# OPTIMIZATION DESIGN AND TEST OF INTERACTIVE ANTI-STICK GEAR FERTILIZER DISCHARGER FOR PINEAPPLE
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# 菠萝专用交互式防粘齿轮排肥器的优化与试验

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*DOI: https://doi.org/10.35633/inmateh-76-39*

***Keywords:*** *Gear fertilizer; EDEM simulation; Fertilization uniformity; Response surface test; Precision fertilization*

## ABSTRACT

*Based on the agronomic characteristics of pineapple fertilization and the challenges posed by moist fertilizer particle adhesion, an interactive gear fertilizer discharger was developed. This device utilizes a pair of continuously meshing, counter-rotating gears to achieve centralized and interactive mixing of fertilizer. Through theoretical analysis, the fertilizer discharge volume and maximum operating speed of the discharger were determined. In the experimental design, the pressure angle and helix angle of the fertilizer wheel were selected as test factors, while the coefficient of fluctuation in fertilizer uniformity served as the test index. A single-factor test was conducted to analyze the influence of each factor on the index and to determine the appropriate range of values. Subsequently, a quadratic general rotary combination design was used to optimize the fertilizer wheel parameters. The results indicated that both the pressure angle and helix angle had a significant effect on the coefficient of fluctuation of fertilizer uniformity (P<0.01). The lowest fluctuation coefficient, 11.82%, was achieved when both angles were set to 30°. A simulation verification test yielded a result of 11.92%, with a relative error of 0.85% compared to the theoretical value. Bench tests conducted under optimal parameters showed a relative error of 2.77% between the experimental and simulated values. Furthermore, the average error between the measured fertilizer discharge flow rate and the theoretical value under varying speeds was 3.75%. No fertilizer adhesion was observed on the surface of the discharge wheel, demonstrating that the system enables fine regulation of fertilizer output while effectively mitigating fertilizer adhesion.*

## 摘要

*根据菠萝施肥的农艺特性以及潮湿肥料颗粒粘连问题，设计了一种交互式防粘齿轮排肥器，其采用一对持续啮合反向挤压旋转的齿轮实现肥料的对中交互混排。通过理论分析确定交互式齿轮排肥器的理论排肥量与最大转速，利用 EDEM 软件对排肥过程进行仿真模拟。以排肥轮的压力角和螺旋角为试验因素，以排肥均匀性波动系数为试验指标，通过单因素试验分析试验因素对试验指标的影响，并确定试验因素的范围。通过二次通用旋转组合设计试验优化出排肥轮的最优参数。试验结果表明：排肥轮压力角和螺旋角对排肥均匀性变异系数均有极显著影响（P＜0.01），当排肥轮压力角和螺旋角均为 30°时，排肥均匀性变异系数最小为 11.82%。仿真验证试验结果为 11.92%，相对误差为 0.85%，最优参数下台架试验结果表明：试验值与仿真值的相对误差为 2.77%，排肥流量可通过排肥轮转速线性调节。其结果表明：在排肥转速流量曲线下排肥流量与理论值平均误差为 3.75%，排肥轮表面并无粘结肥料，实现对排肥量的精量调控且有效降低其肥料对排肥轮的粘连作用。*

## INTRODUCTION

The proper use of fertilizers plays a crucial role in the growth of pineapples in terms of fruit quality and yield. Unreasonable fertilization methods will not only damage crops and reduce their production but also cause some problems, such as the waste of resources, environmental pollution, and land degradation. Studies have shown that compared with unreasonable fertilization methods, precision fertilization can better alleviate the above problems under the premise of meeting the needs of crop growth, which is of great significance for the sustainable development of agriculture *(Chen et al., 2015; Li et al., 2008; Du et al., 2020)*.

At present, the widely used fertilizer discharger in the market is the external grooved wheel type fertilizer discharger, which has high requirements for the physical properties of fertilizers. Still, the effect is good when discharging and applying dry granular fertilizers, and poor when discharging and applying moist granular fertilizers and powdered fertilizers *(Lv et al., 2013; Liu et al., 2021)*. Mechanical fertilizer application can effectively reduce the labor intensity of fruit farmers, improve the efficiency and quality of fertilizer application, and reduce the cost of agricultural production.

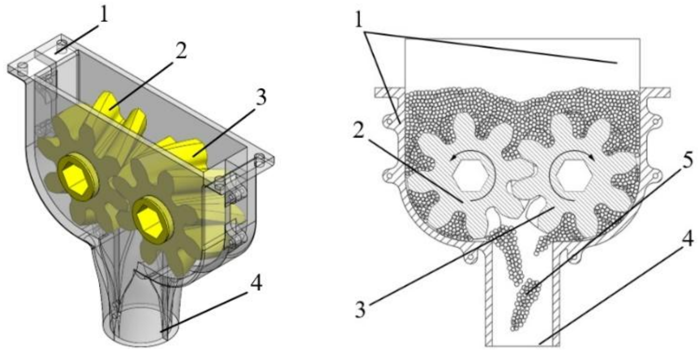
The fertilizer discharger is the key component of the fertilization device, and its performance will directly affect the fertilization effect. If the uniformity of the fertilizer discharger is very low, it will not only reduce the fertilizer utilization rate, and affect the quality and yield of crops, but also make it difficult to achieve precision fertilization *(Tai et al., 2020; Su et al., 2015)*. Relevant experts and scholars have done a lot of research on improving the uniformity of fertilizer discharge and realizing precision fertilization. *Wang et al., (2017),* analyzed the effects of the working length of the outer groove wheel, the rotational speed of the fertilizer shaft, and the opening angle of the fertilizer tongue on the amount of fertilizer and the uniformity of fertilizer discharge. *Dun et al., (2018),* analyzed the influence of the structural parameters of the fertilizer tongue of the outer groove wheel fertilizer discharger on the uniformity of fertilizer discharge by discrete element method. *Zhu et al., (2018),* analyzed the influence of the groove wheel radius, the number of grooves, the effective working length and the shape of the groove section on the uniformity of fertilizer discharge. *Yao et al., (2020),* realized precision fertilization by adjusting the motor speed to control the amount of fertilizer. *Zuo et al., (2016),* developed a precise fertilizer control system, which can adjust the amount of fertilizer in real time according to the operation speed of the machine. *Yu et al., (2020),* designed a double-gear type fertilizer discharger, whose tooth ridge and tooth groove continuously alternating operation even fertilizer effect has been significantly improved, but its uniformity still has room for improvement. The research of experts and scholars in discrete element simulation and precision fertilization has played an important supporting role in this study.

In this study, an interactive gear fertilizer distributor was designed based on the principle of fertilizer alignment and interactive mixing. Through theoretical analysis, the theoretical fertilizer discharge amount and maximum speed of the fertilizer discharger are determined, and the fertilizer discharge process is simulated by discrete element simulation technology. The test range was determined by single factor test, and the influence of different factors on the coefficient of variation of fertilizer uniformity was analyzed by quadratic general rotary combination design test, and the structural parameters of the interactive gear fertilizer distributor were optimized when the coefficient of variation of fertilizer uniformity was the lowest. The interactive gear fertilizer distributor prototype with optimal parameters was made by 3D printing technology. The simulation value and theoretical value were verified by bench test, and the relationship between fertilizer discharge flow and fertilizer discharge wheel speed was analyzed by controlling the rotational speed of fertilizer discharge wheel through motor controller. Based on the speed-flow relationship curve of the fertilizer wheel, an electronically controlled fertilizer discharge controller was developed and its working performance was tested in order to improve the uniformity of fertilizer discharge and achieve precise control of fertilizer discharge.

## MATERIALS AND METHODS

### *The Structure and Working Principle of The Whole Machine*

The three-dimensional model and sectional working diagram of the interactive gear fertilizer discharger are shown in Fig.1. The device consists of a left-handed fertilizer discharge gear, a right-handed fertilizer discharge gear, a fertilizer discharge box, and a fertilizer outlet.




*a)* *b)*

**Fig. 1 - Interactive gear fertilizer apparatus schematic diagram**

*a) Three-dimensional model diagram; b) The schematic diagram of section work*

*1. Fertilizer box; 2. Left-handed fertilizer gear; 3. Right-handed fertilizer gear; 4. Outlet; 5. Fertilize*

When working, the drive motor drives the left-handed fertilizer gear to rotate counterclockwise. The right-handed fertilizer gear rotates clockwise through the gear meshing, and the rotation of the fertilizer gear drives the fertilizer movement. The fertilizer is confined in the fertilizer space formed by the tooth grooves and the fertilizer box. It moves downward along the contour of the fertilizer box until the tooth grooves rotate to the top of the fertilizer outlet. The fertilizer is discharged alternately to fall into the fertilizer outlet by gravity, which ensures the continuity of fertilizer discharge and realizes the uniformity of fertilizer discharge.

Fig. 2 illustrates the anti-sticking mechanism during the fertilizer discharge process. Moisture in the fertilizer can cause particles to stick to the gear surface. As the gears rotate and mesh in the interaction zone, the clinging material is subjected to rolling and squeezing forces between adjacent teeth. This mechanical contact helps dislodge the adhered fertilizer, causing it to fall into the discharge area. The use of diagonally arranged gear teeth increases the meshing duration and overlap, improving the cleaning effect and enhancing anti-adhesion performance.

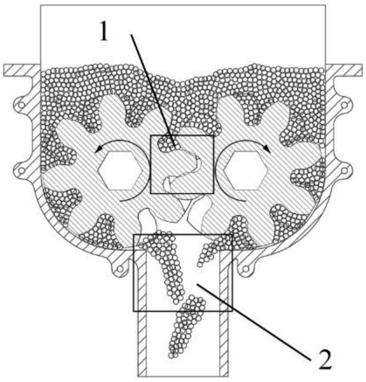



**Fig. 2 - Interactive gear fertilizer apparatus schematic diagram**

*1. Interaction zone; 2. Fertilizer discharge zone.*

***Theoretical Fertilizer Discharge and Maximum Speed***

The interactive gear fertilizer discharger alternately discharges fertilizer through continuous meshing and reverse rotation of a pair of gears. The volume of a single discharge fertilizer is determined by the size of the fertilizer space formed by the tooth groove and the fertilizer discharge box. Therefore, calculating the volume of the tooth groove of the fertilizer discharge gear is of great significance for studying the theoretical fertilizer discharge and maximum speed of the fertilizer discharger. The fertilizer discharge gear model is shown in Fig. 3.

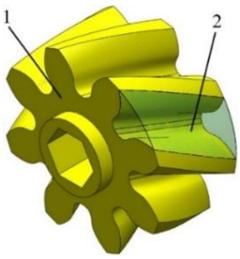



**Fig. 3 - Fertilization gear model**

*1.Fertilizer gear; 2. Fertilizer space.*

According to the existing research *(Hu et al., 2016)*, the area of a single tooth groove of the fertilizer gear is calculated using the following equations:

$$s_c = \frac{s_a - s}{z} \tag{1}$$

$$s_a = \frac{\pi d_a^2}{4} \tag{2}$$

$$da = mz + 2h_a^* m \tag{3}$$

$$s = \frac{\pi d^2}{4} \tag{4}$$

$$d = mz \tag{5}$$

where: $s_c$ is the area of the single tooth groove of the fertilizer gear, [mm$^2$ ]; $s_a$ is the top circle area of fertilizer gear, [mm$^2$]; $s$ is the pitch circle area of the fertilizer gear, [mm$^2$]; $d_a$ is the top circle diameter of fertilizer gear, [mm]; $d$ is the pitch circle diameter of the fertilizer gear, [mm]; $h_a$* is the top height coefficient of fertilizer gear; $z$ is the number of teeth; $m$ is the modulus, [mm].

The total mass of the fertilizer discharged by the fertilizer discharger is calculated as follows:

$$M = \rho\gamma V \tag{6}$$

where:

$$V = \frac{s_c bntz \times 10^{-4}}{3} \tag{7}$$

where: $M$ is total mass of discharged fertilizer, [g]; $P$ is the bulk density of fertilizer, [g/cm$^3$]; $\gamma$ is fertilizer filling coefficient; $V$ is total volume of discharged fertilizer, [cm$^3$]; $b$ is tooth width of fertilizer gear, [mm]; $n$ is the rotational speed of the fertilizer gear, [r/min]; $t$ is the operating time of the fertilizer discharger.

According to the combined formula (5) ~ (7), the total mass of the fertilizer discharged by the fertilizer discharger is:

$$M = \frac{\rho\gamma bnt\pi\left[m^2\left(z+2h_a^*\right)^2-\left(mz\right)^2\right]\times 10^{-4}}{12} \tag{8}$$

The fertilizer gear is a standard cylindrical gear. The tooth width is set to 30 mm, the number of teeth is 8, the modulus is 6 mm, the addendum height coefficient is 1, the fertilizer bulk density is 0.9 g/cm$^3$, and the filling coefficient is 0.7. The maximum moving speed of the fertilizer applicator is 7 km/h. Based on the design of the crop ridge spacing of 65 cm, it can be calculated that in order to meet the fertilization requirements of 750 kg/hm$^2$, the maximum theoretical speed required for the fertilizer distributor is 147.484 r/min *(Dun et al., 2019; Liang et al., 2023; Sun et al., 2019)*.

**Discrete Element Simulation Test**

***Establish Fertilizer Particle Model***

The water content of urea particles on the market is usually less than 0.5%, the surface adhesion is small, more than 0.5% will significantly increase the inter-particle hydrogen bonding, so that the adhesion increases, and most of them are spherical. Therefore, urea is selected as the test material for discrete element simulation *(Wen et al., 2020; Yuan et al., 2018; Michele et al., 2015)*. 80 urea particles produced by Anhui Red Sifang Fertilizer Co. Ltd. were randomly selected to measure the triaxial length and mass. The average radius of urea particles was 1.11 mm and the density was 1158 kg/m$^3$. Therefore, the spherical particles with a particle radius of 1.11 mm are selected as the particle model of discrete element simulation.

***Setting Simulation Parameters***

Hertz-Mindlin (no slip) in EDEM software was selected as the contact model between fertilizer and fertilizer, fertilizer and fertilizer wheel, shell *(Marcinkiewicz et al., 2019)*, and the parameters were set as shown in Table 1 by consulting literature *(Dun et al., 2020)*.

**Table 1**

**Discrete element simulation parameters**

| Item | Particle Property | Numerical Value |
|---|---|---|
| Fertilizers | Poisson's Ratio | 0.25 |
| | Shear modulus/Pa | $2.8\times10^7$ |
| | Density/kg·m$^{-3}$ | 1158 |
| Fertilizers unit | Poisson's Ratio | 0.43 |
| | Shear modulus/Pa | $1.3\times10^7$ |
| | Density/kg·m$^{-3}$ | 1240 |
| Fertilizers - Fertilizers | Restitution coefficient | 0.11 |
| | Static friction coefficient | 0.30 |
| | Rolling friction coefficient | 0.10 |
| Fertilizers - Fertilizers wheel shell | Restitution coefficient | 0.41 |
| | Static friction coefficient | 0.32 |
| | Rolling friction coefficient | 0.18 |

### *Discrete Element Model of Fertilizer Distributor*

SolidWorks 2020 is used to design the structure of the interactive gear fertilizer discharger and establish the three-dimensional model. The specific steps are as follows: The Maidi three-dimensional design tool set is used to generate the fertilizer wheel model with different pressure angles and helix angles, and the model of the fertilizer discharger is completed according to the fertilizer wheel model. Simplify the fertilizer model, save it as a .stl file, and import it into the discrete element simulation software EDEM, and set the fertilizer and model parameters according to Table 1.

Independent particle factories were created above the two rows of fertilizer wheels, separated by a diaphragm in the middle, and the same fertilizer parameters were used to generate particles. The total number of particles generated in both factories was 10,000, and the generation rate was 10,000/s. Then, a fertilizer collection plate will be set up below the fertilizer discharger. To facilitate the observation of the interaction of fertilizer particles and their distribution on the fertilizer collection plate, the rotational speed of the fertilizer wheel was set to 60 r/min, and the movement speed of the fertilizer collection plate was 1 m/s. The simulation step size was $4.89\times10^{-6}$ s, the data recording time interval was 0.01 s, and the total simulation time was 2.6 s. The simulation process is shown in Fig. 4.

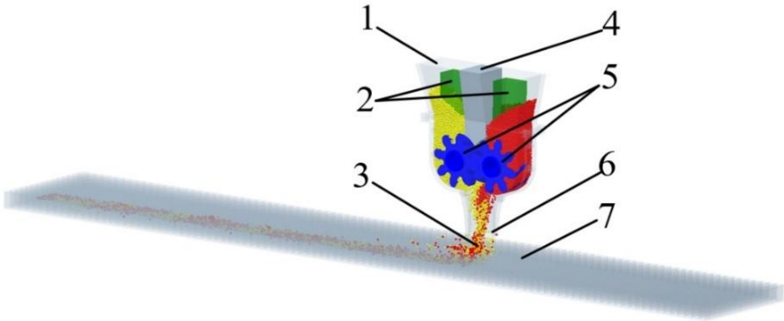



**Fig. 4 - Simulation process**

*1. Fertilizer discharge zone; 2. Particle factory; 3. Fertilizer; 4. Diaphragm; 5. Fertilizer wheel; 6. Fertilizer outlet; 7. Fertilizer collection plate.*

### *Evaluation of Fertilizer Performance*

The timing diagram is used to show the process of fertilizer discharge in order to observe the mixing process of fertilizer particles, as shown in Fig. 4. The fertilizer quality monitoring area was established, and the quality data of yellow particles, red particles and total particles in the monitoring area were collected and the particle quality change curve was made by Origin software. The change process of two kinds of fertilizer particles and total particle quality can be seen more intuitively, as shown in Fig. 5.

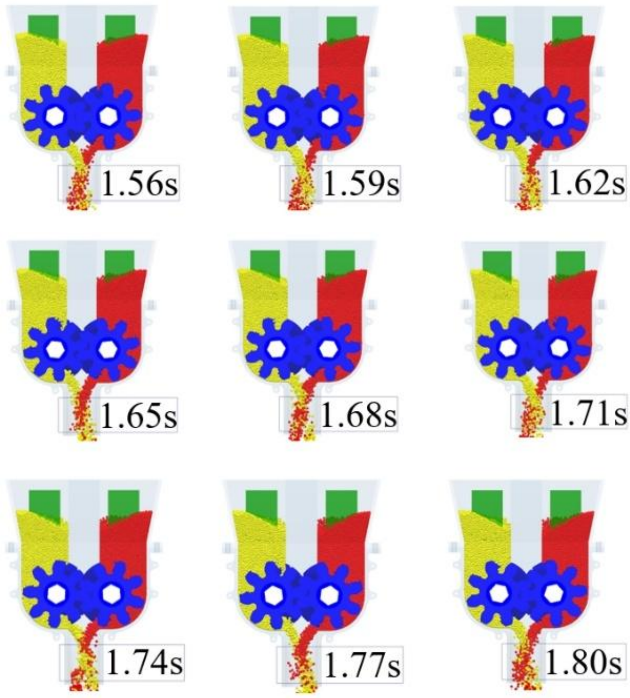



**Fig. 5 - Time sequence diagram of fertilizer discharge process**

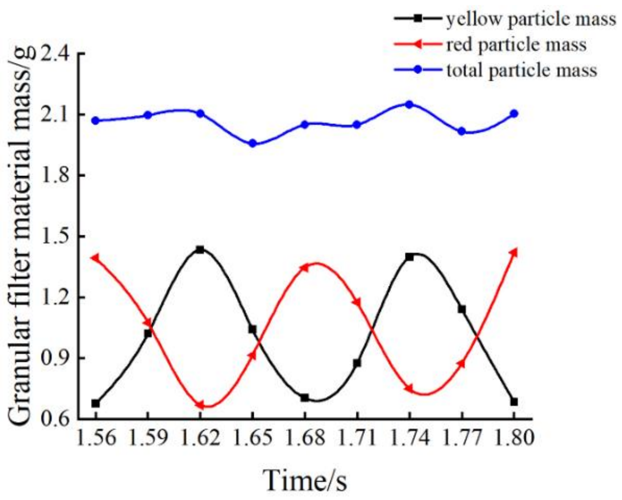



**Fig. 6 - Particle mass change diagram**

It can be seen from Fig. 5 and Fig. 6 that yellow particles and red particles are alternately discharged and mixed with each other under the action of the fertilizer wheel. The mass of yellow particles and red particles fluctuates with time. When the mass of yellow particles is the most, the mass of red particles is the least. When the mass of yellow particles increases, the mass of red particles decreases, and vice versa. This way of fertilizer discharge can ensure the uninterrupted discharge of fertilizer and ensure the uniformity of fertilizer discharge.

In order to accurately evaluate the uniformity of the interactive gear fertilizer distributor, the grid method was used to count the fertilizer quality on the fertilizer collection plate *(Yang et al., 2020)*, as shown in Fig.7.

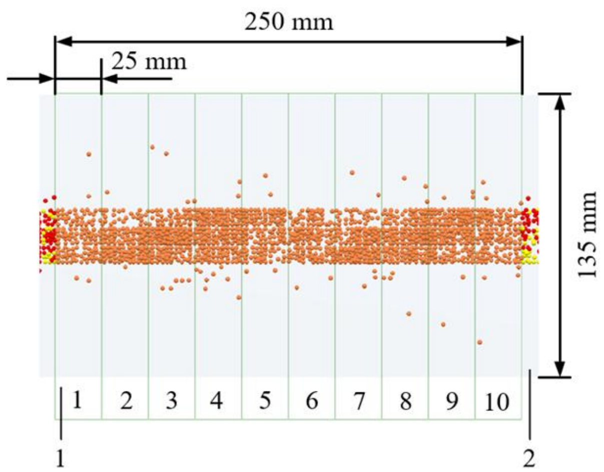



**Fig. 7 - Grid division diagram**

*1. Uniformity test area; 2. Fertilizer collection plate.*

The fertilizer is alternately discharged by the left-handed fertilizer gear and the right-handed fertilizer gear, and presents a periodic distribution on the fertilizer collection plate. According to the rotational speed of the fertilizer wheel and the moving speed of the fertilizer collection plate, the moving distance of the fertilizer collection plate is 125 mm for each cycle of fertilizer discharge. Therefore, the length of the monitoring area is set to 250 mm, and the monitoring area is divided into 10 parts by grid and numbered from 1 to 10, and the fertilizer quality in each grid is counted respectively. The smaller the coefficient of variation of the uniformity of the fertilizer is, the better the uniformity of the fertilizer is. Therefore, the coefficient of variation of the uniformity of the fertilizer is used as the evaluation index of the fertilizer performance of the fertilizer discharger. The average value, standard deviation and coefficient of variation of fertilizer quality in the monitoring area were calculated by formulas (9) ~ (11).

$$\overline{m} = \frac{\sum_{i=1}^{10} m_i}{n} (i = 1, 2, \ldots, 10) \quad (9)$$

$$s=\sqrt{\frac{\sum^{10}(m_i-\overline{m})^2}{n-1}}(i=1,2,\ldots,10) \tag{10}$$

$$\sigma=\frac{s}{\overline{m}}\times 100\% \tag{11}$$

where: $\overline{m}$ is Average quality of fertilizers in the monitoring area, [g]; $m_i$ is the total mass of fertilizer in the $i$ grid, [g]; $n$ is the number of grids, $n$ = 10; $s$ is the standard deviation of fertilizer quality in monitoring area, [g]; $\sigma$ is Coefficient of variation of fertilizer uniformity in monitoring area.

***Relationship Between Pressure Angle of Fertilizer Discharge Wheel and Uniformity of Fertilizer Discharge***

The size of the pressure angle of the fertilizer discharge wheel will affect the size and shape of the fertilizer space *(Liu et al., 2020)*, which in turn will affect the time interval between two adjacent slots discharging fertilizer, the falling speed of fertilizer and other factors during the fertilizer discharge process.

According to the design principle of the involute gear, the pressure angle of the fertilizer discharge wheel is selected as 5°, 10°, 15°, 20°, 25°, 30° *(Chen et al., 2008; Song et al., 2016)*. During the single-factor comparative test of the pressure angle of the fertilizer discharge wheel and the uniformity of fertilizer discharge, the helix angle of the fertilizer discharge wheel was uniformly 0°. The variation coefficient of fertilizer discharge uniformity of fertilizer discharge wheels with different pressure angles is shown in Fig. 8 below.

The variation coefficient of fertilizer discharge uniformity decreases with the increase of pressure angle of fertilizer discharge wheels. When the pressure angle of the fertilizer discharge wheel is 30°, the coefficient of variation of the uniformity of fertilizer discharge is the smallest, indicating that when the pressure angle of the fertilizer discharge wheel is 30°, the distribution of fertilizer on the collecting plate is the most uniform, and the fertilizer discharge performance is the best.

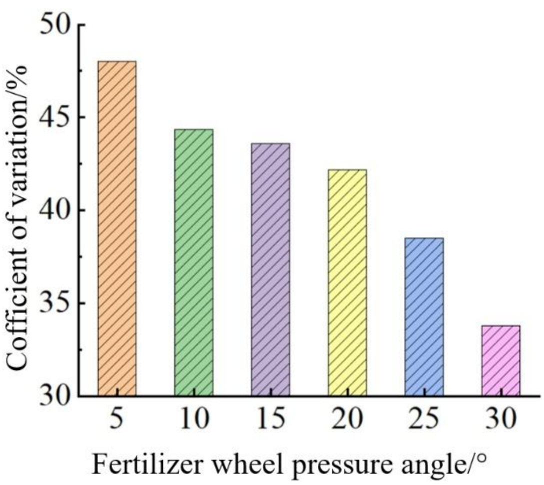



**Fig. 8 - The relationship between the pressure angle of fertilizer wheel and the coefficient of variation of fertilizer uniformity**

***The Relationship Between the Helix Angle of The Fertilizer Discharge Wheel and The Uniformity of Fertilizer Discharge***

The size of the helix angle will also affect the size and shape of the fertilizer space. Compared with the spur gear, the helical gear with the same tooth groove has a longer longitudinal length during the falling process, and the fertilizer is more evenly distributed on the collecting plate. When two adjacent tooth slots of the helical fertilizer discharge gear overlap in the axial direction, the fertilizer in the previous slot may not be fully discharged before the next slot begins releasing fertilizer. This overlapping discharge process ensures a continuous and uninterrupted flow, thereby improving the uniformity and effectiveness of fertilizer application.

According to the design principles of helical gears, the helix angle of the fertilizer discharge wheel was selected as 0°, 5°, 10°, 15°, 20°, 25°, and 30°. In the single-factor comparative experiment evaluating the effect of helix angle on the uniformity of fertilizer discharge, the pressure angle was fixed at 20°. The coefficient of variation in fertilizer discharge uniformity for wheels with different helix angles is presented in Figure 9.

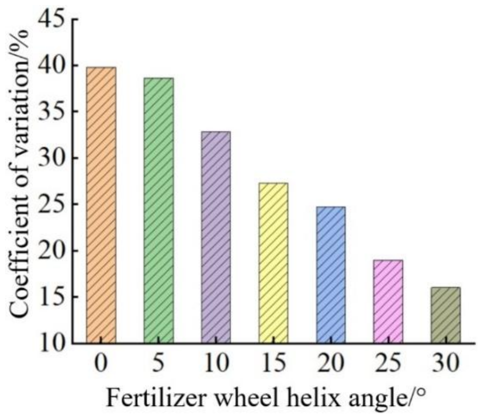



**Fig. 9 - Relationship between the helix angle of the fertilizer discharge wheel and the coefficient of variation of fertilizer discharge uniformity**

The coefficient of variation in fertilizer discharge uniformity decreased with increasing helix angle of the fertilizer discharge wheels. When the helix angle reached 30°, the variation coefficient was at its lowest, indicating the most uniform distribution of fertilizer on the collecting plate. This suggests that a 30° helix angle provides the optimal discharge performance and the highest uniformity in fertilizer application.

## RESULTS

## RESPONSE SURFACE EXPERIMENT

### *Test Design*

Based on the results of the single-factor experiments, it was observed that the coefficient of variation in fertilizer discharge uniformity decreases with increasing pressure angle and helix angle of the fertilizer discharge wheel. By analyzing the effects of different pressure angles and helix angles of the fertilizer discharge wheel on the fertilizer distribution performance of interactive anti-adhesion gears, the structural parameters of the fertilizer discharge wheel are optimized. A secondary general rotational combination test method was selected to analyze the effects of the pressure angle and helix angle of the fertilizer discharge wheel on fertilizer uniformity. The coefficient of variation of fertilizer uniformity was used as the evaluation criterion. Based on the results of single-factor simulation tests, the pressure angle range of the fertilizer discharge wheel was selected as 5° ~ 30°, and the helix angle range was selected as 0° ~ 30°. The coded levels of the experimental factors are shown in Table 2, where $X_1$ and $X_2$ are the factor code values for the pressure angle and helix angle, respectively.

**Table 2**

**Test factor coding table**

| Coding | Test Factor | |
|---|---|---|
| | Fertilizer Wheel Pressure Angle $X_1$ / [°] | Fertilizer Wheel Helix Angle $X_2$ / [°] |
| 1.414 | 30.00 | 30.00 |
| 1 | 26.34 | 25.61 |
| 0 | 17.50 | 15.00 |
| -1 | 8.66 | 4.39 |
| -1.414 | 5.00 | 0.00 |

### *Test Results and Analysis of Variance*

Taking the pressure angle $X_1$ and the helix angle $X_2$ of the fertilizer discharge wheel were selected as test factors, and the coefficient of variation σ of the fertilizer discharge uniformity was used as the evaluation index. Using Design-Expert software a regression analysis was conducted on the experimental data to determine the relationship between discharge uniformity and the two factors. In addition, an analysis of variance (ANOVA) was performed to assess the statistical significance of the regression model (*Dun et al., 2024*). The test scheme and corresponding results are presented in Table 3, while the ANOVA results are shown in Table 4.

Table 3

**Test scheme and results table**

| Serial number | Test Factor | | σ [%] |
|---|---|---|---|
| | Pressure Angle $X_1$ / [°] | Helix Angle $X_2$ / [°] | |
| 1 | 17.50 | 0.00 | 41.47 |
| 2 | 8.66 | 4.39 | 41.74 |
| 3 | 17.50 | 15.00 | 27.75 |
| 4 | 30.00 | 15.00 | 25.17 |
| 5 | 17.50 | 15.00 | 31.13 |
| 6 | 17.50 | 30.00 | 13.40 |
| 7 | 17.50 | 15.00 | 28.41 |
| 8 | 17.50 | 15.00 | 30.72 |
| 9 | 5.00 | 15.00 | 32.61 |
| 10 | 8.66 | 25.61 | 19.65 |
| 11 | 17.50 | 15.00 | 27.40 |
| 12 | 26.34 | 4.39 | 35.46 |
| 13 | 26.34 | 25.61 | 17.08 |

Table 4

**Significance analysis of test parameters**

| Source | Sum of squares | Degree of freedom | Mean square | F number | P value |
|---|---|---|---|---|---|
| Model | 857.58 | 5 | 171.52 | 95.58 | 0.0001** |
| $X_1$ | 46.91 | 1 | 46.91 | 26.14 | 0.0014* |
| $X_2$ | 803.34 | 1 | 803.34 | 447.68 | 0.0001** |
| $X_1X_2$ | 3.44 | 1 | 3.44 | 1.92 | 0.2087 |
| $X_1^2$ | $1.781\times10^{-3}$ | 1 | $1.781\times10^{-3}$ | $9.924\times10^{-4}$ | 0.9757 |
| $X_2^2$ | 3.85 | 1 | 3.85 | 2.14 | 0.1866 |
| Residual | 12.56 | 7 | 1.79 | | |
| Lack of fit | 0.63 | 3 | 0.21 | 0.070 | 0.9728 |
| Pure error | 11.93 | 4 | 2.98 | | |
| Sum | 870.15 | 12 | | | |

*Note: ** indicates highly significant effect (p<0.01), * indicates significant effect (0.01<p<0.05).*

From the analysis of variance in Table 4, it can be seen that the significance test of the model is $F$=95.58, $P$<0.0001, and the coefficient of determination $R^2$=0.9856. This indicates that the regression model is extremely significant, and the test result of the lack of fit item is not significant ($P$>0.05). This also indicates that the regression model fit well within the experimental range. At the same time, $X_1$ and $X_2$ have a very significant effect on the variation coefficient of fertilizer uniformity ($P$<0.01), and the remaining items have no significant effect ($P$>0.05). Remove the coefficients of insignificant factors from the regression equation. The finally regression equation of the fertilizer uniformity coefficient model is:

$$\sigma = 49.1 - 0.42X_1 - 0.92X_2 \tag{12}$$

***Influence of Experimental Factors on Indicators***

The influence of the pressure angle and helix angle of the fertilizer discharge wheel on the uniformity of fertilizer discharge is shown in Fig. 10. It can be seen from the response surface plot in Figure 9 that when the helix angle is 0° and 30°, the coefficient of variation decreases with the increase of the pressure angle, and when the helix angle is 30°, the coefficient of variation is generally lower. When the pressure angle is 5° and 30°, the coefficient of variation decreases with the increase of the helix angle, and when the pressure angle is 30°, the coefficient of variation is generally lower. At the same time, it can be seen that the variation trend of the coefficient of variation with the change of pressure angle is relatively gentle, this is because the influence of pressure angle on the coefficient of variation is smaller than that of the helix angle. Overall, the trend of change is consistent with the results of the single-factor test and analysis of variance. After optimization, it can be obtained that the pressure angle and helix angle of the fertilizer discharge wheel corresponding to the minimum coefficient of variation are both 30°, and the minimum coefficient of variation is 11.82%.

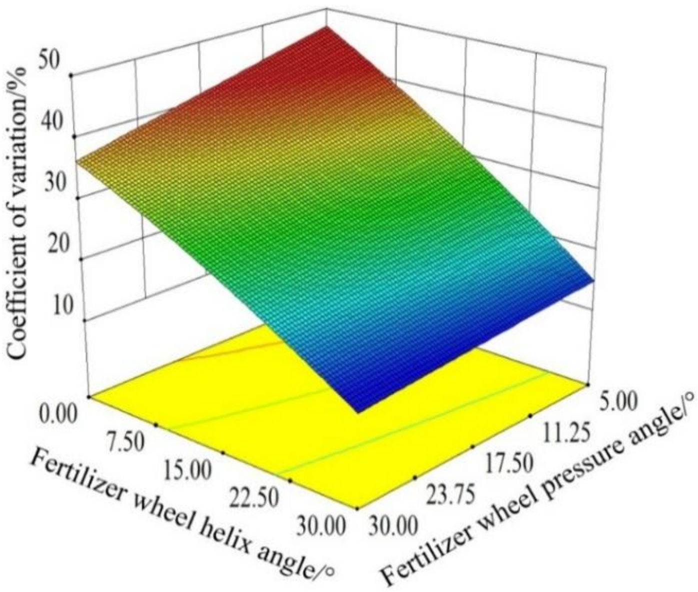



**Fig. 10 - Response Surface Plot**

In the discrete element simulation software EDEM, a discrete element simulation test was carried out on the model of the optimized interactive gear fertilizer discharger. The test measured that the coefficient of variation of the fertilizer uniformity of the optimized interactive gear fertilizer discharger was 11.92%, The relative error with the theoretical value is 0.85%, which proves the accuracy and validity of the theoretical value.

**Bench Experiment and Results**

In order to verify the correctness of the simulated value and the theoretical value, the uniformity of the fertilizer discharge of the interactive gear fertilizer was tested through a bench test, and the relationship between the speed of the fertilizer discharge wheel and the flow rate was analyzed by controlling the speed of the fertilizer discharge wheel. D printing technology was used to make an interactive gear fertilizer prototype with optimal parameters, and urea produced by China Salt Anhui Hongsifang Fertilizer Co. Ltd. was selected as the test material.

***Verification Test***

The width of each fertilizer collection box used in the bench test was 20 mm. To facilitate the calculation of the coefficient of variation for fertilizer discharge uniformity, the monitoring area was divided using 10 fertilizer collection boxes. The conveyor belt speed was set to 0.5 m/s, and the rotational speed of the fertilizer discharge wheel was set to 60 r/min. The test was repeated three times, and the average value was taken as the final result, as shown in Figure 11. The test results showed that the coefficient of variation for fertilizer discharge uniformity of the interactive gear fertilizer discharger was 12.25%, with a relative error of 2.77% compared to the simulation value. The discrepancy is attributed to the fact that the urea particles used in the test were not perfect spheres. However, since the relative error was less than 5%, it is considered within an acceptable range, thus validating the accuracy of the simulation model.

***Fertilizer Discharge Flow Rate Test***

According to the theoretical calculation of the limit speed of the fertilizer discharge wheel, the rotational speed was set to 30 r/min, 60 r/min, 90 r/min, 120 r/min, and 150 r/min, and five groups of experiments were conducted. During testing, the conveyor belt was turned on and maintained at a constant speed of 0.5 m/s. The motor controller was used to adjust the fertilizer discharge wheel to each specified speed. Once the system reached stable operation at each speed, 10 fertilizer collection boxes were used to collect fertilizer discharged from the outlet. The fertilizer discharge flow rate was then calculated based on the time required for all 10 boxes to fill. Each experiment was repeated three times, and the average value was recorded as the final result. The relationship between fertilizer discharge flow rate and the rotational speed of the fertilizer discharge wheel was analyzed using linear fitting in Origin software. The fitting results showed a strong linear correlation, with the regression equation $y=0.74x+1.39$. This indicates that the fertilizer flow rate can be linearly adjusted by controlling the rotational speed of the fertilizer discharge wheel.

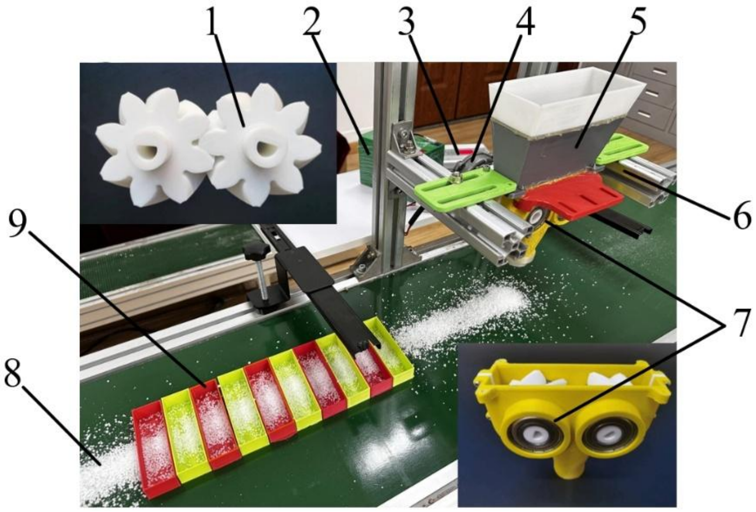



**Fig. 11 - Fertilizer flow and fertilizer wheel speed test**

*1. Fertilizer wheel; 2. Lithium battery; 3. Motor controller; 4. Drive motor; 5. Fertilizer box; 6. Test frame; 7. Interactive gear fertilizer; 8. Urea granules; 9. Fertilizer collection box.*

Five speeds were randomly selected within the range of 30 r/min to 140 r/min, and the fertilizer discharge controller was used to set the fertilizer discharger to the corresponding speeds for testing. The fertilizer discharge flow rate test was conducted at each speed, repeated three times, and the average value was taken as the final result. The measured values were then compared with the corresponding preset target values. The test results are shown in Figure 12. From the results, it can be seen that the mean deviation between the measured discharge flow rate and the preset value is 3.75%, indicating that the system is capable of achieving precise control of the fertilizer discharge amount.

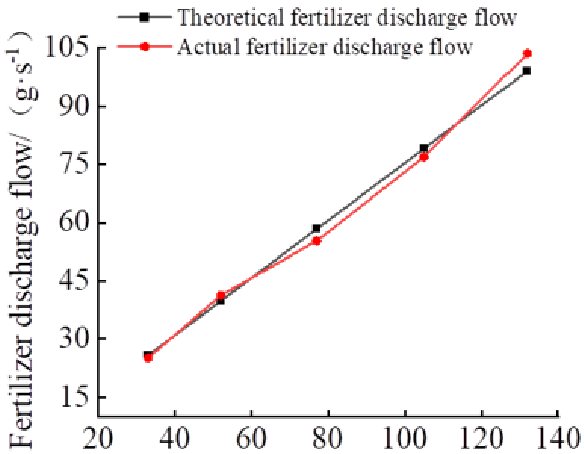



**Fig. 12 - Test result diagram**

***Anti-Adhesion Verification Test***

To simulate real working conditions, urea particles were moistened with water to increase adhesion. The Double-Gear Fertilizer Discharger *(Dun et al., 2019)* was used as a reference. Both the reference discharger and the Interactive Anti-Stick Fertilizer Discharger were tested at a fertilizer discharge wheel speed of 30 r/min. Each test was repeated five times, and the surfaces of the fertilizer discharge wheels were inspected after operation. The results showed that in the Double-Gear Fertilizer Discharger, fertilizer adhesion was clearly observed on the surface and in the grooves of the discharge wheel. Sticking traces were particularly evident at the bottom of the gear grooves, as shown in Figure 13a. In contrast, the Interactive Anti-Stick Fertilizer Discharger exhibited no obvious fertilizer adhesion during or after operation. Upon removal, the gear surfaces showed no significant sticking traces, as seen in Figure 13b. These results suggest that the Interactive Anti-Stick design effectively reduces fertilizer adhesion. Its mechanism allows residual fertilizer on the wheel to be dislodged during gear meshing, where compression between meshing teeth helps detach moist fertilizer particles. Compared to the conventional double-gear design, the anti-sticking performance is significantly improved.

The 3D model was saved in IGS format and imported into EDEM software. Hertz-Mindlin (no slip) in EDEM was selected as the contact model between granular fertilizer and granular fertilizer, caking fertilizer and caking fertilizer, granular fertilizer and caking fertilizer, granular fertilizer and fertilizer discharge device, and caking fertilizer and fertilizer discharge device. The fertilizer discharge device was modeled using PLA (polylactic acid) as the material. The detailed material and contact parameters used in the simulation are provided in Table 2.

*a)* *b)*

**Fig. 13 - Comparison of Fertilizer Wheel Surfaces**

*a) Double-gear Type Fertilizer Discharger; b) Interactive Anti-Stick Fertilizer Wheel*

## CONCLUSIONS

(1) Based on the agronomic fertilization requirements of pineapple orchards, an interactive gear fertilizer discharger was designed using the principle of fertilizer centering and interactive mixed discharge. The system utilizes a pair of continuously meshing, counter-rotating gears to alternately discharge fertilizer. A single-factor experiment and a response surface experiment were conducted using the pressure angle and helix angle as experimental factors, with the coefficient of variation of fertilizer discharge uniformity as the evaluation index. The structural parameters of the fertilizer discharger were optimized, and bench tests were performed to verify the results and analyze the relationship between the fertilizer discharge wheel speed and the fertilizer discharge flow rate.

(2) The results of the single-factor and response surface experiments indicate that both the pressure angle and helix angle of the fertilizer discharge wheel have a highly significant effect on the coefficient of variation of fertilizer discharge uniformity. The coefficient of variation decreases as the pressure angle and helix angle increase. When both angles are set to 30°, the minimum variation coefficient of fertilizer discharge uniformity is achieved at 11.82%.

(3) The bench test results show that the relative error between the theoretical, simulated, and experimental values is 2.77%, confirming the model's accuracy. Additionally, the fertilizer discharge flow rate can be linearly adjusted by changing the rotation speed of the fertilizer discharge wheel. The fitted linear relationship is described by the equation $y=0.74x+1.39$. Under the optimal parameter combination, the average deviation between the actual and preset fertilizer discharge flow rates is 3.75%, indicating a high level of precision and stable performance.

(4) A comparison of fertilizer adhesion on the gear surfaces under identical working conditions demonstrated that the interactive anti-adhesive fertilizer discharge wheel significantly reduces adhesion compared to the conventional double gear-type fertilizer discharger. This verifies the feasibility and effectiveness of the anti-adhesion design, effectively enhancing the anti-stick performance of the fertilizer discharge wheel surface.

(5) Therefore, the interactive anti-stick gear fertilizer discharger developed in this study is well-suited for fertilizer application in pineapple orchards. It effectively enhances the accuracy of fertilizer application, improves the stability of fertilizer discharge, and increases the utilization efficiency of fertilizer, ultimately contributing to higher yield and improved fruit quality. Additionally, the system offers environmental benefits by reducing fertilizer waste. These findings provide a valuable reference for the design and development of fertilizer application machinery for pineapple orchards and other orchard-based fertilization systems.

## ACKNOWLEDGEMENT

This study was funded by the Heilongjiang Province Natural Science Foundation of China (No. LH2023E025). Central Public-interest Scientific Institution Basal Research Fund (No.1630062025018). Harbin Cambridge University Key Scientific Research Application Research Project (No. JQZKY2022021).

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