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Optimizing The Structural Parameters Of The Spiral Grooved-Wheel Fertilizer Discharge Device Using DEM

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Abstract:
Fertilizer discharge process is a critical part of fertilizer application, as it affects the fertilizer discharge rate and uniformity of fertilizer application. Aiming at the poor fertilizer discharge problem of the traditional straight grooved wheel fertilizer applicators, an improved spiral grooved wheel fertilizer discharge device was designed, and the structural parameters of the spiral grooved wheel applicator were analysed. Taking the wheel speed, groove radius, wheel working length, and spiral angle as experimental factors, orthogonal experiments were conducted through DEM simulation to obtain the optimal working parameters of the spiral groove wheel. Based on the results of the simulation experiment, a structural model of the spiral groove wheel fertilizer discharge device was established. In five repeated experiments, the actual fertilization effect was verified. The optimum experimental factors for this device are: wheel speed of 40rpm, groove radius of 6mm, working length of 50mm, and spiral angle of 45°. Under this parameter combination, the coefficient of variation of fertilization uniformity was 5.58%. The coefficient of variation of fertilizer discharge uniformity measured through validation was 5.95%, which was slightly higher than that in the simulation test (5.58%). The error between the simulation and the experimental results was 6.30%. Therefore, it can be confirmed that the simulation test results are basically consistent with the validation test results. The research results provide a theoretical basis for selecting the optimal fertilization device and guiding the design of high-performance fertilization machines.
Key Word: *Spiral grooved-wheel, structural design, DEM simulation, validation experiment.*

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I. Introduction

At present, there are many types of fertilizer discharge devices that can be used for fertilization operation (Ju *et al*., 2025; Bu *et al*., 2022), and the straight groove wheel discharge device is widely used for fertilization because of its simple structure and good versatility (Ru *et al*., 2025; Wang *et al*., 2022). It is reported that most of the existing straight groove wheel fertilizer discharge devices have poor stability in the process of fertilizer discharge, which affects the uniformity of fertilizer application (Ru *et al*., 2025; Bangura *et al.,* 2024).

In recent decades, scholars both home and abroad have conducted extensive research on grooved wheels through discrete element simulations and bench tests (Wang *et al*., 2023; Yu Bing *et al*., 2022; Gao *et al*., 2022; Ding *et al*., 2018). These studies generally explore the influence of grooved wheel parameters on fertilization uniformity. The research field has evolved from traditional straight groove wheels to special structure groove wheels. Shi *et al*. (2021) used a combination of simulation and bench testing to study the effects of groove number, groove radius, and groove cross-sectional shape on the uniformity of fertilizer discharge in the traditional straight grooved fertilizer discharger. Sugirbay *et al*. (2020) optimized the structural parameters of the outer grooved wheel fertilizer discharger using the discrete element method, improving the uniformity of the fertilizer discharged. Ru *et al*. (2025) used discrete element simulation and bench test to study the influence of the working length of the straight groove wheel, the speed of the fertilizer discharge shaft, and the opening angle of the fertilizer discharge tongue on the fertilizer discharge amount. In order to reduce the pulsation of fertilizer discharge, scholars have replaced traditional straight groove wheels with spiral groove wheels and, and optimized their structural parameters (Wang *et al*., 2023; YuBing *et al*., 2022). Wang *et al*. (2023) designed and optimized the spiral groove wheel structure, focusing on groove depth, groove thickness, and helix angle as testing factors. The most uniform distribution was obtained with groove depth of 9 mm, tooth ridge thickness of 2 mm, and helix angle of 45◦. Yang *et al*. (2018) studied the effects of wheel speed, grove radius, and groove helix angle on fertilizer discharge through discrete element simulation and bench tests. Qi *et al*. (2016) designed a fertilizer discharger with two rows of fertilizer discharge teeth arranged alternately, which can effectively reduce the fluctuation of fertilizer output. Liu *et al*. (2021) designed a fertilizer discharge device with a staggered and adjustable outer groove wheel, which has better stability and uniformity than a straight groove wheel.

Considering the above background, and the advantages of the spiral-grooved wheel over the conventional straight groove wheel, this study designed a new spiral-grooved well structure, optimized the effect of it structural parameters on fertilizer discharger performance. The key structural and operational parameters of the spiral-grooved wheel considered in this study are; wheel speed, groove radius, wheel working length and groove spiral angle. These parameters were altered to investigate their effects on fertilizer discharge performance. The study provides a theoretical basis for selecting the best fertilizer discharge device; help to comprehend the discharge behaviour of the spiral-grooved wheel fertilizer applicators, and demonstrate the perfect structural characteristics.

II. Material And Methods

Structure and parameter design of the spiral grooved wheel

Referring to the range of structural parameters of the existing groove wheel fertilizer devices, the maximum effective working diameter of existing grooved-wheels was in the range of 50 to 65 mm and the grooved-wheel length generally varied from 25 to 50 mm (Liping *et al*., 2018, YuBing *et al*., 2022). The structure of the improved spiral groove wheel was shown in Figure 1.

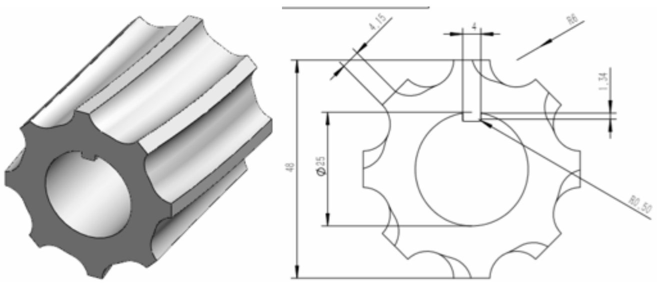

Figure 1. Structure of the spiral groove wheel.

Analysis of the key structural parameters of the spiral grooved wheel

When the fertilizer applicator is in operation, the fertilizer is first filled into the groove of the groove wheel by gravity. Then discharge it through the rotation of the groove. The spiral groove wheel is driven by the fertilizer discharge shaft and continuously rotates under the action of various forces, and the mass of fertilizer discharged when the groove wheel rotates one revolution can be calculated by the following formula:

(1)

where, q is the mass of fertilizer (g/r), S is the cross-sectional area of a single grooves (mm^2), L is the effective working length of the groove wheel (mm), Z is the number of grooves, γ is the filling coefficient of the fertilizer in the groove and ρ is the fertilizer density (g/cm^3).

It is evident from equation (1) that for a particular fertilizer applicator and discharge object, the mass of fertilizer applied per rotation of the grooved wheel is only related to the sectional area S, and that the sectional structural parameters and the fertilizer flow and application performance during the fertilizer transport process, from filling to discharge are inevitably linked (Jinfeng *et al*., 2023). Figure 2 depicts the groove sectional shape of the designed grooved wheel.

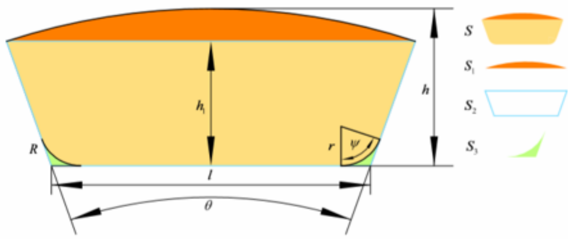

Figure 2. Section shape of the single groove.

The cross-sectional area, S of a single groove obtained from Figure 2 is:

(2)

where, S_1 represents spherical area, S_2 is the area of Isosceles trapezoid and S_3 is bottom corner area. The spherical area is equal to:

(3)

where, θ denotes the centre angle (◦), R is radius of the grooved wheel (mm).
The isosceles trapezoid area is given as:

(4)

where, h_1 is trapezoidal height, is given as: (mm), l—length of trapezoidal short side given as: (mm).

The bottom corner area is equal to:

(5)

where, r represents the groove corner radius (mm), centre angle ( ) (◦).

Equations 2 to 5 make it evident that R, r, θ and h have an impact on S. The groove radius R is one of the main factors taken into account in this work. The value of r must be greater than the radius of the fertilizer particles, which was calculated to be 2 mm based on the size of the fertilizer particles employed in this study. Equation 4.6 provides the particular expression, which relates the center angle θ to both the spiral angle α and the groove thickness b.

(6)

After the fertilizer is filled into the groove of the groove wheel, the motion of the grooved wheel is produced by the combination of axial transnational motion and radial rotational motion along the grooved wheel. The spiral groove is extended, and the spiral line can be represented by straight line. Figure 3 shows the force analysis of fertilizer particles at any point M in the spiral groove.

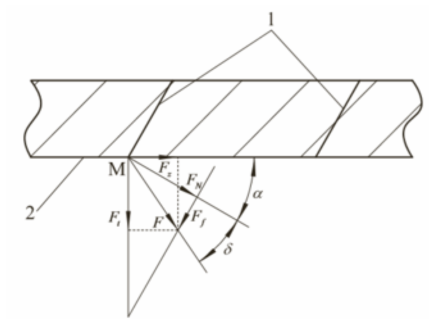

Figure 3. Force analysis of fertilizer particles in the grooves: 1. spiral line 2. Axis.

The fertilizer particles in the grooves are accelerated by a normal force F_N at the point M in the spiral-normal direction. Friction F_f is simultaneously produced as a result of the interaction between the grooves and the fertilizer particles. Between the resultant force F and the normal thrust F_N, friction produces a deflection angle that is about similar to the fertilizer's corresponding angle for external friction δ. The following results are obtained by dividing the resultant force F into its axial force F_Z and circumferential force F_t components:

The expression of each parameter is as follows (Kim *et al*., 2008, Wang *et al*., 2022):

(7)

where, F is the resultant force of the spiral groove acting on the fertilizer particles (N), F_N is the normal force of the spiral groove on the fertilizer particles (N), F_z is the axial force (N), F_t is the circumferential force (N), is the spiral angle of the spiral groove and δ is the friction angle between the spiral groove and the fertilizer particles.

Similarly, the fertilizer particles of the spiral grooves are treated as the mass point m. The speed analysis of this mass point was shown in the equation 8. The movement towards fertilizer particles of the spiral groove is driven by the fertilizer discharge shaft. The implicated velocity v_e is the linear velocity of the particles perpendicular to the axis direction, and the relative velocity v_r is parallel to the spiral direction. In the ideal case without considering friction, the absolute velocity is v_0. In reality, friction will cause the velocity due to friction v' to deviate from the ideal absolute velocity v_0. The deviation angle is and the actual absolute velocity after a deviation is v. At the same time, it can also be decomposed into circumferential velocity v_1 and axial velocity v_2, which can be expressed as equation (8) (YuBing *et al*., 2022).

(8)

The circumferential velocity v_1 and axial velocity v_2 decomposed by the actual absolute velocity v can be expressed as:

(9)

Through trigonometric transformation, it can be obtained as:

(10)

where, v_e represents the implicated velocity (m/s), v_r is the relative velocity (m/s), v_0 is the ideal absolute velocity (m/s), v' is the velocity due to friction (m/s), v is the actual absolute velocity (m/s), v_1 is the circumferential velocity (m/s), v_2 is the axial velocity, (m/s), n is the rotational speed of the double helix groove wheel (r/min), ω is the angular velocity of the double helix groove wheel (rad/s), l is the distance between the fertilizer particle to the axis (mm), β is the angle at which the absolute velocity deviates from the theoretical velocity (°) and α is the spiral angle of the groove wheel (°).

According to the above formula, the velocity change of fertilizer particles in the spiral groove is related to the spiral angle of the groove, the distance between the fertilizer particles and the axis, and the rotation speed of the grooved wheel (Jinfeng *et al*., 2023).

Discrete element simulation model of the spiral grooved wheel

The model of the spiral groove wheel fertilizer discharge device created is mainly composed of a fertilizer discharge box, mounting plate, fertilizer discharge shaft, spiral groove wheel, and fertilizer discharge outlet, as shown in Figure 4. Using the discrete element model parameters of fertilizer particles and discharge assembly, the working process of the spiral groove wheel fertilizer discharge device was simulated.

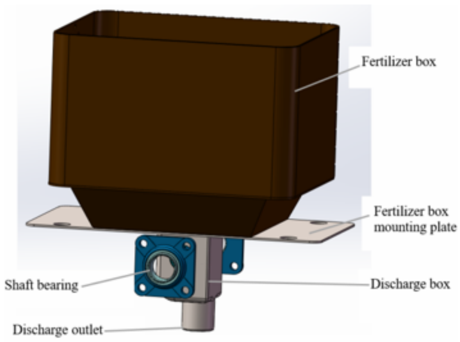

Figure 4. Screenshot of fertilizer discharging device with spiral groove wheel.

Simulation test for the spiral groove wheel discharge device
Simulation test factors

To analyze the influence of the spiral groove wheel structural and operational parameters on the fertilizer discharge performance, this study focused on four key structural and operational parameters of the grooved wheel; wheel speed, groove radius, wheel working length and groove spiral angle as the test factors. The diameter of the spiral groove wheel was 48 mm, the number of spiral grooves was 8. The levels of selected test factors are shown in Table 1

Table 1. Test factor level.

Level	Wheel speed (S), rpm	Groove radius (R), mm	Wheel working length (L), mm	Groove spiral angle (
1	20	5.5	20	45
2	30	6	30	50
3	40	6.5	40	55
4	50	7	50	60

Measurement of coefficient of variation of fertilizer discharge uniformity

The coefficient of variation on fertilizer discharged uniformity was selected as the test evaluation index in this experiment. The simulation of the fertilizer discharge process of the spiral groove device was run under different test factors as shown in Table 1. The discharge mass rate of the spiral grooved wheel device was recorded at every test factor level. The simulation was replicated 5 times for each test factor combination. Each simulation lasted for 3.5 seconds, and the mass of fertilizer discharged was recorded. The coefficient of variation on fertilizer discharged uniformity was assessed by the mean and standard deviation of discharged masses using the Equations (11), (12), and (13).

(11)

(12)

(13)

where, denotes the average mass of fertilizer particles (g), m_i is the mass of fertilizer discharge per time (gs^{-1}), n is the number of measurements, s is the standard deviation of the total mass of the fertilizer discharged (g) and denotes the coefficient of variation of the uniformity of fertilizer discharge (%).

Model validation test

The results of the aforementioned simulation test were used to create a structural model of the spiral grooved wheel fertilizer discharge device, with the grooved wheel rotating at 40 rpm, the groove section radius at 6 mm, the groove working length at 50 mm, and the spiral angle of the groove wheel at 45°. In five repeated tests, the actual fertilization effect was verified through the coefficient of variation of fertilizer discharge quantity. Figure 5 depicts the test setup.

Figure 5. Spiral groove wheel model validation test.

III. Result And Discussions

Simulation results and analysis

To examine how the selected test factors affected the coefficient of variation () of fertilizer discharge quantity, the L16(4) orthogonal test design was generated in SPSS software. Table 2 shows the orthogonal simulation results and the influence of the selected test factors on the coefficient of variation of fertilizer discharged quantity. Figure 6 shows the simulation process.

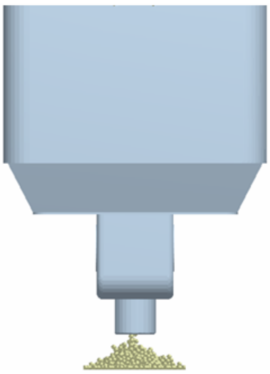

Fig. 6. Fertilization simulation process.

Table 2. L16(4) orthogonal experimental design and results.

Test number	S	R	L		Coefficient of variation of fertilization uniformity (%)
1	1	1	1	1	8.58
2	1	2	2	2	15.75
3	1	3	3	3	13.94
4	1	4	4	4	8.63
5	2	1	2	4	14.04
6	2	2	1	3	8.71
7	2	3	4	2	7.72
8	2	4	3	1	12.36
9	3	1	3	2	14.64
10	3	2	4	1	5.58
11	3	3	1	4	10.39
12	3	4	2	3	15.24
13	4	1	4	3	6.36
14	4	2	3	4	8.93
15	4	3	2	1	9.7
16	4	4	1	2	7.67
	11.725	10.905	8.838	9.055	
	10.708	9.743	13.683	11.445	
	8.165	10.438	12.468	11.063	
	11.463	10.975	7.073	10.498	

Optimal parameters	$S_3R_2L_4$

The results of the simulation test show that the optimum structural parameters of the spiral groove wheel fertilizer application device are: the groove wheel rotation speed of 40 rpm, the groove section radius of 6mm, the groove wheel working length of 50mm, and the groove wheel spiral angle of 45°. Yu Bing *et al.* (2022) observed the optimal fertilization uniformity under the spiral structure parameters of wheel speed of 30rpm, groove radius of 10mm, wheel length of 50mm, and spiral angle of 45^o. In the literature, the range of groove radius is usually 2-10mm, and the groove wheel works well between 30 and 45rpm (Zhang *et al*., 2022; Liping *et al*., 2018; Wang *et al*., 2017). The coefficient of variation of fertilizer uniformity under these parameter settings was 5.58% (Table 2). This proves that the results of this study are consistent with the literature. To further understand the importance of the test parameters of the spiral grooved wheel device on the discharge performance, the variance analysis of the test results was carried out, and Table 3 presents the results.

Table 3. Analysis of the variance.

Source of variation	Deviation sum of squares	Degrees of freedom	Sum of mean squares	F	Significance
S	32.886	3	11.762	3.603	*
R	5.066	3	2.489	1.493	
L	115.241	3	39.214	9.848	**
	4	3	2.133	1.415	
error	14.386	3			

Note: * Significant impact; ** The impact is very significant at the 5% level by LSD

It can be seen from Table 3 that the working length of the spiral groove wheel had a very significant impact on the fertilizer discharge performance, while the rotating speed of the grooved wheel had a significant effect. The spiral angle of the groove and the section radius of the grooved had no significant impact on the fertilizer discharge performance. Yu Bing *et al*. (2022) also found that the length and speed of the spiral groove wheel have a significant impact on the uniformity of fertilizer discharge. However, Wang *et al*. (2023) found that the spiral angle has a significant impact on the uniformity of fertilizer discharge. The contradiction in these results may be caused by the different structural design parameters of spiral groove wheels.

Validation test results

The variation coefficient of fertilizer discharge uniformity assessed through the validation test was 5.95% after five consecutive testing. The results of the validation test had a slightly higher coefficient of variation than that of the simulation test (5.58%). The error between the simulation and experimental results was 6.30%. Many scholars have studied the effect of different structural parameters of spiral groove wheels on fertilizer discharge efficiency. However, their research shows that the coefficient of variation for fertilization uniformity is relatively high, greater than 10% (Wang et al., 2023; Chen *et al*., 2021; Ding *et al*., 2018; Liping *et al*., 2018; Lv *et al*., 2013). This is higher than what was obtained in this study. This indicates that the structural parameters of the spiral groove wheel developed in this study are more reliable for the effective discharge of fertilizers. The simulation and the validation test results are essentially consistent. The results further validate the reliability of using discrete element simulation software to study the fertilizer discharge process of the spiral groove wheel device designed in this paper.

IV. Conclusion

Through discrete element simulation and test, the structural parameters of the spiral groove wheel are optimized. The effects of the rotating speed, the radius of the groove section, the working length of the groove and the spiral angle of the groove on the uniformity of fertilizer discharged were studied, and the optimum structural parameters of the spiral groove wheel were obtained. The use of spiral groove wheel can improve the fertilizer discharge effect, providing a potential solution to the problem of poor fertilizer discharge effect in traditional straight groove wheel devices. These results will also provide a reference basis of selecting the best fertilizer discharge device and guiding the design of high-performance fertilizer applicators.

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