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*Article*

# Optimization Design and Experiment for Precise Control Double Arc Groove Screw Fertilizer Discharger

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**Abstract:** In order to solve the problem of uniform and precise fertilizer discharge, based on experimental analysis of the uneven nature of single-screw fertilizer discharge, a double arc groove screw fertilizer discharger was designed based on the principle of the half-cycle superposition of the fertilizer discharge curve. The fertilizer discharge amount and the instantaneous fertilizer discharge characteristics of the double arc groove screw fertilizer discharger were theoretically analyzed, and the factors affecting the fertilizer discharge uniformity of the double arc groove screw fertilizer discharger were obtained, taking the pitch $S$, arc groove radius $R_p$ and center distance as the test factors. Using the uniformity variation coefficient and fertilization accuracy as test indexes, the experimental indicators were evaluated through a quadratic universal rotation combination design experiment with three factors and five levels. The optimal parameters were pitch $S$ = 35 mm, arc groove radius $R_p$ = 17 mm and center distance $a$ = 40 mm. The fertilizer discharger was produced based on the optimal parameter combination, and a bench verification test and a comparative test were carried out. The test results show that the uniformity variation coefficient of the bench test and the relative error between the fertilization accuracy and the simulation test are 5.60% and 5.52%, respectively, and there is little difference between them, which verifies the correctness of the simulation. The comparative test results show that the uniformity variation coefficient of the optimized double arc groove screw fertilizer discharger is 7.16%, the fertilization accuracy is 3.44% and the fitting curve equation $R^2$ of fertilizer discharge flow is 0.998, all of which are significantly better than in the single-screw fertilizer discharger. We developed an electronic fertilizer discharge controller and conducted bench verification tests on it. The test results show that the average deviation between the measured fertilizer discharge capacity and the preset value of the double arc groove screw fertilizer discharger based on our self-developed controller is 2.78%. This fertilizer discharge device can precisely control fertilizer discharge, effectively solving the problem of uneven fertilizer discharge in single-screw fertilizer dischargers.

**Keywords:** single screw fertilizer discharger; double arc groove screw fertilizer discharger; precision fertilization; structural optimization; discrete element



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## 1. Introduction

China is one of the leading countries in fertilizer applications, but the utilization rate of domestic fertilizer is only 33% [1–3]. Precision fertilization is a method of precise and efficient fertilization according to the supply and demand relationship of crop nutrients [4]. It is of great significance to improve the fertilizer utilization rate and reduce the amount of fertilizer application [5] since the fertilizer discharger is a vital part of precision fertilization. Therefore, improving the accuracy and uniformity of the fertilizer discharged from a fertilizer discharger is significant for achieving precise fertilization [6–8].

At present, the fertilizer dischargers on the market are mainly divided into screw fertilizer dischargers and external groove wheel fertilizer dischargers. As a common fertilizer discharger, screw fertilizer dischargers have the advantages of a simple structure, adjustable fertilizer discharge amount and low price [9–11]. In recent years, relevant scholars have carried out a great deal of research on improving the precision and uniformity of fertilizer discharged from traditional single-screw fertilizer dischargers. Xue et al. [12] conducted simulation and bench experiments on the stability and uniformity of fertilizer discharge via fertilizer dischargers, and they optimized the optimal rotating speed of the fertilizer discharger. However, it is not suitable for situation where the fertilizer output is adjusted by changing the rotational speed. Kretz et al. [13] carried out simulation and bench tests on the influence of screw design parameters and installation inclination angle on the stability of the material flow rate at the screw outlet, and the optimization resulted in the flow rate at the screw outlet being more uniform. Li et al. [14] designed a vertical helical quantitative fertilizer discharger for operating environments in hilly and mountainous areas, and they optimized the structural parameters of the helical blade through theoretical calculations and experiments. With the development of computer technology, the discrete element method and its numerical simulation software EDEM have been widely used in the field of agricultural engineering. Yang et al. [15] used the Hertz–Mindlin Contact Model to simulate the fertilization process by changing the structure size of the sheave and optimized the sheave. Song et al. [16] optimized the screw conveyor mechanism based on the EDEM simulation method using a double-line helical structure at the entrance, and the pulsation peak value of the material flow at the outlet was reduced. However, the ratio between the pulsation amplitude and the average value was still significant, which is not suitable for precision fertilization scenarios. The above research is mainly aimed at single-screw precision fertilization to meet the need for uniform fertilization. However, there are few reports on the optimization of precision fertilization in double-screw fertilizer dischargers.

Our team previously studied and designed a double arc-groove screw fertilizer discharger (DAGSFD). Through optimization, it was determined that its optimal structure is a pitch of 35 mm, arc groove radius of 17.5 mm and center distance of 35 mm. But we did not explore the essence of improving the uniformity and accuracy of fertilizer discharge via the double arc groove screw fertilizer discharger. Therefore, based on the previous analysis, our team calculated and measured the fertilizer output of a single-screw fertilizer discharger (SSFD) through a combination of theoretical analysis and modeling software based on the reasons for uneven fertilizer discharge. We further optimized its factor range through EDEM simulation experiments and three-factor five-level quadratic universal rotation combination design experiments. Three-dimensional-printing technology was used to process the optimized double arc groove screw fertilizer discharger, and a bench test was carried out to verify the correctness of the simulation results. Simultaneously, we designed an electronic fertilizer discharge control system that accurately adjusts the discharge flow rate of the double arc groove screw fertilizer discharger by controlling the rotational speed. We also provide a reference for the optimization design of the double arc groove screw fertilizer discharger.

## 2. Materials and Methods

### *2.1. Design and Working Principle of Double Arc Groove Screw Fertilizer Discharger*

#### 2.1.1. Structure and Working Principle of Double Arc Groove Screw Fertilizer Discharger

The structure of the double arc groove screw fertilizer discharger is shown in Figure 1. It consists of a pair of gears, a pair of fertilizer discharge wheels, a shell and an end cover. A pair of mutually meshing gears rotate in the center to drive a pair of fertilizer discharge wheels to rotate in the center. The fertilizer enters from the fertilizer inlet due to its own gravity and the centering and mixing action of the double fertilizer discharge wheels. Under the combined action of the double fertilizer discharge wheels and the shell, the fertilizer is transported to the fertilizer outlet. The fertilizer falls into the fertilizer discharge pipe due to gravity, and the fertilizer discharge process is completed.

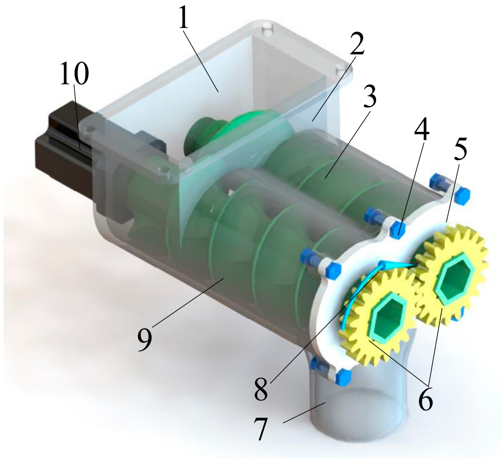


**Figure 1.** Schematic diagram of the double arc groove screw fertilizer discharger: 1. Fertilizer inlet. 2. Shell. 3. Left-handed fertilizer discharge wheel. 4. Bolt fertilizer discharge wheel. 5. End cover. 6. Gear. 7. Fertilizer outlet. 8. Direction of rotation. 9. Right- handed fertilizer discharge wheel. 10. Motor.

#### 2.1.2. Research on Fertilizer Discharge Characteristics of Single-Screw Fertilizer Discharger

In order to study the transition to fertilizer discharge characteristics of the single-screw fertilizer discharger, EDEM 2018 discrete element simulation software was used to simulate and analyze the fertilizer discharge process of the single-screw fertilizer discharger (rotating speed 30 r/min [17]). We determined the parameters of the fertilizer discharge wheel according to the commonly used amount of fertilizer [18]. The large radius of the screw blade is $R$ = 25 mm; the small radius of the screw blade is $r$ = 7.5 mm; the pitch is $S$ = 35 mm; and the thickness of the screw blade is $b$ = 2 mm. The test fertilizer particles were made of Stanley compound fertilizer (average radius, 1.64 mm; density, 1.86 g/cm$^3$). Consulting the relevant literature [19–21], the simulation parameters are set according to Table 1.

**Table 1.** Global variable parameter settings.

| Project | Attributes | Value |
|---|---|---|
| Fertilizer granules | Poisson's ratio | 0.25 |
| | Shear modulus Pa | $1.0 \times 10^7$ |
| | Density kg·m$^{-3}$ | 1861 |
| Fertilizer discharge wheel, shell | Poisson's ratio | 0.394 |
| | Shear modulus Pa | $3.18 \times 10^8$ |
| | Density kg·m$^{-3}$ | 1240 |
| Granules—Granules | Coefficient of restitution | 0.11 |
| | Static friction coefficient | 0.3 |
| | Rolling friction coefficient | 0.1 |
| Granules—Fertilizer discharge wheels, Housings | Coefficient of restitution | 0.41 |
| | Static friction coefficient | 0.32 |
| | Rolling friction coefficient | 0.18 |

The change in fertilizer flow with the opening and closing of the fertilizer outlet in one rotation cycle is shown in Figure 2. By analyzing the instantaneous fertilizer flow at the fertilizer outlet during the single-cycle fertilizer discharge process, it is found that the transient fertilizer discharge amount of the fertilizer outlet changes periodically. The periodic opening and closing of the fertilizer outlet are reasons for the uneven fertilizer discharge of the screw fertilizer discharger.

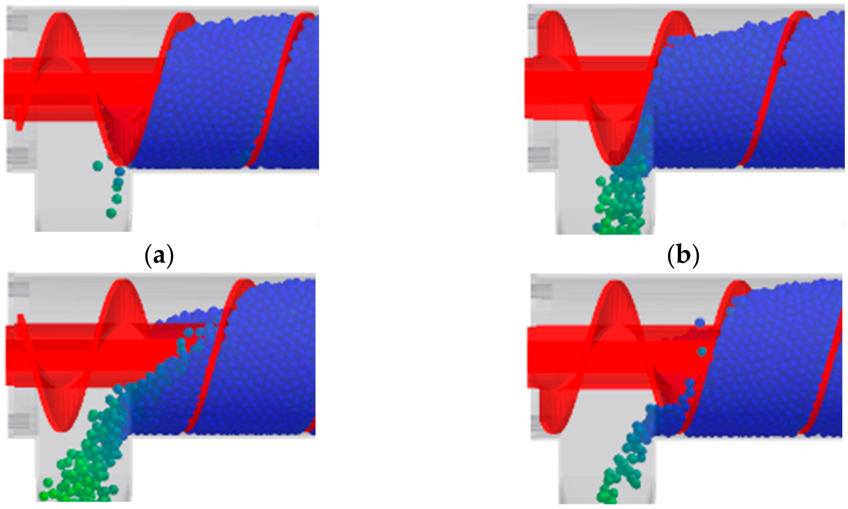

**Figure 2.** Opening size of fertilizer discharge outlet in different phases: (**a**) 0°, (**b**) 90°, (**c**) 180°, (**d**) 270°.

2.1.3. Design of Double Arc Groove Screw Fertilizer Discharger

The fertilizer discharge curve of the single-screw fertilizer discharger changes periodically. The fertilizer discharge curve is idealized as a sinusoidal function. According to the properties of the sinusoidal function of Formula (1), it can be known that increasing the number of fertilizer discharge wheels and adjusting the installation angle can achieve the purpose of a uniform fertilizer discharge.

Each time a fertilizer discharge curve is added, the number of corresponding transmission gears, fertilizer discharge wheels, and cavities are all increased, which reduces the reliability of the system and increases the manufacturing costs. Therefore, under comprehensive consideration, a fertilizer discharger is manufactured by superimposing two fertilizer discharge curves. However, the single-screw fertilizer discharge curve is not a strict sinusoidal curve, so it is necessary to optimize the structure of the double-screw fertilizer discharger to further improve its precise fertilization.

$$\begin{cases} A\sin t + A\sin(t+\pi) = 0 \\ A\sin t + A\sin\left(t + \frac{2}{3}\pi\right) + A\sin\left(t + \frac{4}{3}\pi\right) = 0 \\ A\sin t + A\sin\left(t + \frac{\pi}{2}\right) + A\sin(t+\pi) + A\sin\left(t + \frac{3}{2}\pi\right) = 0 \\ \cdots\cdots \end{cases} \quad (1)$$

In the formula: $t$—rotation time of the fertilizer discharger, s; $A$—coefficient of the fertilizer discharge curve, g.

## *2.2. Double Arc Groove Screw Fertilizer Discharger*

2.2.1. Theoretical Fertilizer Discharge Amount of Double Arc Groove Screw Fertilizer Discharger

The theoretical fertilizer discharge amount of the double arc groove screw fertilizer discharger is mainly determined by the difference between the volume of the inner cavity and the volume of the fertilizer discharge wheel in a single rotation cycle (hereinafter referred to as the volume difference). The volume difference in a single rotation cycle is shown in Figure 3.

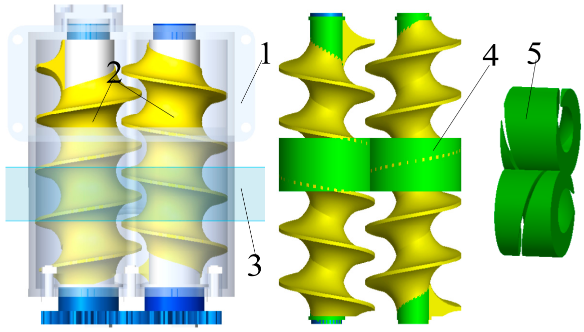


**Figure 3.** Schematic diagram of the difference in volume: 1. Shell. 2. Fertilizer discharge wheel. 3. Pitch. 4. Pitch length inner cavity volume. 5. Volume difference.

The traditional method for calculating volume difference is to calculate the difference between the volume of the double-screw cavity with a single pitch length and the volume of the fertilizer discharge wheel with a single pitch length. As shown in Figure 4, its volume can be calculated according to Formula (4).

$$\alpha = arccos\frac{a}{2R} \tag{2}$$

$$S_{shell}= 2\pi R^2\left(1-\frac{\alpha}{360}\right)+\frac{R}{2}\sqrt{R^2-\frac{a^2}{4}}-2\pi r^2 \tag{3}$$

$$V_{shell}= S_{shell}\times S \tag{4}$$

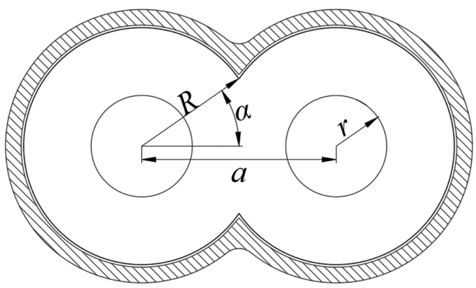


**Figure 4.** Schematic diagram of the inner cavity area.

In the formula: $S_{shell}$—circumferential cross-sectional area of shell, mm$^2$; $R$—outer radius of helical vane, mm; $r$—inner radius of helical vane, mm; $S$—pitch, mm; $\alpha$—included angle of 1/2 coincidence zone, °; $a$ —center distance, mm.

The cross-section of the screw blade of the fertilizer discharge wheel is shown in Figure 5, and its area can be divided into the sum of the volume $V_1$ of the black area and the volume $V_2$ of the shaded area.

$$V_1= 2\int_{-\frac{S-b}{2}}^{\frac{S-b}{2}}\left(r_1+R_p+\sqrt{R_p^2-\left(x-R_p\right)^2}\right)^2dx \tag{5}$$

$$V_1 = \frac{8\pi(r_1+R_p)}{3}\left(\frac{(S-b)^2}{4}-R_p(S-b)\right)^{\frac{3}{2}} \tag{6}$$

$$V_2 = \pi\left(R_1^2-r_1^2\right)b \tag{7}$$

$$V_{blade} = (V_1{+}V_2) \tag{8}$$

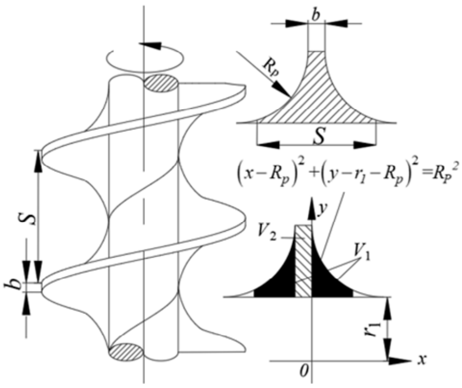


**Figure 5.** Screw blade section.

In the formula: $V_{blade}$ —volume of the helical blade in one revolution, mm$^3$; $V_1$—volume of the black area in one revolution, mm$^3$; $V_2$—volume of the shadow area in one revolution, mm$^3$; $x$—horizontal arc groove curve in the $xy$ coordinate system coordinate, mm; $y$—ordinate of the arc groove curve in the $xy$ coordinate system, mm; $R_p$—arc groove radius, mm; $b$—thickness of the helical blade, mm.

Because manual calculation of theoretical fertilizer volume is cumbersome and complicated, the combined-delete command in the computer software SolidWorks was used to solve 4 (pitch length inner cavity volume) in Figure 3, the main entity; 2 (fertilizer discharge wheel) in Figure 3, the entity to be combined; and 5 in Figure 3 (volume difference) is obtained. The mass attribute (Figure 6) command is used in the evaluation to obtain the volume difference, which is simple and convenient.

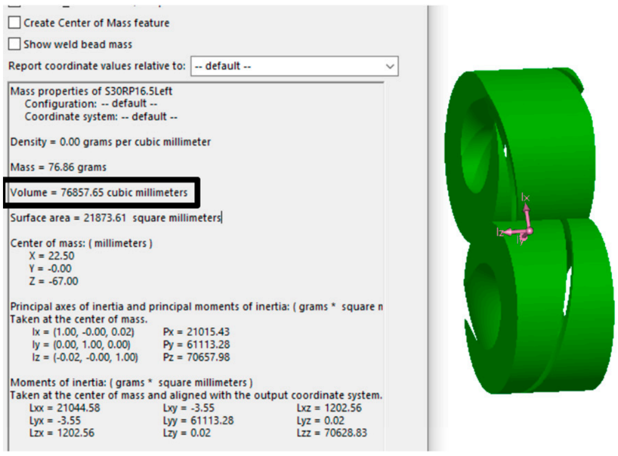


**Figure 6.** Volume recognition.

The theoretical fertilizer discharge amount of the double arc groove screw fertilizer discharger can be calculated according to Formula (9).

$$Q = (V_{shell} - V_{blade})\omega t \varphi \rho \tag{9}$$

In the formula: $Q$—fertilizer discharge amount, mm$^3$/s; $\omega$—fertilizer rotating speed, r/min; $\rho$—fertilizer bulk density, g/cm$^3$; $\varphi$—fertilizer filling factor (0.7) [22].

In order to prevent the occurrence of gaps in the arc of the groove, resulting in residual fertilizer particles, and because the arc groove radius must meet the structural design constraints, as shown in Figure 5, the pitch $S$, the thickness of the screw blade $b$, and the arc groove radius $R_p$ should satisfy Formula (10); the large and small radius s $R$ and $r$ of the helical blade and the arc groove radius $R_p$ should satisfy Formula (11).

$$S \leq 2R_p + b \tag{10}$$

$$Rp \leq R - r \tag{11}$$

From Formulas (10) and (11), the arc groove radius is $16.5 \leq R_p \leq 17.5$ mm, so the experimental optimization interval of the arc groove radius $R_p$ is set as $16.5 \leq R_p \leq 17.5$ mm.

### 2.2.2. Uniformity Analysis of Double Arc Groove Double-Spiral Fertilizer Discharger

Since the fertilizer granules are not fully filled in the fertilizer discharger [23], the effective fertilizer volume $\Delta V$ will fluctuate when the screw blades are in different positions, and the variation in the effective fertilizer volume $\Delta V$ determines whether the fertilizer discharge amount is uniform.

As shown in Figure 7, when there is a large and small radius $R$ and $r$ of the screw blade, the thickness $b$ of the screw blade and the rotational speed $\omega$ of the fertilizer discharger are constant values. Therefore, reducing the fluctuation of effective fertilizer discharge volume $\Delta V$ can be realized by increasing the circumferential cross-sectional area $S_{axial}$ of the fertilizer discharger and reducing the axial cross-sectional area $S_{wheel}$ of the screw blade. The fluctuation in the effective fertilizer discharge volume $\Delta V$ can be reduced. It can be seen from Formula (12) that the circumferential cross-sectional area $S_{axial}$ of the fertilizer discharger is only related to the center distance $a$, the screw pitch $S$, and the arc groove radius $Rp$.

$$S_{axial} = \frac{(S \cdot S_{shell} - V_{blade})}{S} \tag{12}$$

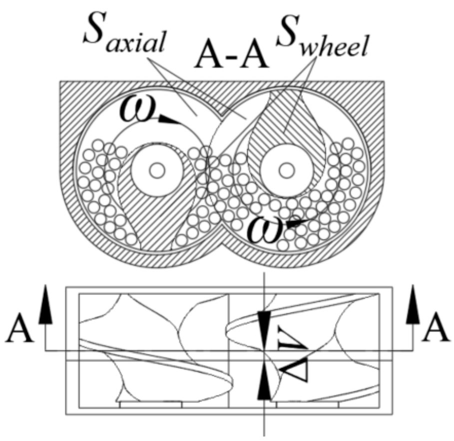


**Figure 7.** Circumferential section of fertilizer ejector.

In the formula: $S_{axial}$—the circumferential cross-sectional area of the fertilizer discharger, mm$^2$.

Center distance $a$ should ensure that the screw blades coincide with each other without collision. The center distance $a$ should satisfy Formula (13), $35 \leq \alpha \leq 40$ mm.

$$R + \frac{r}{2} \leq \alpha \leq 2R \tag{13}$$

In the studies of [11,18], it can be seen that the optimal range of the pitch $S$ is between (0.5~0.7) $2R$, but if the pitch $S$ is too small, the rotating speed $\omega$ of the fertilizer discharger needs to be increased to increase the fertilizer discharge amount. However, the increase in the rotating speed $\omega$ of the fertilizer discharger will aggravate the wear of the fertilizer discharger and reduce the service life of the fertilizer discharger. So, the pitch S should not be too small, and $32 \leq S \leq 35$ mm should be taken into comprehensive consideration.

## 3. Simulation Test of Double Arc Groove Screw Fertilizer Discharger

### 3.1. Simulation Test

In order to determine the optimal structural parameters of the double arc groove screw fertilizer discharger, parameter optimization of the double arc groove screw fertilizer discharger is implemented through simulation experiments. As shown in Figure 8, we constructed a simulation model of the double arc groove screw fertilizer discharger and simplified its unnecessary structure. The structure is simplified, and after the simplification, the fertilizer discharger is mainly composed of five parts: the shell, fertilizer box, double-fertilizer discharge wheel, particle factory and fertilizer collection tank. The fertilizer particles used in the experiment were selected from the Stanley fertilizer particles selected in Section 2.1.2 above. The contact model between particles and the fertilizer discharger in the EDEM was set as the built-in contact model Hertz Mindlin (no slip). Two fertilizer factories are set up at the inlet of the double arc groove screw fertilizer discharger. The fertilizer particles generated in the factory are all the same. After the simulation starts, the fertilizer particles naturally fall into the fertilizer discharger along the negative Z-axis direction. Because the fertilizer has the same motion law in each fertilizer discharge cycle of the fertilizer discharger, in order to facilitate the parameter setting and the extraction of data from the simulation monitoring area, and to compare and analyze the data with the single-screw fertilizer discharger above, the rotating speed of the fertilizer discharge wheel is set to 60 r/min, the moving speed of the fertilizer discharger is 0.2 m/s, the simulation step size is $9.25 \times 10^{-6s}$ and the data recording interval is 0.01 s. The total simulation process is set to 5S. We also set up a monitoring area at the fertilizer collection tank and fertilizer outlet below the fertilizer discharger to monitor the trend of the particle flow rate per second and the trend of the particle total quality changes.

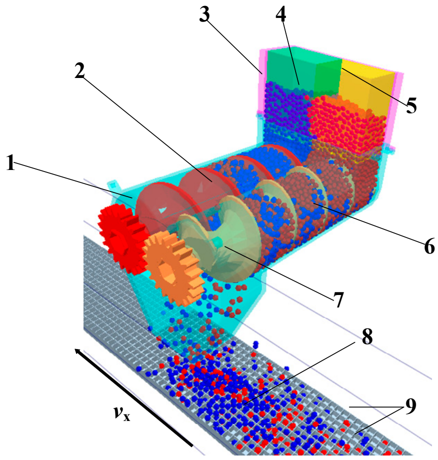


**Figure 8.** EDEM simulation: 1. Shell. 2. Left arc-groove-type fertilizer discharge wheel. 3. Fertilizer box. 4. Left fertilizer particle factory. 5. Right fertilizer particle factory. 6. Fertilizer particles. 7. Right arc-groove-type fertilizer discharge wheel. 8. Fertilizer collection tank 9. Monitoring area. Note: $v_x$ is the movement direction of the fertilizer discharger.

### 3.2. Experimental Factors

Since the center distance, arc groove radius and screw pitch are important parameters that affect the working performance of the fertilizer discharger, they play a decisive role in the fertilization accuracy and uniformity. This studies [24,25] have adopted three factors and five levels of quadratic universal rotation combination in their design tests. The table of test factor levels is shown in Table 2. Design-expert8.0.6 software was used for data processing and statistical analysis.

**Table 2.** Test factor level table.

| Level | Pitch *S*/(mm) | Center Distance *a*/(mm) | Arc Groove Radius $R_p$/(mm) |
|---|---|---|---|
| 1.682 | 35.00 | 40.00 | 17.50 |
| 1 | 34.39 | 38.99 | 17.25 |
| 0 | 33.50 | 37.50 | 17.00 |
| −1 | 32.61 | 36.01 | 16.70 |
| −1.682 | 32.00 | 35.00 | 16.50 |

### *3.3. Analysis of Fertilizer Discharge Performance*

To facilitate the observation of the mixing process of fertilizer particles, as shown in Figure 9, a timing chart is used to display the fertilizer discharge process of the double arc groove screw fertilizer discharger. We established a fertilizer quality monitoring area at the fertilizer outlet of the fertilizer discharger to monitor the quality of red and blue fertilizer particles. The results are shown in Figure 10. We calculated the average, standard deviation and coefficient of variation of particle mass at each monitoring point, as shown in Table 3.

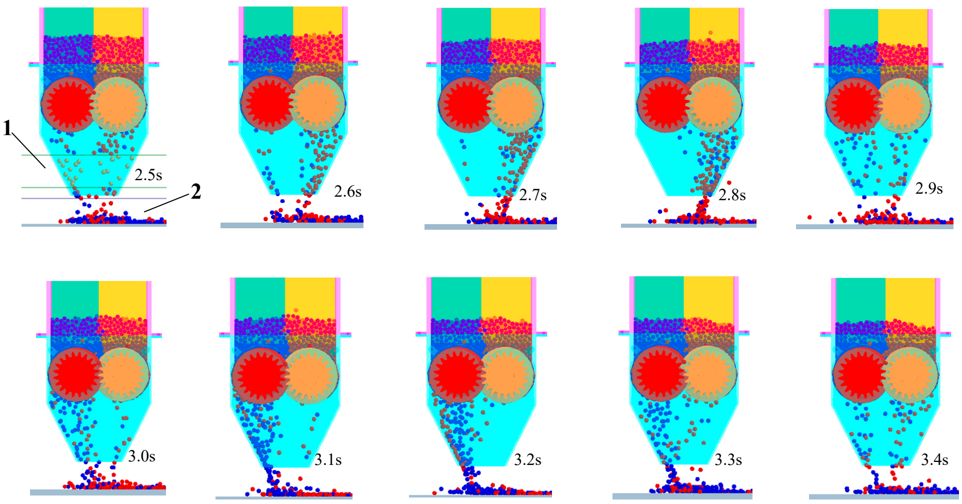


**Figure 9.** Time sequence diagram of working simulation status of double arc groove screw fertilizer discharger: 1. Fertilizer discharge flow monitoring area. 2. Particle quality monitoring area.

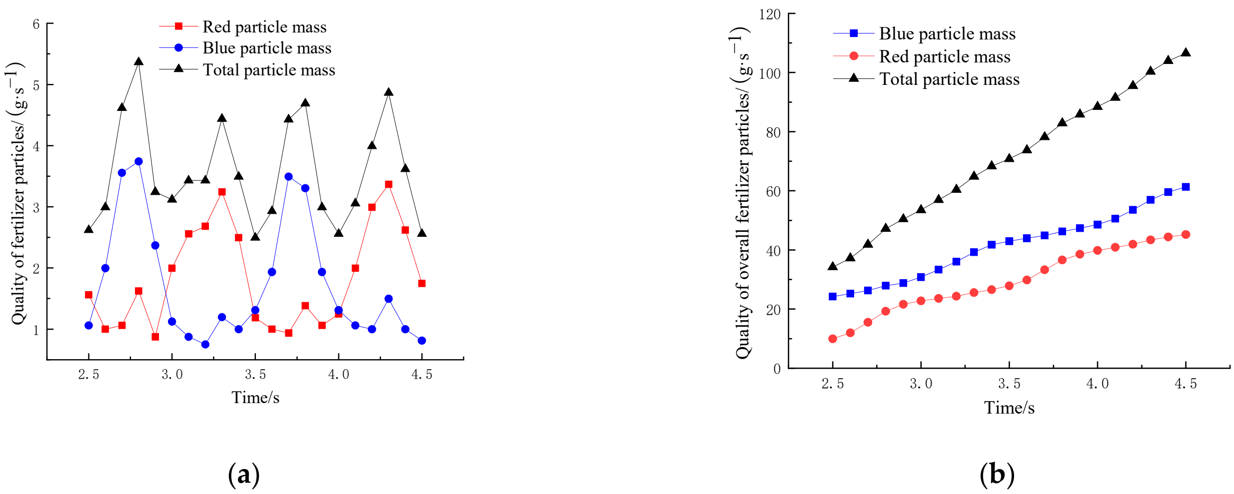


**Figure 10.** Particle mass change trend chart: (**a**) Trend of quality change per second; (**b**) Trend of overall quality change.

**Table 3.** Particle quality results.

| Project | Red Particle | Blue Particle | Total Particle |
|---|---|---|---|
| average mass/g·s$^{-1}$ | 1.839 | 1.729 | 3.568 |
| standard deviation/g·s$^{-1}$ | 0.800 | 0.967 | 0.837 |
| coefficient of variation/% | 43.52 | 55.93 | 23.46 |

Figure 9 shows that the blue particles generated by the left fertilizer box and the red particles generated by the right fertilizer box are alternately discharged under the action of the left and right arc groove fertilizer spirals. As shown in Figure 10a, the mass of blue and red particles fluctuates in a wavy pattern over time. When the mass of blue particles is the highest, the mass of red particles is the lowest. When the mass of blue particles rises, the mass of red particles declines, and vice versa. Figure 10b shows that there are significant fluctuations in the total mass of both red and blue particles, and the overall particle mass fluctuation decreases significantly after the combination of the two types of particles. The results from Table 3 show that the variation coefficients of red particle mass, blue particle mass and total particle mass are 43.52%, 55.93% and 23.46%, respectively, indicating that this fertilizer discharge method ensures uninterrupted fertilizer discharge and improves the uniformity and precision of fertilizer particle discharge.

*3.4. Test Indicators*

The grid method [26] was used to conduct statistics on the uniformity of fertilization. As shown in Figure 11, the smaller the coefficient of variation of fertilizer uniformity between grid units, the better the uniformity of fertilization [27].

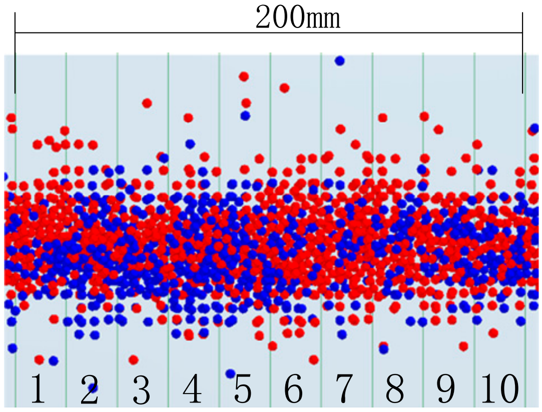


**Figure 11.** Schematic diagram of grid division.

In fertilizer discharge processes of different rotating speeds for any single cycle of a fertilizer discharge wheel, the fertilizer particles have the same motion characteristics. To analyze the uniformity of fertilizer discharge during a single fertilizer discharge cycle, the experimental index was determined as the coefficient of variation of fertilizer discharge uniformity, referring to NY/T1003-2006 "Technical Specification for Fertilization Machinery Quality Evaluation" [28]. According to the fertilizer discharge time of a single cycle and the total length of the grid, the forward rotating speed of the fertilizer discharger is calculated, the grid is divided into 10 parts and the quality of the fertilizer in each grid is counted. The following steps are undertaken: change the grid position, measure the quality of fertilizer particles in the grid at the same rotating speed and different fertilization time and repeat the steps three times. The uniformity coefficient of variation is obtained via Formulas (14) and (15).

$$\overline{m_u} = \frac{\sum_{i=1}^{10} m_i}{n} (i = 1, 2, \cdots, 10) \tag{14}$$

$$\sigma_u = \sqrt{\frac{\sum_{i=1}^{10} (m_i - \overline{m_u})^2}{\overline{m_u}^2 (n-1)}} \times 100\% \ (i = 1, 2, \ldots, 10) \tag{15}$$

In the formula: $m_i$—total mass of fertilizer particles in the $i$-th grid cells, g; $n$—number of grid cells, $n$ = 10; $\overline{m}_u$—average mass of fertilizer particles in the grid cells, g; $\sigma_u$—each grid's uniformity coefficient of variation between grid cells.

The fertilization accuracy represents the difference between the theoretical fertilization amount and the actual fertilization amount. The higher the fertilization accuracy, the higher the fertilization accuracy of the fertilizer discharger [28]. The experiment was repeated three times. The fertilization accuracy is calculated using Equation (17).

$$m_{reality} = \sum_{i=1}^{10} m_i (i = 1, 2, \cdots, 10) \tag{16}$$

$$\sigma = \left| \frac{m_{theory} - m_{reality}}{m_{theory}} \right| \times 100\% \tag{17}$$

In the formula: $m_{theory}$—the theoretical fertilization amount in a single circle, g; $m_{reality}$—the actual simulated fertilization amount in a single circle, g; $\sigma$—the fertilization accuracy.

### *3.5. Test Results and Analysis*

The test results are shown in Table 4, where $x_1$, $x_2$ and $x_3$ represent the factor code values.

**Table 4.** Test and results.

| Serial Number | Factor Level | | | Test Results | |
|---|---|---|---|---|---|
| | $x_1$ | $x_2$ | $x_3$ | Uniformity Coefficient of Variation $y_1$/% | Fertilization Accuracy $y_2$/% |
| 1 | −1.000 | −1.000 | −1.000 | 18.32 | 3.15 |
| 2 | 1.000 | −1.000 | −1.000 | 14.69 | 2.14 |
| 3 | −1.000 | 1.000 | −1.000 | 18.41 | 3.86 |
| 4 | 1.000 | 1.000 | −1.000 | 12.46 | 3.63 |
| 5 | −1.000 | −1.000 | 1.000 | 13.95 | 2.28 |
| 6 | 1.000 | −1.000 | 1.000 | 14.73 | 1.68 |
| 7 | −1.000 | 1.000 | 1.000 | 12.43 | 2.33 |
| 8 | 1.000 | 1.000 | 1.000 | 13.01 | 2.58 |
| 9 | −1.682 | 0.000 | 0.000 | 17.36 | 2.76 |
| 10 | 1.682 | 0.000 | 0.000 | 14.15 | 2.03 |
| 11 | 0.000 | −1.682 | 0.000 | 13.37 | 1.85 |
| 12 | 0.000 | 1.682 | 0.000 | 12.22 | 3.33 |
| 13 | 0.000 | 0.000 | −1.682 | 16.58 | 3.76 |
| 14 | 0.000 | 0.000 | 1.682 | 15.33 | 2.63 |
| 15 | 0.000 | 0.000 | 0.000 | 23.74 | 3.17 |
| 16 | 0.000 | 0.000 | 0.000 | 24.16 | 3.11 |
| 17 | 0.000 | 0.000 | 0.000 | 23.76 | 2.7 |
| 18 | 0.000 | 0.000 | 0.000 | 23.57 | 2.93 |
| 19 | 0.000 | 0.000 | 0.000 | 23.94 | 2.88 |
| 20 | 0.000 | 0.000 | 0.000 | 25.86 | 3.07 |

### *3.6. Influence of Test Factors on Test Indicators*

The variance analysis of the uniform coefficient of variation of the model is shown in Table 5. The model significance test shows that $F$ = 61.48, $p < 0.01$, the regression model is extremely significant and the lack of fit test results are not significant ($p > 0.05$), indicating that the regression model fits well in the test range.

**Table 5.** ANOVA for coefficient of variation of uniformity.

| Evaluation Indicators | Source of Variance | Sum of Square | DF | Mean Square | *F* Value | *p* Value |
|---|---|---|---|---|---|---|
| Coefficient of variation for uniformity | Model | 425.46 | 9 | 47.27 | 61.48 | <0.0001 |
| | $x_1$ | 13.58 | 1 | 13.58 | 17.66 | 0.0018 |
| | $x_2$ | 3.92 | 1 | 3.92 | 5.09 | 0.0476 |
| | $x_3$ | 10.30 | 1 | 10.30 | 13.40 | 0.0044 |
| | $x_1x_2$ | 0.79 | 1 | 0.79 | 1.03 | 0.3335 |
| | $x_1x_3$ | 14.96 | 1 | 14.96 | 19.46 | 0.0013 |
| | $x_2x_3$ | 0.15 | 1 | 0.15 | 0.20 | 0.6668 |
| | ${x_1}^2$ | 119.05 | 1 | 119.05 | 154.83 | <0.0001 |
| | ${x_2}^2$ | 221.53 | 1 | 221.53 | 288.11 | <0.0001 |
| | ${x_3}^2$ | 113.26 | 1 | 113.26 | 147.31 | <0.0001 |
| | Residual | 7.69 | 10 | 0.77 | | |
| | Lack of fit | 4.07 | 5 | 0.81 | 1.12 | 0.4510 |
| | Pure error | 3.62 | 5 | 0.72 | | |
| | Total variation | 433.15 | 19 | | | |

For the uniform coefficient of variation model, $x_1$, $x_3$, $x_1x_3$, ${x_1}^2$, ${x_2}^2$ and ${x_3}^2$ had extremely significant effects on the equation ($p < 0.01$), and $x_2$ had a significant effect on the equation ($0.01 < p < 0.05$). The other factors had no effect on the equation ($p > 0.05$), and the factors that had no significant effect on the coefficients in the regression equation were excluded. The regression equation of each factor and the coefficient of variation of uniformity are the following:

$$y_1 = -1265.39 + 153.28x_1 + 132.71x_2 + 902.71x_3 + 5.16x_1x_3 - 3.61{x_1}^2 - 1.77{x_2}^2 - 31.72{x_2}^2 \quad (18)$$

The variance analysis of the fertilization accuracy model is shown in Table 6. In the model significance test, $F = 32.62$, $p < 0.01$, the regression model is extremely significant and the lack of fit test result is not significant ($p > 0.05$), indicating that the regression model fits well in the test range.

**Table 6.** ANOVA for fertilization accuracy.

| Evaluation Indicators | Source of Variance | Sum of Square | DF | Mean Square | *F* Value | *p* Value |
|---|---|---|---|---|---|---|
| Fertilization accuracy | Model | 6.99 | 9 | 0.78 | 32.62 | <0.0001 |
| | $x_1$ | 0.58 | 1 | 0.58 | 24.41 | 0.0006 |
| | $x_2$ | 2.33 | 1 | 2.33 | 97.75 | <0.0001 |
| | $x_3$ | 2.47 | 1 | 2.47 | 103.78 | <0.0001 |
| | $x_1x_2$ | 0.33 | 1 | 0.33 | 13.94 | 0.0039 |
| | $x_1x_3$ | 0.10 | 1 | 0.10 | 4.16 | 0.0688 |
| | $x_2x_3$ | 0.20 | 1 | 0.20 | 8.20 | 0.0169 |
| | ${x_1}^2$ | 0.62 | 1 | 0.62 | 25.86 | 0.0005 |
| | ${x_2}^2$ | 0.27 | 1 | 0.27 | 11.49 | 0.0069 |
| | ${x_3}^2$ | 0.08 | 1 | 0.08 | 3.50 | 0.0908 |
| | Residual | 0.24 | 10 | 0.02 | | |
| | Lack of fit | 0.09 | 5 | 0.02 | 0.57 | 0.7252 |
| | Pure error | 0.15 | 5 | 0.03 | | |
| | Total variation | 7.23 | 19 | | | |

For the fertilization accuracy model, $x_1$, $x_2$, $x_3$, $x_1x_2$, ${x_1}^2$ and ${x_2}^2$ had extremely significant effects on the equation ($p < 0.01$), and $x_2x_3$ had a significant effect on the equation ($0.01 < p < 0.05$). The other factors had no effect on the equation ($p > 0.05$), and the factors that had no significant effect on the coefficients in the regression equation were excluded.

The regression equation of each factor and the coefficient of variation of uniformity are as follows:

$$y_2 = -402.49 + 12.06x_1 + 6.07x_2 + 11.83x_3 + 0.15x_1x_2 - 0.35x_2x_3 - 0.27{x_1}^2 - 0.07{x_2}^2 \quad (19)$$

By analyzing the response (Figure 12) of the pitch and the arc groove radius to the fertilization accuracy, it can be seen that when the pitch $S$ is at a low level, the uniformity variation coefficient $y_1$ first increases and then decreases with the increase in the arc groove radius $R_p$. When the pitch $S$ is at a high level, the uniformity variation coefficient $y_1$ first increases and then decreases with the increase in the arc groove radius $R_p$.

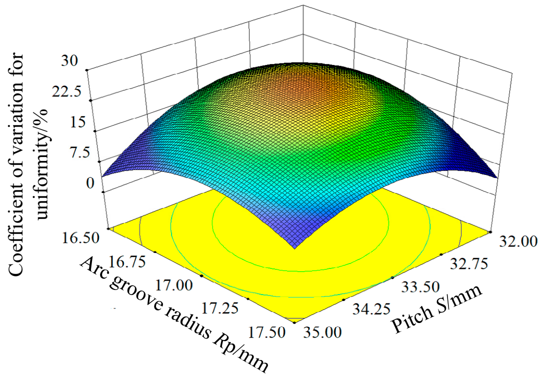


**Figure 12.** Response surface of arc groove radius and center distance to uniformity variation coefficient.

By analyzing the response (Figure 13) of the center distance and the pitch to the fertilization accuracy, it can be seen that when the center distance $a$ is at a low level, the fertilization accuracy $y_2$ decreases with the increase in the pitch $S$, and when the center distance $a$ is at a high level, the fertilization accuracy $y_2$ increases with the increase in the pitch $S$, which first increases and then decreases.

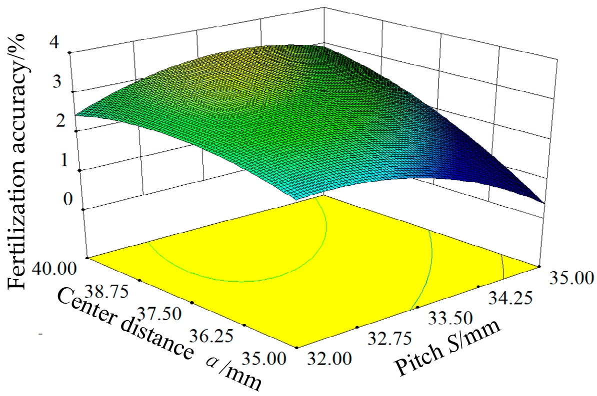


**Figure 13.** Response surface of center distance and screw pitch on fertilization accuracy.

When the pitch $S$ is at a high level, the fertilization accuracy $y_2$ increases with the center distance $a$; when the pitch $S$ is at a low level, the fertilization accuracy $y_2$ increases with the center distance, first as an increase and then a decrease.

By analyzing the response (Figure 14) of the center distance and the arc groove radius on the fertilization accuracy, it can be seen that when the center distance $a$ is at a low level, the fertilization accuracy $y_2$ slightly increases with the increase in the arc groove radius $R_p$; when $a$ is at a high level, the fertilization accuracy $y_2$ increases with the increase in the arc groove radius $R_p$.

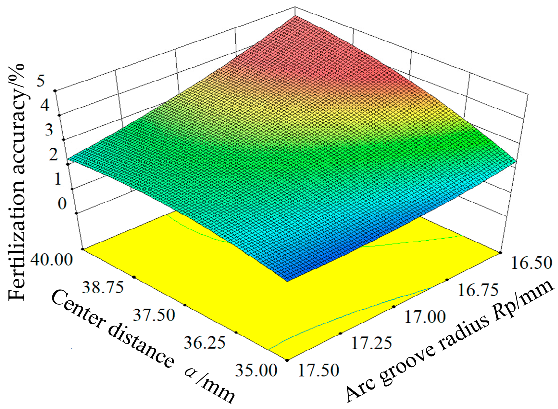


**Figure 14.** Response surface of arc groove radius and center distance on fertilization accuracy.

When the arc groove radius $R_p$ is at a high level, the fertilization accuracy $y_2$ first increases and then decreases slightly with the increase in the center distance $a$; when the arc groove radius $R_p$ is at a low level, the fertilization accuracy $y_2$ increases as the center distance $a$ increases.

When the center distance $a$ is large, the fertilizer discharger is equivalent to two independent fertilizer discharge systems. Therefore, the screw blade has little effect on fertilizer mixing and high fertilization accuracy. When the center distance is small, the overlapping screw blades are equivalent to the screw blades with half the pitch reduced, so the fertilization accuracy is high.

When the arc groove radius $R_p$ is at a low level, the uniformity variation coefficient $y_1$ first increases and then decreases slightly with the increase in the pitch $S$; when the arc groove radius $R_p$ is at a high level, the uniformity variation coefficient $y_1$ increases as the pitch $S$ increases.

### *3.7. Parameter Optimization*

Since the material of the fertilizer discharger is mostly plastic, under the same fertilizer volume, the larger the center distance is, the larger the fertilizer volume is, so the smaller the required rotation speed and the smaller the wear of the fertilizer discharger, meaning that the center distance is set to 40 mm. In order to obtain a parameter combination of the best combination of fertilizer spreaders when the center distance is the largest, a multi-objective optimization method is used in Design-Expert. The objective functions $y_1$, $y_2$ are Equations (18) and (19), and the optimization equation is shown in Equation (20):

$$\begin{cases} 32 \leq x_1 \leq 35 \\ x_2 = 40 \\ 16.5 \leq x_3 \leq 17.5 \\ y_1 = f(x_1, x_2, x_3) \\ y_1 \leq 10\% \\ y_2 \leq 3\% \end{cases} \tag{20}$$

Based on the above optimization (Equation (20), the yellow shadow optimization interval is obtained, as shown in Figure 15. The optimization interval obtained is that when the pitch is within a range of 32–35 mm and the arc groove radius is within a range of 16.83–17.5 mm, the fertilization accuracy is less than 3%, and the coefficient of variation of uniformity is less than 10%. The larger the pitch and the larger the arc groove radius, the smaller the volume of the fertilizer discharge wheel and the lower the manufacturing costs. Based on the optimization results, the selected parameter combination is that the center distance $a$ is 40 mm, the pitch $S$ is 35 mm and the arc groove radius $R_p$ is 17 mm.

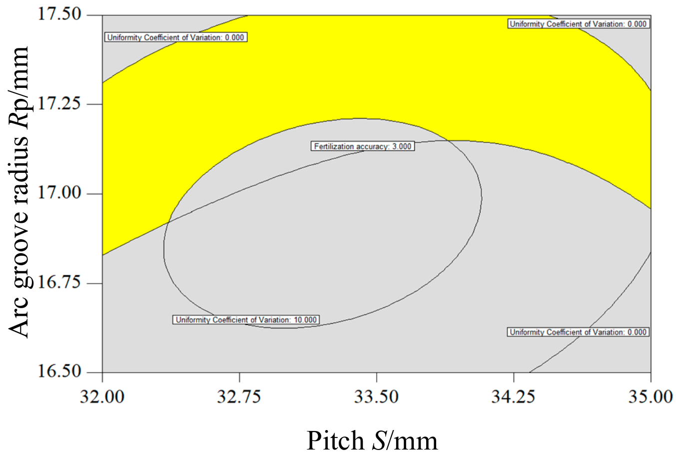


**Figure 15.** Parameter optimization analysis.

## 4. Bench Verification and Comparison Test

### 4.1. Bench Test

The experiment was carried out in July 2021 at the 200 Experimental Center of the Banking School of Northeast Forestry University in Heilongjiang Province. In this experiment, the fertilizer granules used Stanley compound fertilizer (average radius 1.64 mm, density 1.86 g/cm$^3$), and the parameters were a center distance $a$ of 40 mm, a pitch $S$ of 35 mm and an arc groove radius $R_p$ of 17 mm. In a range of 30~105 r/min (excluding the case of low rotating speed), the precise fertilization performance of different types of fertilizer discharger was tested under the condition of a gradient of 15 r/min. After the fertilizer discharge was stable, the motor was started to control the conveyor belt to move at a speed of 0.2 m/s. The length of the fertilizer collecting box was 20 mm. The fertilizer discharger collects 10 copies in a single discharge cycle. The fertilizer was weighed using a precision electronic scale. We replaced the single-screw fertilizer for the comparative test. The same method as the simulation test was used for data statistics. In the bench test, a single grid was replaced by a fertilizer collecting box with a width of 20 mm. Each group of tests was repeated five times to obtain the average value. The test is shown in Figure 16.

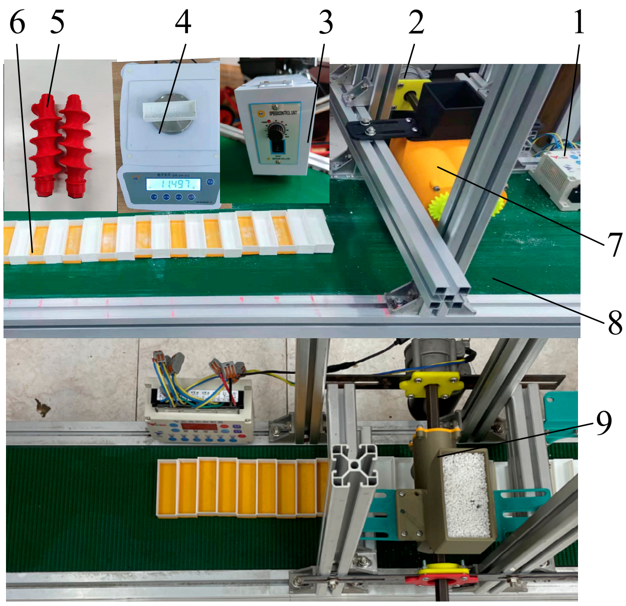


**Figure 16.** Bench test. 1. Motor controller. 2. Drive motor. 3. Conveyor belt controller. 4. Precision electronic scale. 5. Optimized arc groove screw fertilizer discharge wheel. 6. Fertilizer collection box. 7. Fertilizer discharger. 8. Conveyor belt. 9. Single screw fertilizer discharger.

*4.2. Test Results*

According to the test results (Figures 17–19), it can be seen that the optimized double arc groove screw fertilizer discharger has a fertilization accuracy of 3.15% at 60 r/min, which is a relative error of 5% compared to the optimization validation requirements. And within a rotating speed range of 30~105 r/min, the fertilization accuracy is significantly better than that of the single-screw fertilizer discharger at different speeds, and the coefficient of variation of fertilization uniformity is less than 10%, which meets the requirements of fertilization uniformity and precision listed in NY/T1003-2006 "Technical Specification for Fertilization Machinery Quality Evaluation" [28]. The fitting functional equation of the fertilizer discharge flow rate of the optimized double arc groove screw fertilizer discharger is $y = 1.084x - 5.076$, and the coefficient of determination $R^2$ is 0.998. The fitting equation for the fertilizer discharge flow rate of the single-screw fertilizer discharger is $y = 0.797x - 7.275$, and $R^2$ is 0.982. By analyzing Figures 15–17, it can be seen that the fertilizer discharge performance of the optimized double arc groove screw fertilizer discharger is better than that of the single-screw fertilizer discharger.

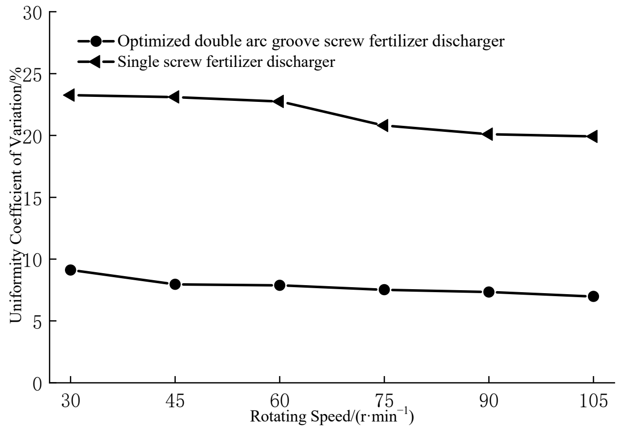


**Figure 17.** Uniformity coefficient of variation comparison test.

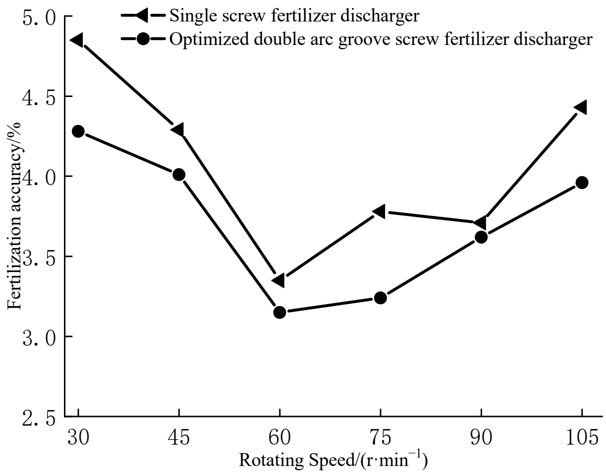


**Figure 18.** Fertilization accuracy comparison test.

Table 7 shows that the uniformity variation coefficient of the bench test, the uniformity variation coefficient of the simulation test and the relative error of the fertilization accuracy are 5.60% and 5.52%, respectively, indicating that the simulation optimization result is correct. Moreover, the main cause of the error is that spherical fertilizer granules are used in the simulation test, but the sphericity of the compound fertilizer in the bench test is less than 100%, and there is occasionally agglomerated fertilizer. There is an error in the distribution characteristics of fertilizer particles in the bench test compared to the simulation test, but the error is small. This proves that factors such as agglomerated fertilizer and sphericity can have a negligible impact on the optimized double arc groove screw fertilizer discharger's fertilizer discharge performance.

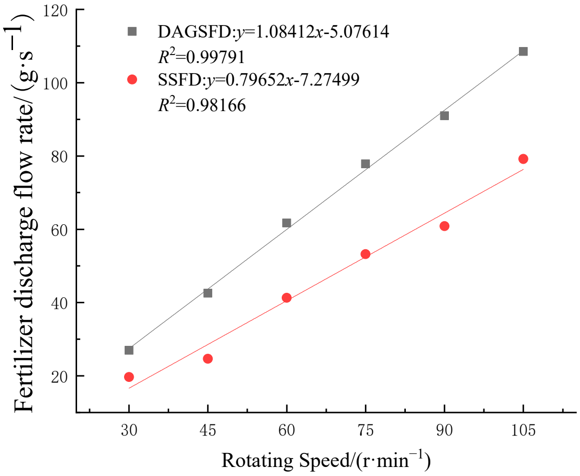


**Figure 19.** Fertilization discharge flow rate comparison test.

**Table 7.** Bench verification and comparison test results.

| Fertilizer Type | Test Type | Test Index | |
|---|---|---|---|
| | | Uniformity Coefficient of Variation/% | Fertilization Accuracy/% |
| Optimized DAGSFD | Simulation test | 6.78% | 3.26% |
| | Bench test | 7.16% | 3.44% |
| SSFD | Bench test | 21.66% | 4.28% |

From the data in Table 7, it can be seen that the fertilization accuracy of the optimized double arc groove screw fertilizer discharger is 3.44%, and the fertilization accuracy is higher. The coefficient of variation for uniformity is reduced by 14.50% on average, and the optimized double arc groove screw fertilizer discharger has good fertilizer discharge uniformity, which effectively solves the problem of uneven fertilizer discharge of a single-screw fertilizer discharger.

To achieve precise control of the fertilizer discharge flow rate, based on equation $y = 1.084x - 5.076$, an electrically controlled fertilizer discharge system was developed and designed to adjust the speed according to the required fertilizer amount accurately. As shown in Figure 20, the electrically controlled fertilizer discharge system was tested and verified in the bench test. We randomly selected rotational speeds of 35, 49, 57, 75, 82 and 108 r/min from 30 to 105 r/min. We then carried out three-fold repetition tests. After stable fertilizer discharge, we recorded the data, measured the mass of fertilizer particles in the fertilizer collection box within 5 s, calculated the fertilizer discharge flow rate and compared it with the preset values of the electrically controlled fertilizer discharge system. The results are shown in Figure 21. Analysis shows that the average error between the discharge flow rate and the preset value of the optimized double arc groove screw fertilizer discharger controlled by the electric-controlled fertilizer discharge system is 2.78%, achieving the goal of automatically adjusting the rotational speed through the electronic control system to achieve precise fertilization.

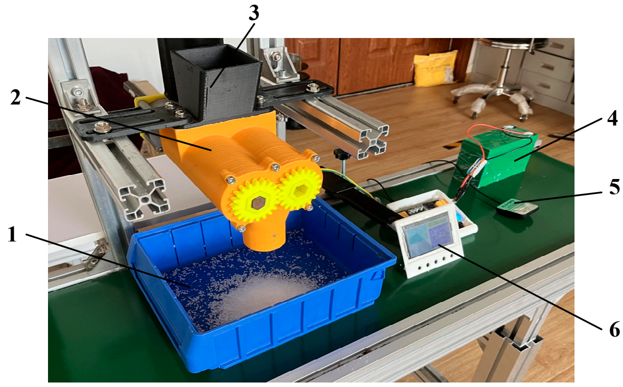


**Figure 20.** Bench test of electronic fertilizer discharge system. 1. Fertilizer collection box. 2. Optimized arc groove screw fertilizer discharge wheel. 3. Fertilizer box. 4. Motor controller. 5. GPS receiver. 6. Electronic fertilizer discharge system.

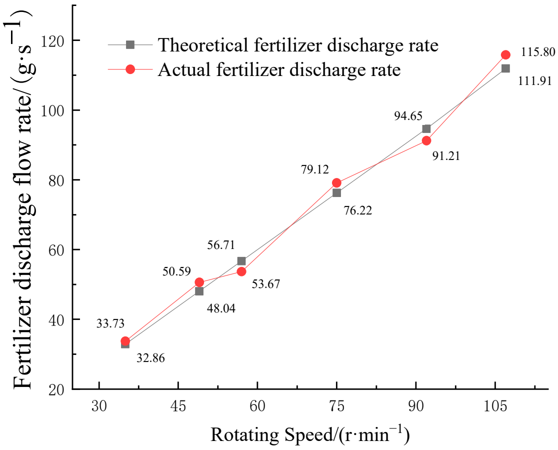


**Figure 21.** Comparison curve of fertilizer discharge flow rate in electric control fertilizer discharge test.

## 5. Conclusions

(1). Through the bench test of the single-screw fertilizer discharger, the uneven fertilizer discharge phenomenon of the single-screw fertilizer discharger was analyzed, and an improvement plan for the double arc groove screw fertilizer discharger was put forward. The instantaneous fertilizer discharge characteristics of the fertilizer discharger were theoretically analyzed, and the factors affecting the fertilizer discharge uniformity of the double arc groove screw fertilizer discharger were obtained, respectively, as the pitch $S$, the center distance $a$ and the arc groove radius $R_p$.

(2). Taking the pitch $S$, the center distance $a$ and the arc groove radius $R_p$ as the test factors, and the uniformity coefficient of variation as the test index, the three factors and five levels of quadratic universal rotation combination design test were carried out. According to the established uniformity coefficient of variation, fertilization accuracy regression model and the use of Design-expert8.0.6 software to obtain the relationship between the influence of test factors on test indicators, the effect of the screw pitch and arc groove radius on the uniformity coefficient of variation is extremely significant ($p < 0.01$). The effect of center distance on the uniformity variation coefficient was significant ($0.01 < p < 0.05$). The effect of screw pitch, center distance and arc groove radius on the fertilization accuracy was extremely significant ($p < 0.01$), and in the center distance 40 mm, $y_1 \leq 10\%$, $y_2 \leq 3\%$. On the basis of the minimum manufacturing cost, the optimal parameters of the fertilizer discharger were optimized as a pitch $S$ of 35 mm and an arc groove radius $R_p$ of 17 mm.

(3). In order to verify the accuracy of the optimized analysis results, a bench verification test was carried out with Stanley compound fertilizer as the test material. The test results show that the coefficient of variation of uniformity, fertilization accuracy of bench test and the relative error of simulation test are 5.60% and 5.52%, respectively. The optimized fertilization accuracy of the double arc groove screw fertilizer discharger is 3.44%, and the fertilization accuracy is high. The coefficient of variation of the uniformity of the double arc groove screw fertilizer discharger is 14.50% lower than that of the single-screw fertilizer discharger. Moreover, the fitting equation of the fertilizer discharge flow rate of the double arc groove screw fertilizer discharger is significantly better than that of the single-screw fertilizer discharger. Therefore, an electric control fertilizer discharge system was designed based on the optimal parameter fertilizer discharge flow rate fitting equation. The bench test results show that the electric control system can accurately adjust the double arc groove screw fertilizer discharger fertilizer discharge flow rate by adjusting the rotational speed. The double arc groove screw fertilizer discharger controlled by an electronic control fertilizer discharge system has good uniformity in fertilizer discharge and a controllable fertilizer discharge flow, which effectively solves the problem of the uniformity of the fertilizer discharged by the single-screw fertilizer discharger.

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