficient supply of fertilizer during all growth periods of the maize plant, this study was based on the agronomic basis of the growth and development of the maize plant root system and its fertilizer uptake pattern, and the fertilizer was applied to the soil in two layers (as shown in Figure 2). The upper layer of fertilizer is 10 cm deep to meet the nutritional requirements of the maize plant before the nodulation stage, and since the horizontal distribution of the root system is much less than 25 cm (the theoretical spacing of the maize plant) at this time, the fertilizer granules are point-applied 5 to 10 cm from the plant. The lower layer of fertilizer was applied at a depth of 20 cm to meet the nutritional requirements of the maize plant after the nodulation stage, when the horizontal distribution of the root system at a depth of 20 cm is almost equal to 25 cm (the theoretical spacing of the maize plant), so the fertilizer granules were applied in banding 5 to 10 cm from the plant rows.

In order to realize the above fertilizer application pattern, this study designed a layered fertilizer shovel. The structure and parameters of the layered fertilizer shovel were investigated by discrete element simulation experiments with the objective of layered distance, and the optimal combination of structural parameters was optimized and field trials were conducted in order to provide a research basis for the maize stratified fertilizer application device.

STRUCTURE AND WORKING PRINCIPLE

The structure of the internal pneumatic-filled maize precision seed rower is shown in Figure 2 and consists mainly of a fertilizer tank, fertilizer feeder, fertilizer supply tube, fertilizer point-applied device, layered plates, shovel body and shovel tip. The fertilizer point-applied device transforms the continuous flow of fertilizer from the fertilizer feeder into a fertilizer pile and discharges it, the detailed principle of which has been described in previous studies (*Du et al.*, 2022).

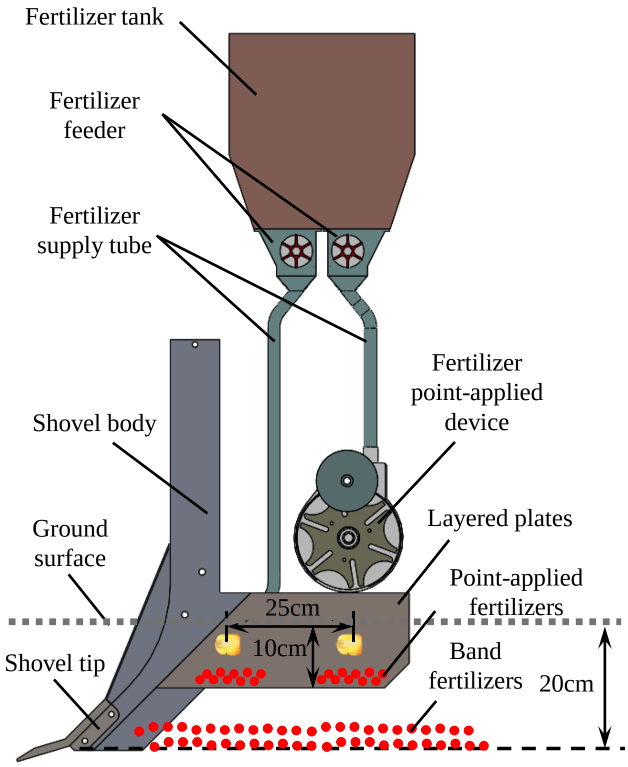

Fig. 2 – Schematic diagram of the structure and principle of the layered fertilizer application unit

When working, fertilizer particles flow out of the fertilizer tank through the fertilizer feeder of the outer groove wheel and flow into the fertilizer shovel and the fertilizer point-applied device respectively under the guidance of the fertilizer supply tube. The soil is destroyed by the action of the shovel tip and the shovel body to form a 20 cm deep trench, the fertilizer particles flowing into the shovel fall into the deep trench in the form of banding application. The soil flows back into the trench by its own gravity and buries the fertilizer particles. Due to the existence of the layered plate, the soil cannot completely flow back and will form a 10 cm deep shallow trench. The fertilizer particles form a fertilizer pile gathered by the action of the point-applied device and are discharged into the shallow trench. Finally, the soil completely flows back to bury the shallow trench.

MATERIALS AND METHODS

Soil model and simulation model construction

According to the literature, the properties of soil particles are usually nucleated, flaky, striped and blocky, as shown in Figure 3(a) to (d) (*Ma et al., 2019; Ding et al., 2018; Wang et al., 2017)*. The smaller the particle size of the soil, the more time consuming the simulation will take. In order to improve the computational efficiency and save simulation time, four types of spherical particles with a radius of 4 mm are used: nuclei, flakes, strips and blocks. The Poisson's ratio, shear modulus and density of the soil particles are 0.3, 1×10^6 Pa and 2600 kg/m^3, respectively. The coefficient of restitution, static friction and rolling friction between soil particles are 0.6, 0.14 and 0.33, respectively.

A soil box of length, width and height 1200 mm x 400 mm x 450 mm is modelled in EDEM (as shown in Figure 3(e)). The tillage layer was set at a depth of 300 mm and was randomly filled with 64078 nucleated particles, 64077 flake particles, 64074 strip particles and 64071 block particles. The fertilizer shovel was plowed to a depth of 200 mm and made of 65Mn with Poisson's ratio, shear modulus and density of 0.427, 1×10^6 Pa and 7820 kg/m^3, respectively. The coefficient of restitution, static friction and rolling friction between the fertilizer shovel and soil particles were 0.6, 0.14 and 0.33, respectively.

The triaxle dimensions of the fertilizer granules were 4.08 mm x 3.97 mm x 3.89 mm, with equivalent diameters and sphericity of 3.98 mm and 0.975. A single sphere particle with a diameter of 3.98 mm was created in EDEM to simulate fertilizer particles with Poisson's ratio, shear modulus and density of 0.3, 1×10^6 Pa and 2600 kg/m^3 respectively. The coefficient of restitution, static friction and rolling friction between fertilizer particles were 0.509, 0.176 and 0.033, respectively. The coefficient of restitution, static friction and rolling friction between fertilizer particles and soil particles were 0.1, 0.5 and 0.1, respectively. The coefficient of restitution, static friction and rolling friction between the fertilizer granules and the fertilizer shovel were 0.47, 0.42 and 0.095, respectively. The total simulation time was set to 10 s, the Rayleigh time step was 2.5×10^{-6} s, the grid size cell was 2.5 times the minimum particle radius and the data was recorded at 0.01 s intervals.

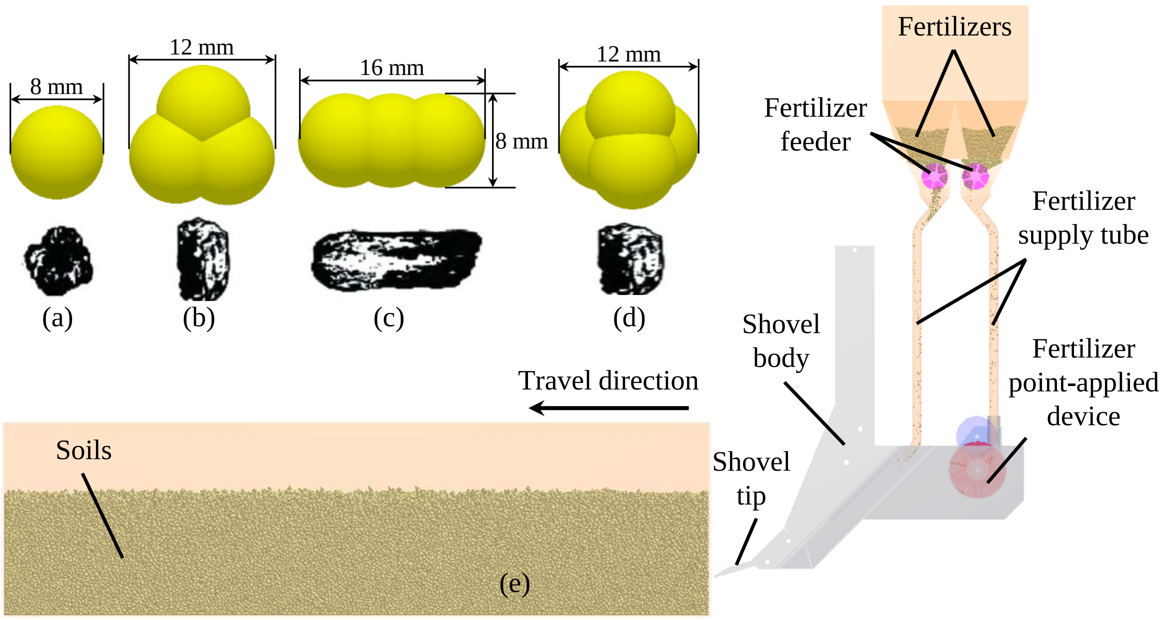

Fig. 3 – Soil particle model

Soil contact model

To better represent the strain relations in soils, researchers at the University of Edinburgh, UK, have proposed a model that considers both nonlinear elasto-plastic deformation and bonded contact, with the inter-particle normal force-displacement relationship shown in Figure 4 (*Subhash et al., 2014*). When loaded with an external force, the overlap δ of the 2 particles increases and the strain relationship changes according to the loading curve. When an external force is unloaded, the overlap of the 2 particles δ decreases and the strain relationship follows the unloading/reloading curve and will continue to follow the unloading/reloading curve when reloaded by any external force before the 2 particles are separated. The bonding force between the particles is characterized when f_n is less than 0. When the bonding force decays to the extreme value f_{min} the bonding between the particles disappears and will thereafter gradually decrease to the initial contact force f0 between the 2 particles in accordance with - $k_{adh}\delta^n$.

The main model parameters to be considered for the application of the EEPA model in EDEM include the initial contact force f0, the habitual contact surface energy Δγ, the contact plasticity ratio λp, the non-linear curve power index n, the adhesion branching curve power index *x* and the tangential stiffness factor ξ_{tm}. For reference (*Wang et al.*, 2017; *Janda et al.*, 2016), each parameter was set to f_0=0，$\Delta\gamma$=50，λ_p=0.7，n=1.5，x=5，ξ_{tm}=0.28571.

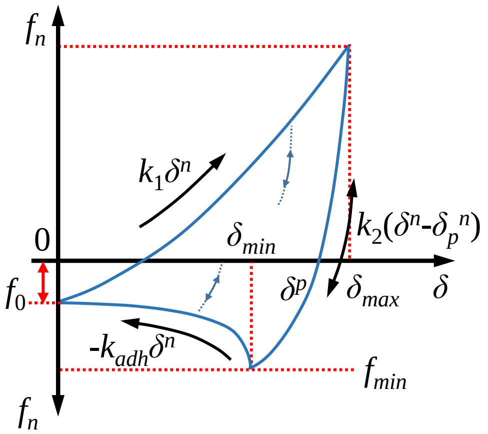

Fig. 4 – Normal contact force-displacement curve

Experimental design and experimental indicators

In this paper, the inter-layer distance (as shown in Figure 5) is selected as the test index. The inter-layer distance is the vertical distance between the banding-applied fertilizer layer and the point-applied fertilizer layer, which is calculated by selecting the middle of the fertilizer layer as the measurement point after the layering operation, using the ground as the coordinate reference point, and measuring the longitudinal coordinate values of the banding-applied fertilizer layer and the point-applied fertilizer layer respectively, and then subtracting them to obtain the fertilizer strip layering distance *h*. Each group of tests is repeated three times to obtain the average value.

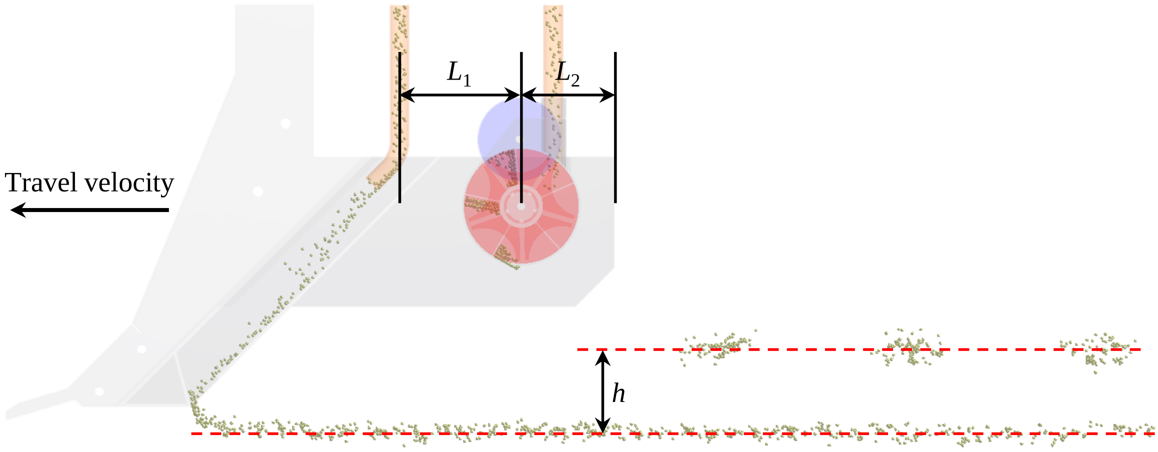

Fig. 5 – Inter-layer distance measurement chart

RESULTS

Operating speed V

A single-factor test was designed with a distance L_1 between banding fertilizer discharge pipe and point-applied device and a distance L_2 between the fertilizer layered plate and the point-applied device of 13 cm and 16 cm, and operating speeds *V* of 1.8, 2.7, 3.6, 4.5 and 5.4 km/h. The results of the test are shown in Figure 6.

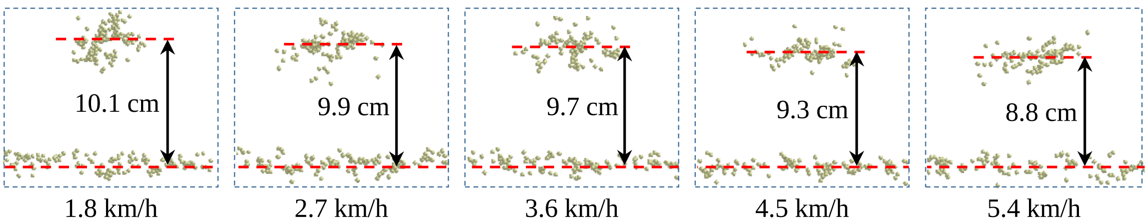

Fig. 6 – Plot of interlayer distance *h* against operating speed *V*

As can be seen from Figure 6, the interlayer distance *h* decreases with the increase of operating speed *V*. When the operating speed *V* is 1.8 km/h, the maximum interlayer distance *h* is 10.1 cm, and when the operating speed *V* gradually increases to 5.4 km/h, the interlayer distance *h* gradually decreases to 8.8 cm. As the soil is fluid, after the trencher has opened the soil out of the deep trench, the soil in the cultivated layer, which is not covered by the layered plates, will flow back into the trench by gravity. At the same time the soil is viscoelastic and flows back slowly, so when the operating speed V increases, some of the soil particles do not flow back into the furrow in time resulting in a reduction in the distance h between the layers of fertilizer particles.

Distance L_1 between banding fertilizer discharge pipe and point-applied device

A single-factor test was designed with operating speeds *V* and a distance L_2 between the fertilizer layered plate and the point-applied device of 3.6 km/h and 16 cm, and a distance L_1 between banding fertilizer discharge pipe and point-applied device of 12, 13, 14, 15 and 16 cm. The results of the test are shown in Figure 7.

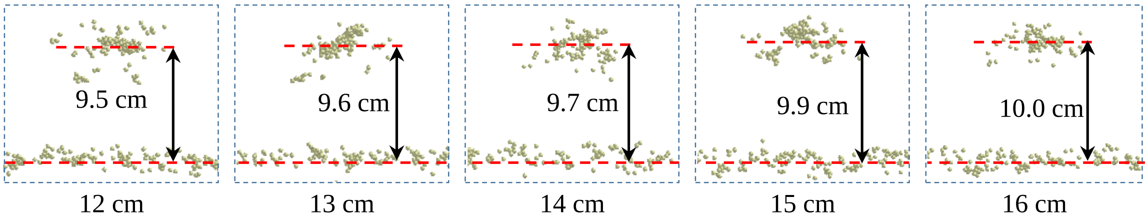

Fig. 7 – Plot of interlayer distance *h* against distance between banding fertilizer discharge L_1 pipe and point-applied device

As can be seen from Figure 7, the interlayer distance *h* increases with the increase of the distance L_1 between banding fertilizer discharge pipe and point-applied device, and the minimum interlayer distance *h* is 9.5 cm when the distance L_1 between banding fertilizer discharge pipe and point-applied device is 12 cm. When the distance L_1 between banding fertilizer discharge pipe and point-applied device gradually increases to 16 cm, the distance *h* between layers gradually increases to 10.0 cm. The larger the L_1 the more time the tilled soil has to flow back into the furrow under the influence of gravity, and conversely the smaller the distance *h* between the layers of fertilizer particles.

Distance L_2 between the fertilizer layered plate and the point-applied device

A single-factor test was designed with operating speeds *V* and a distance L_1 between banding fertilizer discharge pipe and point-applied device of 3.6 km/h and 13 cm, and a distance L_2 between the fertilizer layered plate and the point-applied device of 12, 14, 16, 18 and 20 cm. The results of the test are shown in Figure 8.

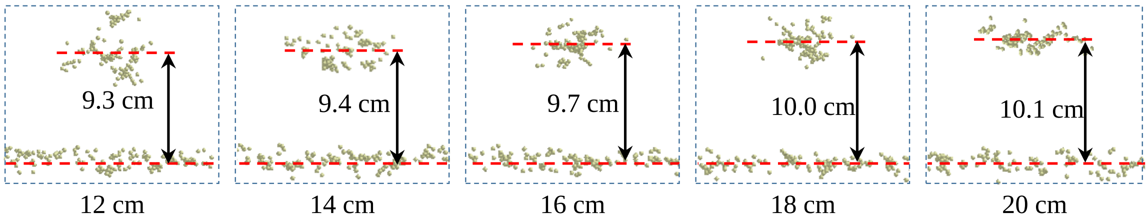

Fig. 8 – Plot of interlayer distance *h* against distance L_2 between the fertilizer layered plate and the point-applied device

As can be seen from Figure 8, the interlayer distance *h* increases as the distance L_2 between the fertilizer layered plate and the point-applied device increases, and the minimum interlayer distance is 9.3 cm when the distance L_2 is 12 cm. When the distance L_2 between the fertilizer layered plate and the point-applied device is gradually increased to 20 cm, the distance *h* between layers is gradually increased to 10.1 cm. The greater the distance between the fertilizer layered plate and the point-applied device, the more time the fertilizer particles have to fall into the furrow, otherwise the upper layer of fertilizer particles will have a larger vertical distribution and affect the stability of the distance *h* between the layers of fertilizer particles.

Box-Behnken design

Based on the results of the above single-factor test, the scope of work for each influencing factor and the factor codes were determined as shown in Table 1. A response surface test was designed to investigate the influence pattern of the interaction between factors on the indicators, with 17 treatment groups in the test protocol, and the test results are shown in Table 2. To further analyze the effects of the factors and interactions between factors on the test indicators, multiple regressions were fitted to the test results using Design-Expert 8.0.6 to establish a quadratic regression model between the test indicators and the factors, and the results of their significance tests are shown in Table 3.

The results of the ANOVA in Table 3 show that the quadratic regression model for the layered distance *h* between fertilizers is highly significant and the misfit term is not significant, indicating that the model is highly accurate and the regression equation fits well with the actual situation. The factors affecting the layered distance are, in descending order, the operating speed *V*, the distance L_1 between banding fertilizer discharge pipe and point-applied device and the distance L_2 between the fertilizer layered plate and the point-applied device. The interaction between the *V* and L_2, L_1 and L_2 had a significant effect on the layered distance *h*.

Table 1

Box-Behnken test factor coding

Codes	Factors		
	V/ km/h	L_1/ cm	L_2/ cm
-1	1.8	14	16
0	3.6	15	18
+1	5.4	16	20

Table 2

Box-Behnken test program and results

No.	Test factors			Test indicators
	V/ km/h	L_1/ cm	L_2/ cm	*h*/cm
1	1.8	14	18	9.93
2	5.4	14	18	9.35
3	1.8	16	18	10.03
4	5.4	16	18	9.55
5	1.8	15	16	9.90
6	5.4	15	16	9.48
7	1.8	15	20	10.08
8	5.4	15	20	9.50
9	3.6	14	16	9.65
10	3.6	16	16	9.86
11	3.6	14	20	9.85
12	3.6	16	20	9.93
13	3.6	15	18	9.92
14	3.6	15	18	9.85
15	3.6	15	18	9.89
16	3.6	15	18	9.86
17	3.6	15	18	9.88

The quadratic regression equation between each test factor and the test indicator is

$$h=-6.690+0.124V+1.554L_1+0.459L_2+0.014VL_1-0.011VL_2-0.01L_1L_2\text{-}0.038V^2-0.041L_1^2-0.004L_2^2 \tag{1}$$

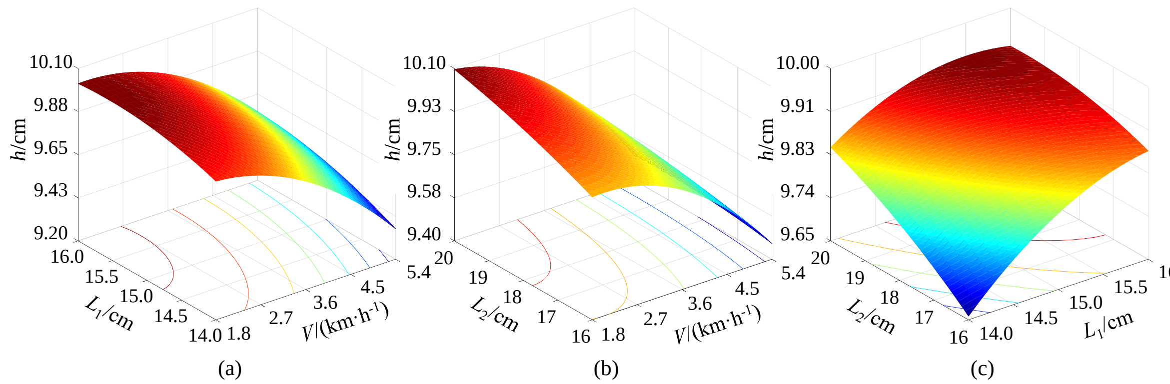

Fig. 9 – Effect of factor interactions on layered distances *h*

To visually analyze the effect of factor interactions on the rate of missed seeding, response surface plots were drawn as shown in Figure 9. As can be seen from Figure 9(a), there is a maximum layered distance *h* for a minimum operating speed *V* and a maximum distance L_1 between banding fertilizer discharge pipe and point-applied device. From Figure 9(b), it can be seen that there is a maximum layered distance *h* for a minimum operating speed *V* and a maximum distance L_2 between the fertilizer layered plate and the point-applied device. From Figure 9(c), it can be seen that a maximum value of layered distance *h* exists at the maximum distance L_1 between banding fertilizer discharge pipe and point-applied device and at the maximum distance L_2 between the fertilizer layered plate and the point-applied device.

Table 3

Analysis of variance table

Source of variation	Square	df	*F* value	*P* value
Model	0.6915	9	131.99	<0.0001*
V	0.5305	1	911.20	<0.0001*
L_1	0.0435	1	74.75	0.0001*
L_2	0.0276	1	47.43	0.0002*
$V L_1$	0.0025	1	4.29	0.0770
$V L_2$	0.0064	1	10.99	0.0128*
$L_1 L_2$	0.0042	1	7.26	0.0309*
V^2	0.0645	1	110.76	<0.0001*
L_1^2	0.0072	1	12.31	0.0099*
L_2^2	0.0011	1	1.91	0.2095
Residual	0.0041	7		
Lack of Fit	0.0011	3	0.48	0.7149
Cor Total	0.6956	16		

Notes：*Shows that the term is significant (i.e., $P < 0.05$).

In order to accurately find the optimal combination of parameters for each factor, the quadratic regression model established with the layered distance *h*=10 cm as the final optimization objective, combined with the boundary conditions, is solved optimally for multiple factors with the function objective and constraints as

$$\begin{cases} h = 10 \text{ cm}\left(V, L_1, L_2\right) \\ \text{s.t.} \begin{cases} 1.8 \text{ km/h} \le V \le 5.4 \text{ km/h} \\ 14 \text{ cm} \le L_1 \le 16 \text{ cm} \\ 16 \text{ cm} \le L_2 \le 20 \text{ cm} \end{cases} \end{cases} \tag{2}$$

The optimized solution was carried out using Design-expert 8.0.6 and the predicted layered distance *h* was 10 cm for the operating speed *V*, the distance L_1 between banding fertilizer discharge pipe and point-applied device and the distance L_2 between the fertilizer layered plate and the point-applied device for 2.7 km/h, was 15.3 cm and 18.2 cm respectively. The simulated value of the layered distance *h* is 9.9 cm, which is a small error compared to the predicted value.

Field trials

To verify the accuracy of the simulation tests and the performance of the field work, based on the optimal combination of working parameters determined from the above tests, a layered fertilizer application shovel was designed and machined and tested at different operating speeds (as shown in Figure 10). The fertilizer was applied at a depth of 10 cm (upper layer) and 20 cm (lower layer), with the upper layer applied in holes at a theoretical spacing of 25 cm and a theoretical application rate of 2.5 g per hole, and the lower layer applied in strips at a rate of 500 kg/hm^2, using Stanley slow-release compound fertilizer granules (N-P_2O_5-K_2O 15-15-15), with the results shown in Table 4.

Table 4

Fertilizer layered distances at different operating speeds

Operating speed *V* (km/h)	Upper depth h_1 (cm)	Lower depth h_2 (cm)	layered distance *h* (cm)
1.8	9.8	19.3	9.5
2.7	10.1	19.2	9.1
3.6	10.4	19.3	8.9
4.5	10.7	19.4	8.7
5.4	11.2	19.2	8.0

From Table 4, it can be seen that the layered distance *h* gradually decreases with increasing operating speed, and when the operating speed *V* is greater than 4.5 km/h, the stratification distance h decreases sharply. The layered distance *h* is 9.1 cm at an operating speed *V* of 2.7 km/h. The relative error compared to the simulation value is 8.1%, which can be considered a high degree of confidence that the simulation test can accurately simulate the distribution of fertilizer particles in the real environment in the field. When the operating speed *V* is 1.8 to 5.4 km/h, the distribution of the layered distance *h* ranges from 8.0 to 9.5 cm, which meets the agronomic requirements for fertilizer stratification.

(a) (b)

Fig. 10 – Operating speed adaptation results

CONCLUSIONS

A layered fertilizer application shovel was designed to achieve a double layer of fertilizer, with the upper layer at a depth of 10 cm and the lower layer at a depth of 20 cm, in response to the current problem of large losses in fertilizer efficiency with a single strip application.

The key structural parameters of the layered shovel were designed and the operating speed *V*, the distance L_1 between banding fertilizer discharge pipe and point-applied device and the distance L_2 between the fertilizer layered plate and the point-applied device were identified as the main factors influencing the layered distance *h*.

With the layered distance *h*=10 cm as the optimization target, the predicted value of *h* is 10 cm when the *V*, L_1 and L_2 are 2.7 km/h, 15.3 cm and 18.2 cm respectively. The simulated value is 9.9 cm, which is a small error compared to the predicted value.

The results of the field test with the optimal combination of parameters show that the *h* is 9.1 cm at the *V* of 2.7 km/h, with a relative error of 8.1% compared to the simulated value, which can be considered a high degree of confidence that the simulation test can accurately simulate the distribution of fertilizer particles in the real environment in the field. When the *V* is 1.8~5.4 km/h, the *h* is 8.0~9.5 cm, which can meet the agronomic requirements of fertilizer stratification application.

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