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CASE REPORT

Optimisation and Testing of Structural Parameters of External Tank Wheel Fertiliser Dischargers

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Abstract:
The external trough wheel fertiliser discharger, the most common component of bio-organic fertilizer application systems, the number of grooves, arc-center distance, and effective working length of the groove wheel have a significant impact on its performance. This paper analyzes the effects of these three structural parameters on the uniformity of fertilizer discharge from the external groove wheel, which is the most widely used component in bio-organic fertilizer applicators, using discrete element simulation techniques and orthogonal testing. An simulation orthogonal test was conducted with the coefficient of variation of fertilizer discharge uniformity as the evaluation criterion. The results indicated that the factors influencing fertilizer discharge performance ranked as follows: number of grooves > arc-center distance > effective working length. Among these, the number of grooves had the most significant effect, and the optimal parameter combination derived from the orthogonal test was: 7 grooves, an effective working length of 47.4 mm, and an arc-center distance of 35.7 mm. Under this combination, the coefficient of variation of fertilizer discharge uniformity was 3.53%. To validate the simulation results, a solid prototype was constructed, and the test results showed that the error between the simulation and the actual results was less than 5%, confirming the feasibility of using discrete element simulation technology to study the factors influencing the performance of the external grooved wheel for fertilizer discharge. The findings of this study may offer valuable insights for optimizing the structural parameters of external trough wheel fertilizer discharger.

Keywords: Agricultural machinery, Fertiliser spreader, Discrete element simulation, Structural parameters, Fertiliser spreading performance

Introduction

Hunan is one of the most important tobacco-producing regions in China[1,2]. Tobacco, as a crucial economic crop, plays a pivotal role in the national economy. Fertilization is a key process in tobacco cultivation, with the period of substantial fertilizer absorption occurring between 45 and 75 days after transplanting. This period is concentrated, but to avoid issues such as root burning from excessive fertilizer or nutrient deficiencies later, it is essential to apply smaller amounts of fertilizer multiple times. Therefore, the precise and reasonable application of fertilizer can effectively improve both the yield and quality of tobacco while reducing planting costs[3,4].

The application of solid bio-organic fertilizer is an important method to enhance the soil quality of tobacco fields and improve the quality of tobacco products [5]. In tobacco fields, the application rate of bio-organic fertilizer is typically between 2000 and 3000 kg/hm^2, which is beneficial for tobacco growth [6]. The most common fertilizer application method is strip application, utilizing an external grooved wheel discharger as the fertilizer delivery component.

However, practical applications face issues such as large pulsations and poor stability in external trough wheel fertilizer dispensers. To improve the performance of these dispensers, researchers both domestically and internationally have conducted extensive studies. Zhu Qingzhen and colleagues from Northwest Agriculture and Forestry University explored the influence of the groove section shape and related parameters of the external grooved wheel on fertilizer discharge performance [7]. Zhang Xin and his team from Southwest University studied the effect of the outer groove wheel's volume on the fertilizer discharge rate [8]. Wang Botao and others analyzed how factors like the working length of the external grooved wheel, the rotational speed of the fertilizer discharge shaft, and the opening angle of the fertilizer discharge tongue affected fertilizer discharge volume and pulsation, using simulated orthogonal tests [9].

The discrete element method (EDEM), an effective analytical tool, is widely used to study the mechanical behavior of granular systems. By creating a discrete element parametric model of the particulate system, the motion behavior of fertilizer particles during application can be simulated and analyzed, thus significantly reducing experimental costs. Liedekerke [10] simulated the motion of fertilizer particles on the rotating disc of a centrifugal discharger using EDEM, focusing on the trajectories of individual particles and comparing the simulation results with experimental data. The results showed that the simulated particle trajectories closely matched the experimental trends. Xudong Liang and colleagues [11] used EDEM to analyze the spreading process of fertilizer particles, studying the uniform distribution of fertilizer in the field. Their results demonstrated that the uniformity of the fertilizer distribution was significantly influenced by the material properties of the fertilizer particles.

In this paper, an EDEM simulation model is established to study the effects of key structural parameters and the interaction of various factors on the fertilizer discharge performance of the external trough wheel fertilizer discharger. Finally, the reliability of the simulation orthogonal test results is verified through experimental testing.

2. Materials and Methods

2.1 The overall structure and working principle of the external groove wheel fertiliser discharger

The external trough wheel fertilizer discharger as one of the most widely used types of manure dischargers [12,13]. It consists of a fertiliser box, a grooved wheel, a fertiliser box and a fertiliser discharge tongue, as shown in Figure 1.

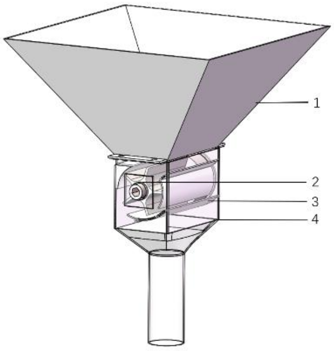


Figure 1 - Schematic diagram of fertiliser discharger mechanism

1. **Fertiliser box 2.Trough wheel 3.Fertiliser discharge tongue 4.Fertiliser box**

According to the principle of fertiliser discharge operation, the amount of fertiliser discharged per rotation of the key working part can be derived from the following formula:

$$\begin{cases} q = q_1 + q_2 \\ q_1 = \dfrac{\rho \tau z s L}{1000} \\ q_2 = \dfrac{\rho \pi d L \lambda}{1000} \end{cases} \tag{1}$$

Where: q_1 for the mass of fertiliser discharged from the forced layer, g/r; q_2 for the mass of fertiliser discharged from the driven layer, g/r; q for the mass of fertiliser discharged from the grooved wheel rotating for 1 week, g/r; ρ for the density of fertiliser particles, kg/m^3; τ for the filling coefficient of fertiliser in the grooves; z for the number of grooves; s for the cross-sectional area of individual grooves,mm^2; L for the effective length of the grooved wheel, mm^2; ; d for the diameter of the grooved wheel,mm; λ for the fertiliser particles of the is the driving layer coefficient of fertiliser particles [14].

As shown in equation (1), the structural parameters of the external groove wheel fertiliser discharger that affect the amount of fertiliser discharged are the number of grooves z, the effective length of the groove wheel L, the diameter of the groove wheel d, and the cross-sectional area of the individual grooves s, etc.

2.2 Key structural design and analysis of external grooved wheels

The groove wheel is the core component of the external groove wheel fertiliser discharger, and in this paper, the commonly used circular arc-shaped groove is chosen as the cross-section shape of the groove wheel groove [15]. In the process of fertiliser discharge, the structure of the groove of the groove wheel, the arrangement of fertiliser particles in the groove, and the force of the groove wheel will affect the performance of the external groove wheel fertiliser discharger, making it difficult to precisely control the amount of fertiliser discharged in the process of fertiliser discharge. Therefore, the establishment of the correlation model of the groove cross-section of the groove wheel is crucial for the precise control of fertiliser discharge, and also provides a theoretical basis for the optimisation of the fertiliser discharger. The correlation model is shown in Figure 2.

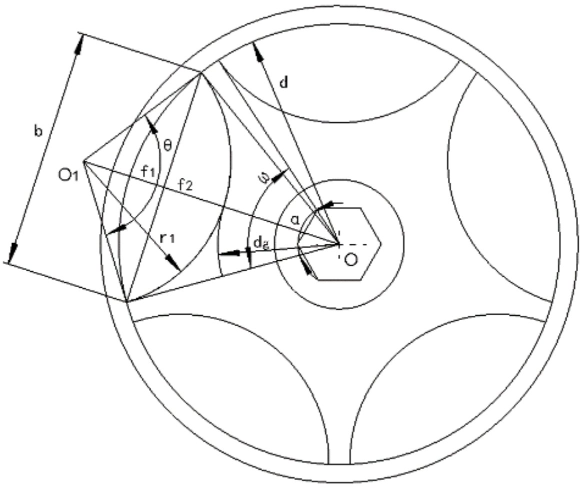


Figure 2 - Cross-section of the groove wheel

α is the pitch angle between adjacent grooves, rad; θ is the arc angle of individual grooves, rad; ω is the span of individual grooves, rad; R is the arc-centre distance, mm; r is the radius of the grooves, mm; d_g is the diameter of the root circle of the grooved wheel, mm; and b is the chord length of the circular arc grooves, mm.

From equation (2), the cross sectional area of the groove can be expressed by the number of grooves and the arc centre distance. In summary, for the circular arc-shaped groove fertiliser discharger, the number of grooves z, the effective length of the groove wheel L and the arc-centre distance R are the key structural parameters affecting the fertiliser discharge.

$$\begin{cases} \omega = \dfrac{2\pi}{z} \\ \alpha = 2\arcsin\dfrac{b}{d} = \dfrac{\omega(z-1)}{z} \\ \theta = 2\arcsin\dfrac{b}{2r} \\ b = \sqrt{\dfrac{d^2}{2} + 2r^2 + \dfrac{d^2 r^2}{2R^2} - R^2 - \dfrac{d^4}{16R^2} - \dfrac{r^4}{R^2}} \\ R = \dfrac{d_g}{2} + r \\ s = f_1 + f_2 = \dfrac{d^2}{8}(\alpha - \sin\alpha) + \dfrac{r_1^2}{2}(\theta - \sin\theta) \end{cases} \tag{2}$$

From equation (2), the cross sectional area of the groove can be expressed by the number of grooves and the arc centre distance. In conclusion, for the circular arc-shaped groove fertiliser discharger, the number of grooves z, the working effective length of the groove wheel L and the arc-centre distance R are the key structural parameters affecting the fertiliser discharge.

2.3 Discrete element simulation platform construction

Discrete Elemental Modelling of Organic Fertiliser Fertiliser Particles

To simulate the fertilizer discharge process of the fertilizer discharger using the EDEM discrete element method, it is essential to construct a three-dimensional model of the external grooved wheel fertilizer discharger, a discrete element model of the fertilizer particles, and set the relevant simulation parameters. By integrating these two models, a discrete element simulation model of the fertilizer discharger can be developed, providing an effective simulation platform for subsequent research. In this study, bio-organic fertilizer is chosen as the fertilizer for the discharger, and the fertilizer particles are modeled as single spheres, as shown in Fig. 3. During the 3D modeling process, the method for modeling fertilizer particles is referenced, and 100 particles are randomly selected from the fertilizer bag for 3D dimension measurement, with the final result being the average value. The measurement results show that the length, width, and height of the fertilizer particles are 3.51 mm, 3.42 mm, and 3.54 mm, respectively. Using Eqs. (3) and (4), the equivalent diameters and sphericity of the fertilizer particles are calculated as follows:

$$D = \sqrt[3]{lwh} \tag{3}$$

$$\varphi_1 = \frac{D}{l} \times 100\% \tag{4}$$

where: D denotes the equivalent diameter of fertiliser particles, mm; φ_1 denotes the sphericity of fertiliser particles, %; l, w and h denote the length, width and height of fertiliser particles, mm.

After measurement and calculation, the equivalent diameter of the particles is found to be 3.49 mm, and the sphericity of the fertilizer particle sample exceeds 90%. This indicates that the particles in this sample exhibit high sphericity, making it appropriate to model the fertilizer particles as spheres in the three-dimensional discrete element model.

Figure 3 - Discrete elemental modelling of bio-organic fertiliser particles

Discrete Element Contact Model

In view of the lack of adhesion on the surface of the organic fertiliser particles, the contact model between the organic fertiliser particles, the external trough wheel fertilizer discharger, and the soil ground was set to Hertz-mindlin (no-slip), and the fertiliser box, grooved wheel, discharging tongue, and fertiliser box of the fertiliser discharger were set to the Q235 material properties. The combination of experimental measurements and review of relevant literature used in this paper to determine the material and contact mechanics parameters related to fertiliser particles, fertiliser discharger and soil ground[16] is shown in Table 1.

Table 1 Material and contact mechanics parameters for discrete element models

Materials	**Shear modulus** G/MPa	**Density** ρ/kg▪m^{-3}	**Poisson's ratio**	**Crash recovery factor**	**coefficient of static friction**	**coefficient of kinetic friction**
Organic Fertiliser Pellets	2.5	1470	0.25	0.21	0.40	0.27
Q235	8.2×10^4	7860	0.29	0.09	0.32	0.21
soil surface	120	2500	0.38	0.02	1.25	1.24

2.4 Simulation Test Parameter Setting

Simulation Test Method

The structural model of the fertilizer discharger was imported into the simulation software EDEM. To facilitate observation, a plane with dimensions of 1200 × 250 mm was placed 300 mm above the bottom of the fertilizer box to simulate the soil surface. Based on previous studies, the rotational speed of the grooved wheel was set to 35 r/min in this paper [17]. Referring to literature [18], the forward speed of the tractor was set to 0.3 m/s, and the relevant material and contact model parameters were defined according to Table 1.

A particle factory was set up above the fertilizer box to continuously generate fertilizer particles during the simulation. The total number of particles produced by the factory was set to 10,000, with a generation rate of 3,000 particles per second. Once the number of particles reached a set threshold, the rotational speed of the grooved wheel and the movement of the soil surface were activated, initiating the simulation test. The process of the simulation test is shown in Fig. 4.

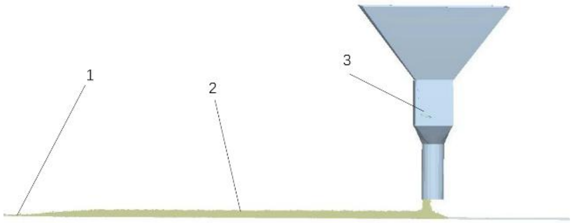


Figure 4 - Simulation of the working process of the fertiliser discharger

1. Soil ground 2. Organic fertiliser granules 3. Fertiliser drainer

Methods for evaluating the performance of fertiliser drainage

To quantitatively describe the degree of fertilizer discharge pulsation of the external grooved wheel discharger, this paper defines the coefficient of variation of fertilizer discharge pulsation as a measure, which accurately reflects the evaluation data. This is specifically shown in equations (5), (6), and (7).

$$\delta = \frac{\sum_{n=1}^{m} Q_n}{n} \tag{5}$$

$$\sigma = \sqrt{\frac{\sum_{n=1}^{m} (Q_n - \delta)^2}{n}} \tag{6}$$

$$Z = \frac{\sigma}{\delta} \times 100\% \tag{7}$$

where: δ is the mean value of all data in the discharge pulsation monitoring area, g; Q_n is a data point collected in the discharge pulsation monitoring area, g; σ is the standard deviation of all data in the discharge pulsation monitoring area; n is the number of data points collected in the discharge pulsation monitoring area; m is the total number of data points collected in the discharge pulsation monitoring area; Z is the coefficient of variation of the discharge pulsation.

Using the formulas (5), (6), and (7), the coefficient of variation of fertilizer discharge pulsation for the external grooved wheel discharger can be calculated. The coefficient of variation serves as an index to measure the degree of pulsation; a smaller pulsation coefficient indicates a lower degree of pulsation and better uniformity of fertilizer discharge.

Based on the working principle of the external grooved wheel fertilizer discharger and the analysis of how the structural parameters of the grooved wheel affect the fertilizer discharge performance, the test selected the following key structural parameters: the arc-center distance of the grooved wheel, the number of grooves, and the effective length of the grooved wheel. According to market research and literature, the number of grooves of the external grooved wheel discharger generally does not exceed 8, the groove radius typically ranges from 2 to 9 mm, and the groove wheel diameter is generally no more than 60 mm. Therefore, this paper selects a maximum arc-center distance of 40 mm, which can effectively increase the rotational speed of the grooved wheel shaft, enhance the pulse frequency, and improve the uniformity of organic fertilizer particle distribution. Additionally, the effective length of the grooved wheel is limited to no more than 55 mm [19]. In line with practical application requirements, three levels were selected for each of the three factors, as shown in Table 2.

Table 2. Orthogonal test factor levels

Level	**Number of grooves X1**	**Effective working length X2（mm）**	**Arc distance X3（mm）**
-1	5	45	30
0	6	50	35
1	7	55	40

3. Results and Analysis

3.1 Results of Multifactor Test and Establishment of Regression Equation

To investigate the effect of various factors on the coefficient of variation in fertilizer discharge uniformity, a three-factor, three-level experimental design was conducted using the Box-Behnken method in Design-Expert 12 software [20,21].

Table 3. Pilot Programme and Test Results

Level	**Number of grooves X1**	**Effective working length X2（mm）**	**Arc distance X3（mm）**	**coefficient of variation Z（%）**
1	7	50	40	4.2
2	7	45	35	3.6
3	6	55	30	16.1
4	6	55	40	13.4
5	6	45	30	13.1
6	7	50	30	3.6
7	5	50	40	9.1
8	6	50	35	12.0
9	6	50	35	12.1
10	6	50	35	11.9
11	6	50	35	12.0
12	5	45	35	15.9
13	5	55	35	16.2
14	7	55	35	4.0
15	5	50	30	15.9
16	6	45	40	9.1
17	6	50	35	14.1

Quadratic regression analysis of the experimental results was carried out using Design Expert 12 software and the regression mathematical model for the coefficient of variation of fertiliser discharge was obtained as:

$$Z = 12.42 - 5.21X_1 + X_2 - 1.61X_3 + 0.025X_1X_2 + 1.85X_1X_3 + 0.325X_2X_3 - 3.61X_1^2 + 1.12X_2^2 - 0.61X_3^2 \quad (8)$$

The experimental results and the analysis of variance (ANOVA) for the regression equations are presented in Table 3. In the table, X_1, X_2, and X_3 represent the coded levels for the number of grooves, effective working length, and arc-center distance, respectively. Z denotes the coefficient of variation in fertilizer discharge (%). The lack-of-fit term for each regression model is not significant, indicating a good fit with the actual test results. As shown in Table 4, the regression model for the coefficient of variation has $p<0.05$, suggesting that the mathematical model is statistically significant and that each factor significantly affects the coefficient of variation. Furthermore, the lack-of-fit term has $p=0.0884>0.05$, indicating that the equations are well-fitted and no significant lack-of-fit term is present [22]. From equation (6), the influence of each factor on the coefficient of variation is ranked as follows: number of grooves > arc-center distance > effective working length of the grooved wheel.

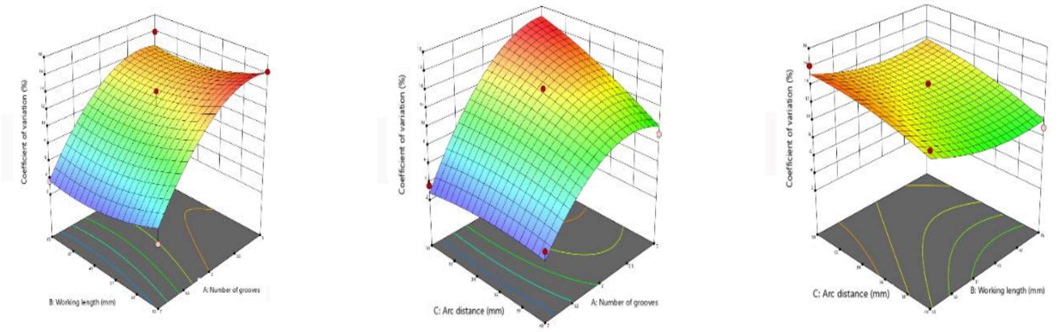
Table 4. Quadratic regression analysis of variance

Source	**Sum of squares**	**Freedom**	**Mean square**	***F* value**	***P* value**
Model	321.14	9	35.68	15.92	0.0007
X_1	8.00	1	217.36	97.00	<0.0001
X_2	217.36	1	8.00	3.57	0.1008
X_3	20.80	1	20.80	9.28	0.0187
X_1X_2	0.0025	1	0.0025	0.0011	0.9743
X_1X_3	13.69	1	13.69	6.11	0.0427
X_2X_3	0.4225	1	0.4225	0.1885	0.6772
X_1^2	54.87	1	54.87	24.49	0.0017
X_2^2	5.23	1	5.23	2.34	0.1703
X_3^2	1.57	1	1.57	0.6992	0.4307
Residual	15.69	7	2.24		
Lack of fit	12.14	3	4.05	4.56	0.0884
Pure Error	3.55	4	0.8870		
Sum	336.82	16			

Note: $P < 0.01$ (highly significant), $P < 0.05$ (significant).

3.2 Response Analysis and Optimisation of Uniform Performance of Fertiliser Discharge

To investigate the effect of the number of grooves, effective working length of the grooved wheels, and arc-center distance on fertilizer discharge uniformity, as well as the interrelationships between these factors, the response surface was plotted using Design-Expert 12, as shown in Fig. 5.



(a) (b) (c)

Figure 5 - Response surfaces between individual test factors and the coefficient of variation of fertiliser discharge uniformity

(a) Influence of the number of grooves and effective working length of the groove wheel on the coefficient of variation of the uniformity of fertiliser discharge (b) Effect of number of grooves and arc-centre distance of grooved wheels on the coefficient of variation of uniformity of fertiliser discharge (c) Effect of effective working length and arc-centre distance of the groove wheel on the coefficient of variation of fertiliser discharge uniformity

Figure 8a shows the response surface of the number of grooves and the effective working length of the grooved wheel on the coefficient of variation in fertilizer discharge when the arc-center distance is 35 mm. Within the parameter range of the number of grooves $5 < X_1 < 7$, effective working length $45mm < X_2 < 55mm$, and arc-center distance $30mm < X_3 < 40mm$, increasing the effective working length results in an increase in the degree of pulsation of fertilizer discharge, while increasing the number of grooves decreases the degree of pulsation. Figure 8b illustrates that when the effective working length is 50 mm, the response surface of the number of grooves and the arc-center distance on the coefficient of variation in fertilizer discharge exhibits a downward-opening parabolic shape. When the arc-center distance is fixed, the uniformity of fertilizer discharge initially increases and then decreases with the increase in the number of grooves. Conversely, when the number of grooves is fixed, the arc-center distance first increases and then decreases within the range of 30–40 mm, with a maximum value observed in this arc-center distance range. Figure 8c shows the response surface of the arc-center distance and effective working length on the variation coefficient of fertilizer discharge when the number of grooves is fixed at 6. When the effective working length is fixed, the variation coefficient of fertilizer discharge uniformity decreases as the arc-center distance increases, while fixing the arc-center distance leads to an increase in the variation coefficient as the effective working length increases.

To achieve optimal fertilizer discharge performance, the working parameters of the external grooved wheel fertilizer discharger were optimized. The optimal parameter combinations for each factor were determined using Design-Expert 12 software, as follows: number of grooves $X_1 = 7$, effective working length $X_2 = 47.4mm$, and arc-center distance $X_3 = 35.7mm$. In the simulation test of fertilizer discharge performance, the coefficient of variation of fertilizer discharge uniformity was 3.53%. This combination of structural parameter levels for the external grooved wheel fertilizer discharger exhibited the best fertilizer discharge performance compared to the results of 17 sets of simulation orthogonal tests.

3.3 Verification Test

To verify the reliability of the optimization results, a validation test was conducted using the optimized parameters, as shown in Fig. 6. Following the simulation test conditions, the rotational speed of the grooved wheel during the verification test was set to 35 r/min, the forward speed of the tractor was set to 0.3 m/s, and the height of the fertilizer discharge pipe was 300 mm. Bio-organic fertilizer was used for the test. At the end of the test, the distribution pattern of the fertilizer particles on the ground was recorded. The test was repeated five times, and the average coefficient of variation in fertilizer discharge uniformity was found to be 7.25%. The error between the experimental results and the simulated orthogonal test results was less than 5%, indicating that it is feasible to use the orthogonal simulation test to study the effect of structural parameters of the external grooved wheel discharger on fertilizer discharge uniformity.

Figure 6 - Fertiliser drainage validation test

3.4 Discussion

When comparing the coefficients of variation for the uniformity of fertilizer discharge during the operation of the external grooved wheel discharger in both the simulated orthogonal test and the validation test, a certain deviation was observed. The reasons for this deviation were analyzed. It was found that the organic fertilizer particles used in the actual test were not strictly spherical, and the uniformity and degree of dispersion of the bio-organic fertilizer particles in the validation test were relatively poor. Additionally, there were processing errors in the mechanical structure of the external grooved wheel fertilizer discharger, as well as errors in factors such as the tractor's forward angle, speed, and measurement inaccuracies. As a result, the coefficient of variation obtained from the validation test was slightly higher than that from the simulation orthogonal test. Despite this, the results of both tests were considered to be essentially the same. The validation test confirms that using discrete element simulation software and response surface analysis to simulate the operation of the external grooved wheel fertilizer discharger and study the effects of its structural parameters on fertilizer discharge uniformity is a reliable approach.

4. Conclusions

(1) Based on the working principle of the external grooved wheel fertilizer discharger, a prototype was developed, comprising a fertilizer box, grooved wheel, fertilizer discharge tongue, and discharge box. The prototype was then studied using discrete element simulation, orthogonal testing, response surface analysis, and validation tests.

(2) Bio-organic fertilizer was selected as the fertilizer application material, and EDEM software was used to create the simulation platform for the operation of the external grooved wheel fertilizer discharger. The three-dimensional model of the discharger and the particle model of bio-organic fertilizer were imported into the discrete element software to simulate the discharger's operation and analyze the effects of three structural parameters—groove number, effective working length, and arc-centre distance—on the coefficient of variation in fertilizer discharge uniformity.

(3) A three-factor, three-level orthogonal test was conducted to establish a mathematical model describing the relationship between the number of grooves, effective working length, and arc-centre distance of the fertilizer spreader and the coefficient of variation in fertilizer spreading uniformity. Regression analysis of the orthogonal test data was used to derive this model. Response surface analysis was then performed to assess the impact of each parameter on the coefficient of variation in fertilizer discharge uniformity, leading to the optimal parameter combination: 7 grooves, an effective working length of 47.4 mm, and an arc-centre distance of 35.7 mm, resulting in a coefficient of variation of 3.53%. Finally,

validation tests showed that the error between the simulation results and experimental data was within 5%, confirming the feasibility of using discrete element simulation to study the impact of structural parameters on fertilizer discharger performance.

Author Contributions: Conceptualization, Ting GUO and Xi Xiao; methodology, Linji LI; software, Yuanfeng SHOU; validation, Xiaye CHEN; formal analysis, Jinlong YU; investigation, Jinlong YU; resources, Yuanfeng SHOU; data curation, Ting GUO; writing—original draft preparation, Ting GUO; writing—review and editing, Ting GUO; visualization, Chunlin CAI; supervision, Chunlin CAI; project administration, Linji LI; funding acquisition, Linji LI; All authors have read and agreed to the published version of the manuscript.

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