DESIGN AND PARAMETER OPTIMIZATION OF LAYERED FERTILIZATION OPENER FOR WHEAT, BASED ON EDEM
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基于 EDEM 的小麦分层施肥开沟器设计及参数优化

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ABSTRACT
Applying different types of fertilizers to different depths of soil according to demand is advantageous in that it can optimize the distribution of nutrients in arable soil, adjust the nutrient supply of each growth stage of wheat, and increase grain yield. In the study, a layered fertilization opener that could realize the layered fertilization was developed. The interaction model between the opener, fertilizer and soil was established using EDEM simulation software. A response surface analysis was used to determine the optimal parameters of the opener. Specifically, the horizontal distance between the fertilizer drop openings was 140 mm, the machine speed was 1.05 m/s, and the angle of the opener was 37°. Furthermore, field experiments demonstrated that the average depth of upper layer was 8.39 cm, the average depth of middle layer was 16.465 cm, the average depth of lower layer was 24.025 cm, the average spacing of upper layer was 8.075 cm, and the average spacing of lower layer was 7.6 cm. The corresponding findings demonstrated that the layering effect of the opener met the requirements of the fertilization standard.

摘要
将不同种类的肥料根据需求量分层施入不同深度土层，可优化养分在耕层土壤中的分布，调节小麦各生长发育阶段的养分供给，进而提高籽粒产量。本文设计了一种分层施肥开沟器并进行了参数优化。利用 EDEM 仿真软件建立施肥装置与土壤相互作用模型，分析了机具行进速度、落肥口之间的水平距离、开沟器倾斜角等参数对土壤回流以及肥料分层效果的影响。利用响应面分析各因素对分层施肥效果的影响，并得到最优参数为落肥口水平距离为 140 mm，机具行进速度为 1.05 m/s，开沟器倾角为 37°。对样机加工并进行田间试验，试验得出上层施肥平均深度 8.39 cm，中层施肥平均深度 16.465 cm，底层施肥平均深度 24.025 cm，上层施肥间距平均 8.075 cm，下层分层施肥间距平均 7.6 cm。整机分层效果较好，符合分层施肥作业标准要求。

INTRODUCTION
The utilization of granular fertilizers is an important method in increasing crop yields in agricultural production (*Li B et al, 2021*). In China, fertilizers are used at early and later stages, and fertilizers are usually applied on the soil surface manually or mechanically (Yang Q et al, 2020). This mode of fertilization can improve the fertilizer utilization rate, which has been widely adopted in practice. However, late topdressing increased the number of machines entering the field, resulting in problems such as soil compaction.

In order to improve fertilizer utilization, various research has been conducted that focused on the deep application of fertilizers (*Bautista E et al, 2001; Quinn D et al, 2020*). The deep application of fertilizers involves using fertilizer machinery to place fertilizers to the lower side of the seed in a quantitative and uniform manner. This method of fertilization can improve fertilizer utilization while reducing environmental pollution (*Kargbo M. et al, 2016; Min J et al, 2021*). Layered fertilization involves applying the fertilizer required by the crop into the soil at a time suitable to meet the nutrient requirements of the crop in different growth periods, which can increase the fertilizer utilization rate and yield (*Abbas A. et al, 2014*). In order to achieve a good layered fertilization effect, some studies focused on the design and analysis of layered fertilization opener. *Yang R et al. (2018)* proposed layered fertilization technology based on surface drainage and V type anti-blocking structure, and developed a layered fertilization opener for potato planter. While, some studies optimized the parameters of the layered fertilization device by using simulation method.

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Yang Q. et al., (2020), researched the working process of the layered fertilization device based on EDEM, the relationship between the amount of fertilizer discharged of the upper and middle fertilizer outlets and the factors such as front-end width, rear-end width and installation angle of fertilization adjustment piece was determined. *Wang Y. et al., (2016),* investigated the trend of fertilizer distribution ratio for different lift angles and working length of fertilization-piece based on the DEM. *Ding S. et al., (2018),* studied the layer fertilization device and developed an integrated model to simulate the metering and banding processes of the dual-band applicator using the DEM. Fertilizer fertilization involves the interaction of soil, fertilizer, and machinery. However, the above studies rarely involve the effect of soil return on the layering effect of fertilizers.

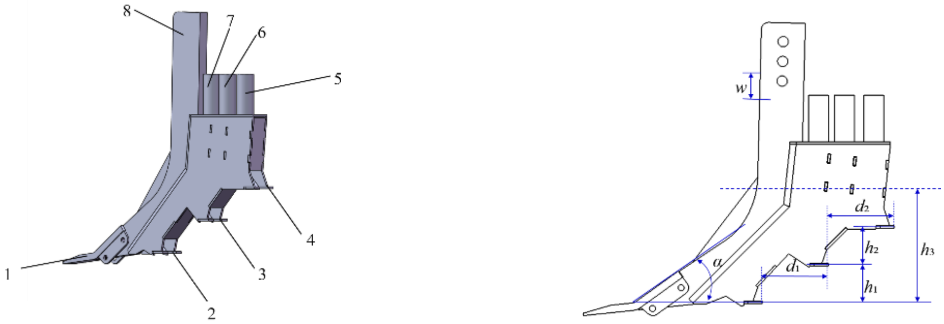
The objective of the present study is to design a layered fertilization opener to attain precise layered fertilization, develop a simulation model to study the motion of granular fertilizer following fertilization, analyze the speed of the machine and horizontal distance between the openings on the effect of layered fertilization, determine the optimal parameters, and verify the layered effect through field experiments.

MATERIALS AND METHODS

STRUCTURE DESIGN OF THE LAYERED FERTILIZATION OPENER

Studies have shown that applying fertilizers in the subsoil layers of 8 cm, 16 cm, and 24 cm according to demand of wheat optimizes the distribution of nutrients in the soil and regulates the nutrient supply at each growth stage of wheat, thereby increasing the yield (*Wen Y et al, 2017*). In order to provide the nutrients necessary for different growth periods of wheat, the layered fertilization device should be able to apply different types of fertilizers in layers, while ensuring that the layer spacing is 8 cm.

The layered fertilizer opener was mainly made up of a shovel point, shank, fertilizer grooves and fertilizer drop opening, as shown in Fig.1(a). The fertilizer grooves and fertilizer metering device were connected through three independent fertilizer tubes to ensure that fertilizers with different nutrients may be applied to each layer. The three fertilizer openings were distributed in a ladder shape to allow a certain horizontal distance between the openings to increase soil fall time. As shown in Fig.1(b), according to the agronomic requirements of layered fertilization for wheat, the fertilization depth h_3 was 24 cm, and the width w of the opener was 2.6 cm. The vertical spacing h_1 between the bottom and middle fertilizer drop opening, as well as that of h_2 between the middle and the upper fertilizer drop opening, were both 8 cm. In order to ensure that the effect of stratification was obvious, the horizontal distance d_1 between the bottom and middle fertilizer drop opening and the horizontal distance d_2 between the middle and upper fertilizer drop opening should be greater than 11.5 cm. In order to meet the requirements of having a compact structure, the angle α should be selected within the range of 20°~50° (*Zhang J. et al, 2014*).



a. Three-dimensional view *b. Two-dimensional view*

Fig. 1 - Layered fertilization opener

1. Shovel point; 2. Lower fertilizer drop opening; 3. Middle fertilizer drop opening; 4. Upper fertilizer drop opening; 5. Upper fertilizer tube; 6. Middle fertilizer tube; 7. Lower fertilizer tube; 8. Shank

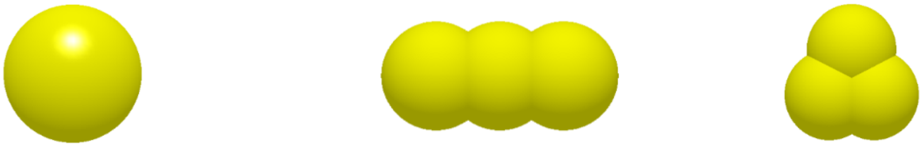
SIMULATION AND PARAMETER OPTIMIZATION OF LAYERED FERTILIZATION OPENER

Establishment of the simulation model

(1) Establishment of the soil particle model

According to the earlier soil collection results, 0-12 cm was the depth of rotary tillage, in which the soil following rotary tillage was found to have large porosity, good air permeability and small soil particles. The soil below 12 cm had little disturbance, large soil particles and irregular shapes. The shape of soil particles was usually cluster, nucleus, block and so forth (*Michele M. et al, 2015*). Therefore, the upper soil particles were replaced by spherical particles, the deep soil was built in two layers, the middle soil particles were replaced by nucleated particles, and the bottom soil particles were replaced by massive particles.

The established soil particle model was shown in Fig.2. The contact model between soil particles adopted the Hertz-Mindlin with JKR model after which the value of JKR was set. In this paper, the JKR value was determined to be 2 after calibration test.



(a) Spherical particle *(b) nucleated particles* *(c)massive particles*

Fig. 2 - Soil particle model

(2) Establishment of the soil tank model

The particles were defined, and a soil tank was established with length of 1000 mm, width of 500 mm, and height of 300 mm. The soil tank was built in three layers, of which the upper layer was 12 cm. In addition, the lower soil was built in two layers, in which the middle and bottom layers were each 9 cm. The bottom layer was made of massive particles with a total of 23,000 particles, while the middle layer was made of nucleated particles with a total of 73,000 particles and the upper layer was made of spherical particles with a total of 270,000 particles. The time step was set to 20% of the Rayleigh time step, the grid size was 3 times the minimum particle radius, and the total time was 4 s. The soil particles were generated within 3 s and settled to 4 s. The corresponding soil tank was shown in Fig.3.

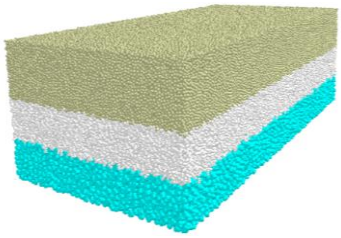


Fig. 3 - Soil tank model

(3) Establishment of the fertilizer particle model

According to the measurement of the compound fertilizer, the density was 1527 g/cm^3, equivalent diameter was 4.03 mm, and sphericity rate was 93.02%. The spherical particles were used instead of fertilizer particles, and the particle radius was set to 2 mm. The contact model between fertilizer particles, the contact model between the fertilizer and opener were all set to Hertz-Mindlin (no-slip) (*Coskun M. et al, 2006*).

(4) Establishment of the opener model

SolidWorks software was used to establish a three-dimensional model of the opener at a ratio of 1:1. After the 3D model of the opener was created, it was saved in the 'igs.' format and imported into EDEM software.

(5) Parameter settings of the simulation model

The furrow depth was set to 24 cm, and the pellet factory was established on the top of the three fertilizer tubes of the opener. Fertilizer particles were then generated at a speed of 0.05 kg/s, and the gravity acceleration of fertilizer particles was set to 9.81 m/s^2 along the negative direction of the Z axis. The opener and pellet factory were then set to run together along the positive direction of the Y axis.

RESULTS

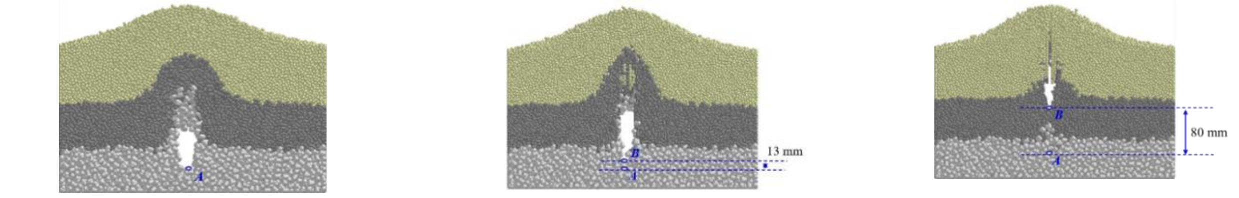
Determination of key parameters for the layered fertilization opener

(1) The effect of horizontal distance between the fertilizer openings and machine speed on soil falling

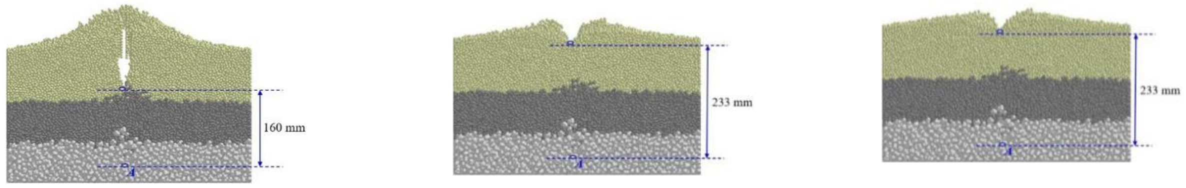
Given that the machine speed was 0.8 m/s, and the speed direction was along the positive direction of the Y-axis. The Slice function in the Clipping option was used to slice the simulation results. The soil falling section after slicing was shown in Fig.4.

By selecting any time on the time axis randomly and placing the slice boundary at the position where the soil had yet to fall, point *A* was determined. The time axis moved, the opener advanced, the soil began to fall, and the falling height *h* was measured. When the height of the soil falling was 80 mm, it was considered to be point *B*. At this time, the distance from point *A* that has yet to fall to point *A*' under the opener was 96 mm. Here, no movement trend of certain soil particles from point *A* to *A*' was observed, as shown in Fig.5.

Essentially, when the horizontal distance between the lower and middle fertilizer drop opening was set to 96 mm, the fertilization interval achieved was 80 mm. When the soil fell from 80 mm to 160 mm, the opener traveled 80 mm. Specifically, when the horizontal distance between the middle and upper fertilizer drop opening was 80 mm, the fertilizer layer spacing became 80 mm.



(a) Soil didn't fall after furrow opening *(b) The opener travelled 48 mm* *(c) The opener travelled 96 mm*



(d)The opener travelled 176mm *(e)The opener travelled 272 mm* *(f)The opener travelled 304 mm*

Fig. 4 - Cross section of soil falling

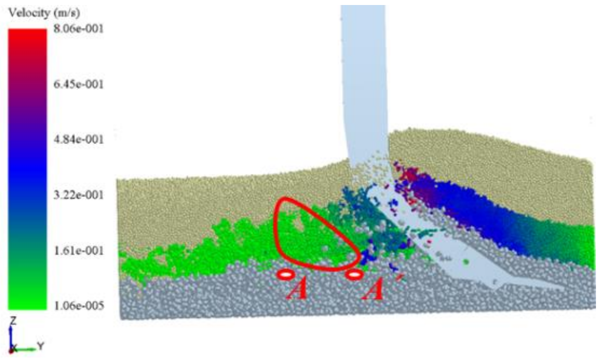


Fig. 5 - Soil particle velocity change

In order to analyze the change in soil falling height under different speeds, the speed was set to 0.8 m/s, 1.05 m/s, and 1.3 m/s and the result was shown in Fig.6. When the speed was 0.8 m/s, the horizontal distance between the lower and middle fertilizer drop opening was 96 mm, and the horizontal distance between the middle and the upper fertilizer drop opening was 80 mm. When the speed was 1.05 m/s, the horizontal distance between the lower and the middle fertilizer drop opening was 126 mm, and the horizontal distance between the middle and the upper fertilizer drop opening was 75 mm. When the speed was 1.3 m/s, the horizontal distance between the lower and middle fertilizer drop opening was 140 mm, and the horizontal distance between the middle and upper fertilizer drop opening was 77 mm. In summary, the horizontal distance between the lower and middle fertilizer drop opening should be greater than 140 mm, and the horizontal distance between the middle and the upper fertilizer drop opening should be greater than 80 mm.

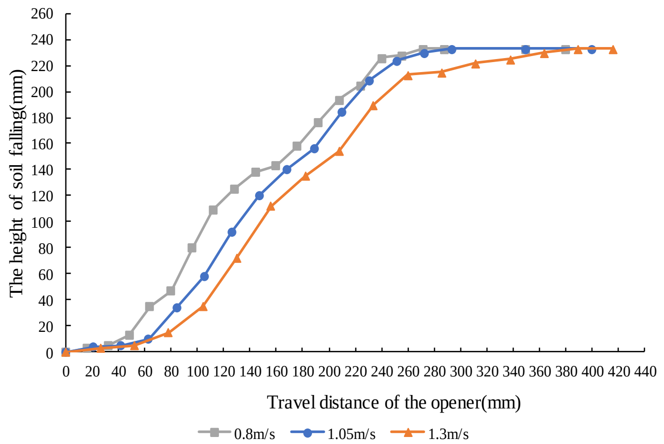
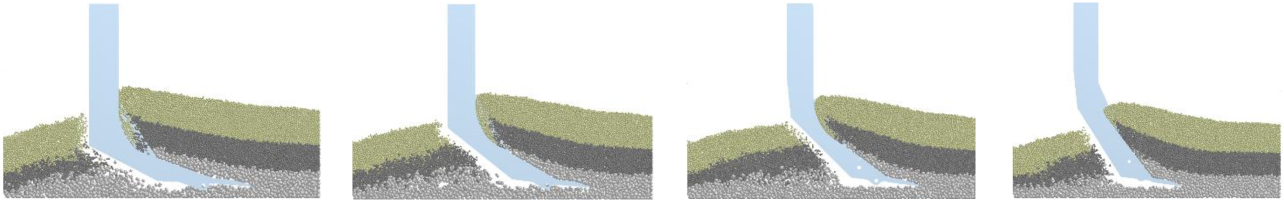


Fig. 6 - Variations of the height of soil falling with the travel distance of the opener under different speeds

(2) The effect of the inclination angle of the opener on soil falling

A simulation analysis was conducted on soil falling after ditching with the opener placed at different angles. The inclination angles of the openers were set as 20°, 30°, 40° and 50°, respectively. The cross sections of the openers at different angles were shown in Fig.7. The height of soil falling was measured according to the above method; when the height of soil falling was 80 mm, the travel distance of the opener, that was the horizontal distance between the fertilizer drop openings, was measured. The relationship between the horizontal distance between the fertilizer drop openings and inclination angle was shown in Fig.8. Here, according to the trend line function, the inclination angle of the opener was 37° when the horizontal distance between the fertilizer openings was the smallest.



(a)The angle was 20° *(b)The angle was 30°* *(c)The angle was 40°* *(d)The angle was 50°*

Fig. 7 - The cross section of the soil under different inclination angles of the openers

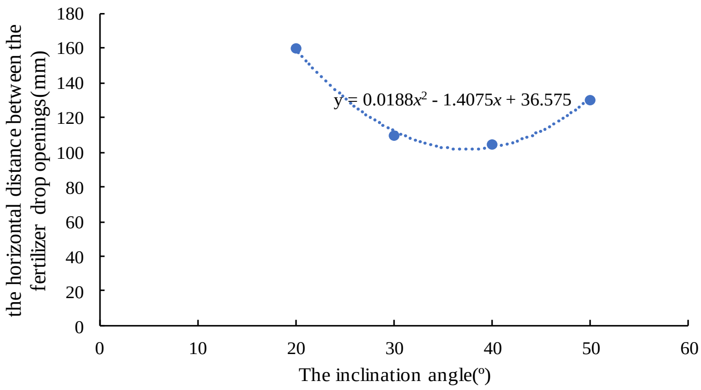
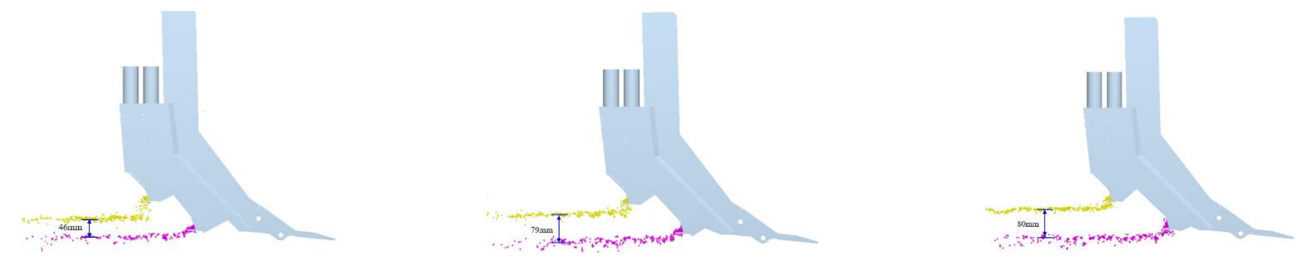


Fig. 8 - The relationship between the horizontal distance and the inclination angle

(3) The effect of the horizontal distance between the fertilizer drop openings on fertilizer layering

According to the above analysis, the horizontal distance between the lower and middle fertilizer drop opening should be greater than 140 mm, while the horizontal distance between the middle and upper fertilizer drop opening should be greater than 80 mm.

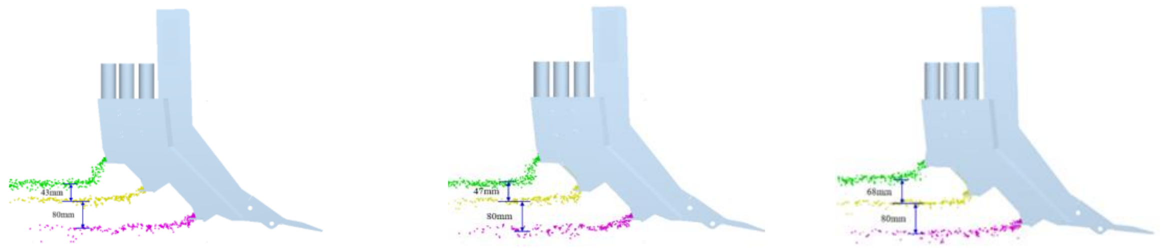
The simulation was performed when the horizontal distance between the lower and middle fertilizer drop opening was 120 mm, 140 mm, and 160 mm. Meanwhile, the inclination angle of the opener was 37° and the speed was 0.8 m/s. The distance from the middle position of the lower fertilizer layer to the middle position of the middle fertilizer layer was then measured, in which the effect of fertilizer layering was shown in Fig.9. When the horizontal distance was 120 mm, the interval between middle fertilizer and lower fertilizer was 46 mm, the interval between fertilizer layers was 79 mm when the horizontal distance was 140 mm, and the interval between fertilizer layers was 80 mm when the horizontal distance was 160 mm. The vertical distribution height of the middle fertilizer layer was 11 mm, and the vertical distribution height of the bottom fertilizer layer was 14 mm. The stratification effect was observed to be obvious.



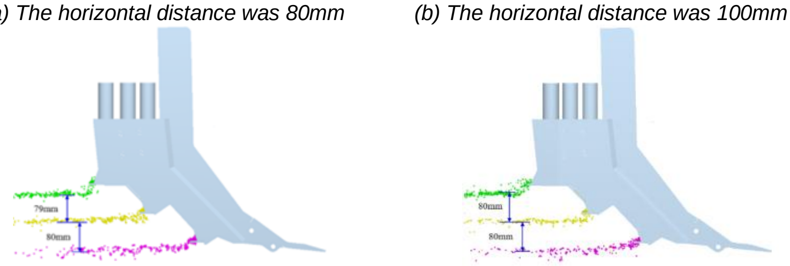
(a) The horizontal distance was 120mm *(b) The horizontal distance was 40mm* *(c) The horizontal distance was 160mm*

Fig. 9 - The effect of middle and lower fertilizer layering

The simulation was carried out when the horizontal distances between the middle and upper fertilizer drop openings were set to 80 mm, 100 mm, 120 mm, 140 mm, and 160 mm, respectively. The spacing between the upper fertilizer layer and middle fertilizer layer was measured, and the effect of fertilizer layering was obtained, as shown in Fig.10. The vertical distribution height of the upper fertilizer layer was 22 mm. Evidently, the layer spacing of the upper layer fertilizer was found to rise along with the horizontal distance between fertilizer drop openings until the distance reached 140mm. Meanwhile, the layer spacing was constant when the distance was bigger than 140 mm.



(a) The horizontal distance was 80mm *(b) The horizontal distance was 100mm* *(c) The horizontal distance was 120mm*

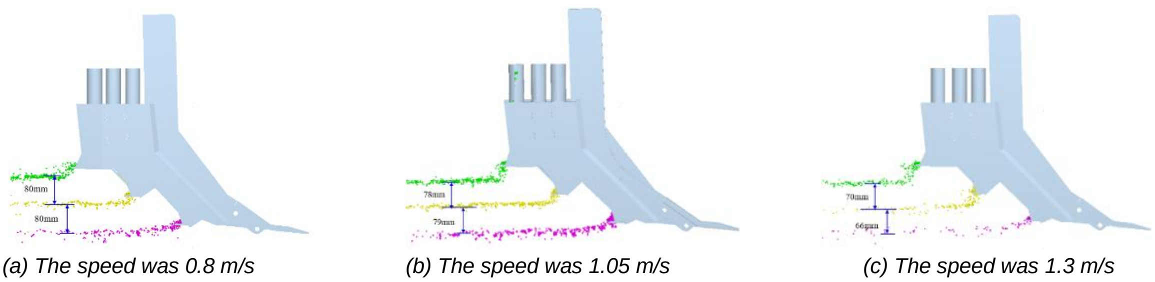


(d) The horizontal distance was 140mm *(e)The horizontal distance was 160mm*

Fig. 10 - The effect of middle and upper fertilizer layering

(4) The effect of machine speed on the fertilizer layering

The simulation of fertilizer layering was conducted when the horizontal distance between the fertilizer drop openings was 140 mm, the inclination angle of the opener was 37°, and the speed was 0.8 m/s, 1.05 m/s, and 1.3 m/s, respectively. The effect of layered fertilization corresponding to different speeds was shown in Fig.11. According to the results, when the speed was 0.8 m/s and 1.05 m/s, the layer spacing was noted to be stable at 80 mm and the vertical distribution height of fertilizers in each layer was 18 mm. When the forward speed was 1.3m/s, the layer spacing was 70 mm. This occurred because, as the other parameters were constant, the faster the speed, the greater the distance traveled, and the less the amount of soil return that could cause the fertilizer to move downward.



(a) The speed was 0.8 m/s *(b) The speed was 1.05 m/s* *(c) The speed was 1.3 m/s*

Fig. 11 - Effect of fertilizer layering at different speeds

Parameter optimization of layered fertilization opener

(1) Test factor coding

The simulation optimization test regarded the inclination angle of the opener, the machine speed and the horizontal distance between the fertilizer drop openings as the test factors. In addition, the upper fertilizer layer spacing and lower fertilizer layer spacing were taken as evaluation indicators. Quadratic regression orthogonal test with three-factor three-level was designed using Design-Expert. According to the results of the previous simulation test, the range of the inclination angle of the opener was found to be 30°~44°, while the machine speed was 0.8~1.3 m/s and the horizontal distance between the fertilizer drop openings was 120~160 mm. The factors and levels of the simulation optimization test was shown in Table 1.

Table 1

Factors and levels of simulation test

Levels	Factors		
	The inclination angle of the opener a (°)	Machine speed b (m/s)	The horizontal distance between the fertilizer drop openings c (mm)
-1	30	0.8	120
0	37	1.05	140
1	44	1.3	160

(2) Analysis of test results

The tests were performed according to the designed plan and the results were shown in Table 2.

Table 2

Simulation test results

No.	Inclination angle A (°)	Machine speed B (m/s)	Horizontal distance C (mm)	Upper fertilizer layer spacing Y1 (mm)	Lower fertilizer layer spacing Y2 (mm)
1	0	-1	-1	64	51
2	1	0	-1	60	46
3	-1	0	1	78	73
4	0	0	0	78	76
5	-1	0	-1	60	43
6	1	1	0	60	47
7	0	0	0	80	77
8	0	0	0	81	77
9	-1	-1	0	75	70
10	0	0	0	76	74
11	0	1	1	73	65
12	0	1	-1	55	42
13	1	0	1	75	68
14	1	-1	0	70	60
15	-1	1	0	63	53
16	0	-1	1	80	80
17	0	0	0	78	74

The Design-expert 8.0 software was used to perform binary regression fitting on the experimental data, in which the following regression equations of each factor with the upper fertilizer layer spacing and lower fertilizer layer spacing were obtained:

$$Y1=78.60-1.37A-4.75B+8.38C-0.5AB-0.75AC+0.5BC-5.68A^2-5.93B^2-4.67C^2 \quad (1)$$

$$Y2=75.60-2.25A-6.75B+13.00C+1.0AB-2.0AC-1.5BC-10.05A^2-8.05B^2-8.05C^2 \quad (2)$$

The results of the variance analysis of the regression equation were shown in Tables 3. The *P* value of the regression model of the upper and lower fertilization layer spacing was found to be less than 0.01, indicating that the regression model was significant. The *P* value of the lack-of-fit item was noted to be greater than 0.05, indicating that the model possessed a high fit degree. The determination coefficient of the two models was close to 1, signifying that this regression model had high reliability.

Table 3

Variance analysis of quadratic polynomial model of upper fertilizer layer spacing

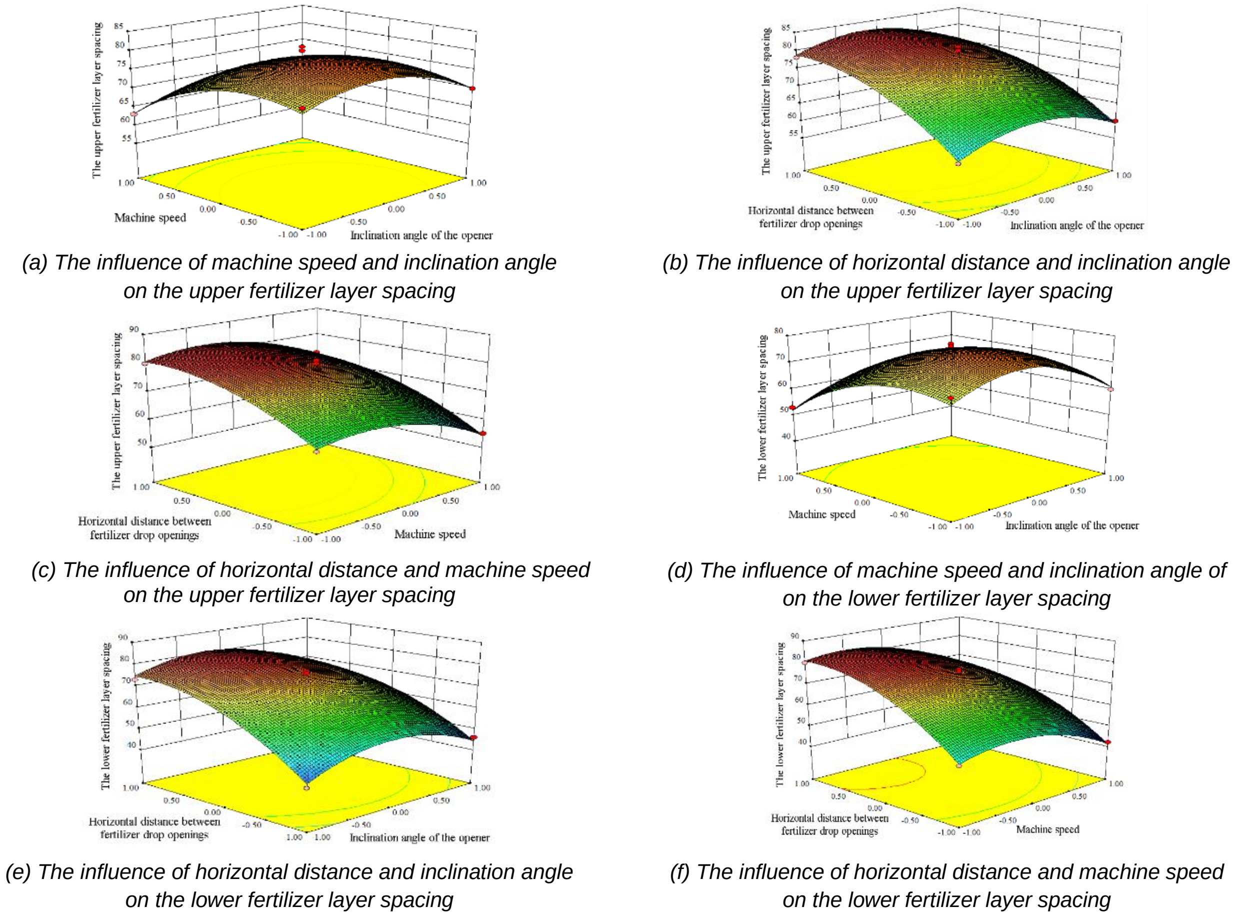
Item	Sources	Mean square	Freedom	Sum of squares	P value
Quadratic polynomial model of upper fertilizer layer spacing	Model	1179.99	9	131.11	<0.0001**
	A	15.13	1	15.13	0. 0688
	B	180.50	1	180.50	0.0001**
	C	561.13	1	561.13	<0.0001**
	AB	1.00	1	1.00	0.5979
	AC	2.25	1	2.25	0.4348

Table 3
(continuation)

Item	Sources	Mean square	Freedom	Sum of squares	P value
	BC	1.00	1	1.00	0.5979
	A^2	135.60	1	135.60	0.0004
	B^2	147.81	1	147.81	0.0003
	C^2	92.02	1	92.02	0.0011
	Residual	22.95	7	3.28	
	Lack of Fit	7.75	3	2.58	0.6088
	Pure Error	15.20	4	3.80	
	Cor Total	1202.94	16		
Quadratic polynomial model of lower fertilizer layer spacing	Model	2869.33	9	318.81	<0.0001**
	A	40.50	1	40.50	0.0296*
	B	364.50	1	364.50	<0.0001**
	C	1352.00	1	1352.00	<0.0001**
	AB	4.00	1	4.00	0.4203
	AC	16.00	1	16.00	0.1306
	BC	9.00	1	9.00	0.2399
	A^2	425.27	1	425.27	<0.0001
	B^2	272.85	1	275.85	0.0002
	C^2	272.85	1	275.85	0.0002
	Residual	38.20	7	5.46	
	Lack of Fit	29.00	3	9.67	0.0996
	Pure Error	9.20	4	2.30	

*** represents highly significant (P<0.01); * represents significant (P<0.05).*

According to the analysis of the regression model, Design-expert 8.0 was used to plot the response surface graph, as shown in Fig.12.



(a) The influence of machine speed and inclination angle on the upper fertilizer layer spacing

(b) The influence of horizontal distance and inclination angle on the upper fertilizer layer spacing

(c) The influence of horizontal distance and machine speed on the upper fertilizer layer spacing

(d) The influence of machine speed and inclination angle of on the lower fertilizer layer spacing

(e) The influence of horizontal distance and inclination angle on the lower fertilizer layer spacing

(f) The influence of horizontal distance and machine speed on the lower fertilizer layer spacing

Fig. 12 - Response surface between different factors and fertilizer layer spacing

As shown in Fig.12 (a) and (d), the machine speed was kept constant. In addition, the fertilizer layer spacing was found to initially increase and then decrease as the inclination angle of the opener increased. The inclination angle of the opener was unchanged, and the fertilizer layer spacing was found to decrease as the machine speed rose. This was because as the machine speed increased, the amount of returned soil decreased, and the distance between the two fertilizer layers decreased.

As shown in Fig.12 (b) and (e), the horizontal distance between the fertilizer drop openings remained unchanged, in which the fertilizer layer spacing initially rose and then decreased as the inclination of the opener increased. The inclination angle of the opener was constant, and the fertilizer layer spacing increased as the horizontal distance between the fertilizer drop openings increased. When the horizontal distance rose more than 140mm, the increasing trend of the layer spacing decreased until it no longer rose.

As shown in Fig.12 (c) and (f), the horizontal distance between the fertilizer drop openings remained constant, and the fertilizer layer spacing decreased as the machine speed rose. This was because the machine speed increased, the amount of returned soil decreased, and the distance between the two fertilizer layers decreased. The machine speed was constant, and the fertilizer layer spacing increased as the horizontal distance between the fertilizer drop openings rose. When the horizontal distance rose beyond 140 mm, the increasing trend of the layer spacing decreased until it no longer rose.

Parameter optimization

In order to achieve the ideal layered fertilization effect, the upper and lower fertilization spacing were taken as the performance index, and influencing factors, such as the inclination angle of the opener, the horizontal distance between the fertilizer drop openings, and the machine speed, were then optimized. Design-expert 8.0 was used to optimize the parameters. The optimal parameters were obtained: the inclination angle of the opener was 37°, the horizontal distance between the fertilizer drop openings was 140 mm, and the machine speed was 1.05m/s. The optimized layered fertilization opener was shown in Fig.13.

Fig. 13 - Layered fertilization opener

FIELD TESTS

Test equipment and methods

In order to determine the fertilization depth and fertilizer layer spacing, tools such as shovels, tape measures were used to collect the experimental data. The test was carried out in Yanzhou District, Jining City, Shandong Province in September 2020. This paper took "GB/T 20346.2-2006 Fertilization Machinery Test Method" and "DB23/T1208-2008 Layered Fertilization Operation Quality Standard" as standards. The planter was driven by the tractor at a speed of 2-5 km/h. The test procedure was shown in Fig.14.

Fig. 14 - The test process of the prototype

The five-point method was used, and five testing points were randomly selected. In each testing point area, a shovel was used to dig a section of each fertilizer ditch vertically. The shovel was then used to clean the surrounding soil, gently scrape the surface soil, find easily observable fertilizer, and measure the fertilization depth. After the fertilization depth was measured, the data was recorded as shown in Fig.15.

Fig. 15 - Field data measurement and fertilization effect

According to operating standards, the fertilization depth (*H*) was qualified when the fertilization depth was *H±2* cm, and the fertilizer layer spacing (*S)* was qualified when the fertilizer layer spacing was *S±2* cm. The qualified rate of fertilization depth Q_1 as well as the qualified rate of fertilizer layer spacing Q_2 were calculated according to Formulas (3-4).

$$Q_1=\frac{n_1}{N}\times 100\% \tag{3}$$

$$Q_2=\frac{n_2}{N}\times 100\% \tag{4}$$

where, Q_1 was the qualified rate of fertilization depth, %; Q_2 was the qualified rate of fertilizer layer spacing, %; n_1 referred to points of fertilization depth which is qualified; n_2 referred to points of fertilizer layer spacing which is qualified; *N* was the total number of points measured.

Test results

A ruler was used to measure the fertilization depth, for which the data was given in Table 4.

Table 4

Fertilization depth

Fertilization row		**Point 1 (cm)**	**Point 2 (cm)**	**Point 3 (cm)**	**Point 4 (cm)**	**Point 5 (cm)**	**Mean (cm)**	**Qualified rate (%)**
First row	upper layer	9.0	7.3	8.2	8.7	8.5	8.34	100
	middle layer	16.2	15.7	16.0	16.2	16.8	16.18	100
	lower layer	23.5	23.3	24.0	23.5	24.3	23.72	100
Second row	upper layer	8.7	8.4	8.3	8.3	8.5	8.44	100
	middle layer	16.8	16.8	16.5	16.7	16.7	16.70	100
	lower layer	24.4	24.7	23.8	24.0	24.6	24.30	100
Third row	upper layer	7.2	8.2	7.8	8.1	9.3	8.12	100
	middle layer	14.8	16.2	15.8	16.4	17.3	16.10	100
	lower layer	21.6	23.8	23.5	24.3	25.2	23.68	80
Forth row	upper layer	7.8	8.7	8.9	9.4	8.5	8.66	100
	middle layer	16.2	16.5	18.0	17.1	16.6	16.88	100
	lower layer	23.7	24.2	25.1	24.6	24.4	24.40	100
Mean	upper layer	8.390						
	middle layer	16.465						
	lower layer	24.025						

It was calculated that the average fertilization depth of upper layer was 8.39 cm, the average fertilization depth of middle layer was 16.465 cm, and the average fertilization depth of bottom layer was 24.025 cm. It could be seen from Table 4 that the qualified rate of the average fertilization depth of upper layer and middle layer was 100%, and the qualified rate of the average fertilization depth of lower layer qualified rate was 95%, and the fertilization depth met the requirements of layered fertilization operations.

The measured spacing of fertilizer layer was shown in Table 5.

Table 5

The fertilizer layer spacing

Fertilization row		Point 1 (cm)	Point 2 (cm)	Point 3 (cm)	Point 4 (cm)	Point 5 (cm)	Mean (cm)	Qualified rate (%)
First row	upper layer	7.2	8.4	7.8	7.5	8.3	7.84	100%
	lower layer	7.3	7.6	8.0	7.3	7.5	7.50	100%
Second row	upper layer	8.1	8.4	8.2	8.4	8.2	8.26	100%
	lower layer	7.6	7.9	7.3	7.3	7.9	7.60	100%
Third row	upper layer	7.6	8.0	8.0	8.3	8.0	7.98	100%
	lower layer	6.8	7.6	7.7	7.9	7.9	7.58	100%
Forth row	upper layer	8.4	7.8	9.1	7.7	8.1	8.22	100%
	lower layer	7.5	7.7	7.1	7.5	7.8	7.52	100%
Mean	upper layer	8.075						
	lower layer	7.600						

According to Table 5, the average fertilizer spacing of the upper layer was 8.075 cm, and the maximum spacing error was 1.1 cm; the average fertilizer spacing of lower layer was 7.6 cm, and the maximum spacing error was 1.2 cm. Therefore, the fertilizer spacing satisfied the operating requirements.

CONCLUSIONS

(1) In this study, according to the agronomic requirements of the layered fertilization of wheat, a layered fertilization opener was designed, which comprised of a shovel point, shank, fertilizer grooves and fertilizer drop openings.

(2) The interaction model between the opener, the soil and fertilizers were then established, and soil falling and fertilizer falling simulation experiments were carried out to determine the main parameters of the opener. The optimal parameters were obtained: horizontal distance between the fertilizer drop openings of 14 cm, machine speed of 1.05 m/s, and opener inclination angle of 37°.

(3) The field test results signified that the average depth of upper layer fertilization was 8.39 cm, the average depth of middle layer fertilization was 16.465 cm, and the average depth of lower layer fertilization was 24.025 cm. Furthermore, the average spacing of the upper fertilizer layer was found to be 8.075 cm, while the average spacing of the lower fertilizer layer was 7.6 cm, thus satisfying the requirements of the layered fertilization standard.

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