DESIGN AND EXPERIMENTAL STUDY OF A CRAWLER-TYPE PRECISION PESTICIDE APPLICATOR BASED ON DEM

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基于 DEM 的履带式精准施药机设计与试验研究

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DOI: https://doi.org/10.35633/inmateh-76-15

Keywords: *precision quantitative, solid particles, discrete element method, response surface experiment*

ABSTRACT

This study is based on the discrete element method to design a tracked precision solid particle pesticide applicator and establish a coupling model between the pesticide application device and particle swarm EDEM. Simulation shows that particle characteristics significantly affect the uniformity of pesticide application. The coefficients of variation for particles 1, 2, and 3 are 4.25%, 4.63%, and 5.57%, respectively, with relative deviations of 8.51%, 9.28%, and 11.33%. After response surface testing optimization, the measured coefficient of variation of the prototype was 8.25% and the relative deviation was 18.07%, both of which met industry standards.

摘要

本研究基于离散元法设计履带式精准固体颗粒施药机，建立施药装置-颗粒群 EDEM 耦合模型。仿真表明：颗粒特性显著影响施药均匀性，颗粒 1、2、3 的变异系数分别为 4.25%、4.63%、5.57%，相对偏差 8.51%、9.28%、11.33%。响应面试验优化后，样机实测变异系数 8.25%、相对偏差 18.07%，均达行业标准。

INTRODUCTION

Liquid pesticide spraying is the dominant method for pest control in China; however, its effectiveness is limited by issues such as high droplet drift rates, low pesticide utilization efficiency, and environmental pollution (*Nation H.J.*, 1972). As modern agriculture transitions toward precision and intelligent technologies, solid granular pesticides have demonstrated significant potential for applications such as corn borer control and soil disinfection due to their ability to be applied directly to target areas, high resistance to drift, and prolonged efficacy (*Ministry of Agriculture and Rural Affairs, 2022*). However, existing solid granular pesticide application equipment faces technical challenges such as poor quantitative accuracy, uneven discharge, and limited terrain adaptability, restricting its widespread adoption (*Jiang Y.Y. et al., 2021*). Therefore, overcoming these challenges and enhancing the accuracy and adaptability of pesticide applicators are crucial for advancing precision spraying technology.

In recent years, with the rapid development of intelligent agriculture, precision pesticide application technology has been widely adopted. Research in this area primarily focuses on variable pesticide application control, operational parameter optimization, and equipment improvement (*He X.K., 2020*). *Zhai Changyuan et al. (2024)* designed a precision variable spraying monitoring system based on traceability management, which enables real-time detection of pesticide type, ratio, spraying volume, spray pressure, and operating speed, integrating precision pesticide application with traceability management. Gou Yujiang et al. developed a handheld variable fertilizer spreader and constructed a regression model using discrete element simulation experiments to optimize fertilization parameters and improve spreading uniformity. Dong Jiwei et al. designed a crawler-type target-matching pesticide spreader to meet the operational needs of orchards in hilly and mountainous areas. Its lifting and closing mechanism allow flexible adjustment of spraying distance and height, adapting to different fruit tree types. Currently, research on fertilizer and pesticide application equipment with wheeled chassis in plain areas is relatively advanced, with significant progress in variable pesticide application

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and operational optimization technologies. However, under the complex terrain conditions of hilly and mountainous areas, research on the coupling mechanism between crawler walking systems and solid granular pesticide discharge mechanisms remains limited (*Hazra D.K. et al., 2019*).

Based on discrete element method (DEM) numerical simulation technology, this study designs a precision quantitative solid granular pesticide applicator suitable for hilly and mountainous areas. By integrating response surface tests, key operational parameters were optimized, and the effects of factors such as operating speed, material port diameter, and application angle on application uniformity were examined. The findings not only provide theoretical support for the development of precision pesticide application equipment in hilly and mountainous areas but also contribute to reducing pesticide use, minimizing environmental pollution, and promoting precision agriculture. This research is of great significance for the intelligent transformation of China's plant protection machinery.

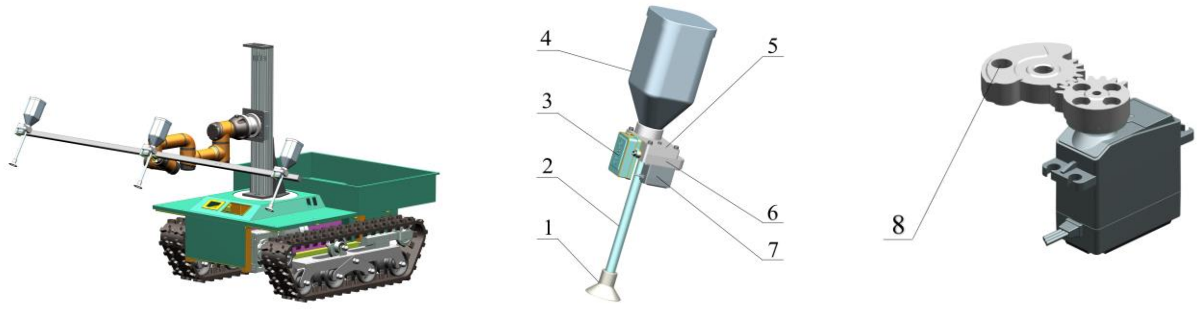
MATERIALS AND METHODS

Machine structure and workflow

Machine structure

To address the complex agricultural environments in hilly and mountainous regions, this study developed a crawler-type precise quantitative solid particle sprayer. The system includes a crawler chassis power platform, a robotic arm, a rotating lifting mechanism, a spraying system, and a control system. The gear transmission component is manufactured by a CNC universal gear grinding machine (YW7232CNC). The power platform uses a self-propelled crawler chassis, known for its superior obstacle-crossing ability and stability, enhancing mobility in challenging terrains (*Qi X.Y. et al., 2015*). The robotic arm features a multi-joint structure for precise control of the spraying device's motion, and combined with the rotating lifting mechanism, it allows for fine-tuned multi-directional adjustments, improving spraying accuracy in diverse crop environments. The spraying system consists of three electronically controlled devices (Fig. 1a), with adjustable spraying spacing for synchronized multi-channel operation, boosting efficiency. The pesticide application device (Fig. 1b) includes a dispensing port, guide pipe, IoT module, material box, loading and unloading module, and servo motor. Solid granular pesticides are evenly dispensed via a rotating material tray (Fig. 1c), ensuring precise coverage and optimal pesticide use. The control system integrates robotic arm motion, pesticide application activation, and operational parameter adjustment. Operators can input commands or use preset programs for precise pesticide application to meet various operational needs.

The concept of targeted pesticide application originated from the manual handheld pesticide application process. In order to improve the utilization rate of granular drugs and reduce the transport and loss in ineffective spaces, the nozzle is aimed at the center of the seedlings during manual pesticide application, and the handheld spray rod is aimed at the seedlings for pesticide application. The tracked precision quantitative solid particle pesticide applicator adopts an automated targeted pesticide application method, and multiple components in the system work together to achieve efficient, precise, and environmentally friendly pesticide application. The pesticide application operation starts from the action of the robotic arm and the pesticide application device. The robotic arm can precisely control the movement of the pesticide application device to ensure that the pesticide is spread in the correct position. Solid particle pesticides are released to the target through the feeding port to ensure precise coverage of the target area. The parameter settings of the pesticide applicator, including the application amount, operating speed, and application angle, are adjusted through the control platform (*Meshram A.T., 2022*).



a) b) c)

Fig. 1 - Precision quantitative pesticide applicator and pesticide applicator

a) Machine structure b) Application system c) Discharge mechanism; 1. Feeding port 2. Flow guide tube 3. Internet of Things module 4. Material box 5. Feeding port module 6. Discharge port module 7. Servo 8. Feeding port.

Workflow

The crawler-type precision quantitative solid particle applicator developed in this study employs an automated targeted application strategy to ensure efficient, precise, and environmentally friendly pesticide delivery. Targeted application technology originates from the manual handheld precision application method, in which the nozzle remains aimed at the center of the crop throughout the process, enhancing pesticide utilization efficiency and minimizing unnecessary dispersion. The application process is executed by the robotic arm in conjunction with the application device. During operation, the robotic arm precisely adjusts the position of the application device, ensuring the directional release of solid particle pesticides through the drop port for even coverage of the target crop (*Chen Z.W. et al., 2023*). The control system enables intelligent adjustment of application parameters, including dosage, operating speed, and application angle, to accommodate various environmental conditions and agronomic requirements.

Simulation and experiment

Discrete Element Simulation Model

In EDEM software, common particle contact models include the Hertz-Mindlin (no-slip) model, the Hertz-Mindlin with bonding model, the Hertz-Mindlin with JKR (Johnson-Kendall-Roberts) model, and the Linear Cohesion model. These models are suited to different granular materials and conditions. The Hertz-Mindlin with JKR model is preferred for simulating pesticide particle contact due to its ability to characterize particle bonding and agglomeration. Unlike the Linear Cohesion model, which only accounts for normal bonding forces and ignores tangential forces, the JKR model considers both normal and tangential bonding, making it more accurate for complex bonding materials (*Nie C.X. et al., 2022*).

Pesticide particles, with small size, high surface roughness, and moisture content, tend to agglomerate and adhere due to electrostatic and intermolecular forces. The JKR model effectively captures this behavior, which is further intensified in humid climates like those in southwestern regions. Traditional rigid or non-adhesive models are inadequate for such conditions. Thus, this study uses the JKR model to better simulate the flow and application behavior of pesticide particles, providing a solid theoretical foundation for designing and optimizing precision pesticide application equipment (*Wang S. et al., 2024*).

Particle Characterization

To accurately characterize the different physical properties of Imidacloprid pesticide particles and ensure the reliability of the simulation, key parameters such as particle density, moisture content, angle of repose, and particle size distribution were measured (Fig. 2). These parameters are essential for constructing the discrete element simulation model.

a) *b)* *c)*

Fig. 2 - Pesticide particles with different material properties

a) Particles 1; b) Particles 2; c) Particles 3

a) *b)* *c)* *d)*

Fig. 3 - Test equipment

a) Repose angle measuring device; b) Electronic balance; c) Halogen Moisture Analyzer; d) Standard test sieve

Particle density was determined using the drainage method, as per GB/T 24528 and GB/T 13477.2-2002 standards. The density was calculated by measuring the particle volume after drainage and combining it with the mass measured by a high-precision electronic balance. Each group was measured three times, and the average value was taken for stability. Moisture content was measured using an FBS-760A halogen moisture analyzer, which heated and dried the samples while automatically recording water evaporation and mass changes. Each group was measured three times, and the average value was used to minimize error. The angle of repose was measured using the natural piling method, where particles fell through a funnel to form a cone, and the angle between the cone and the horizontal plane was recorded. This experiment was repeated 10 times to ensure reliability. Particle size distribution was determined by sieving 1000 g of particles using standard test sieves (GB/T 6003.1-2012). The mass retained on each sieve was recorded to calculate mass percentages. All experiments followed national standards, with multiple repetitions to ensure accuracy and reliability. The measurement tools and results are shown in Fig. 3 and Table 1.

Table 1

Test particle parameter measurement results

Item		**Measurements**		
		Particles 1	**Particles 2**	**Particles 3**
Particle size analysis (mass percentage passing through the sieve/%)	0.25mm	0	0	0
	0.50mm	5.98	12.38	0
	1.00mm	69.33	22.14	13.50
	1.60mm	16.35	47.12	42.47
	2.00mm	8.34	18.36	38.55
	2.50mm	0	0	5.48
Bulk density /（kg/m^3）		5.85×103	0.55×103	2.66×103
Moisture content /%		0.170	3.533	0. 54
Angle of repose /（°）		18.6	23.4	32.5
Air humidity during the test /%		68	72	72

Simulation test

Discrete Element Simulation

In this study, the Hertz-Mindlin with JKR model was used to describe the interaction forces between particles and equipment, enabling a more accurate simulation of particle adhesion. Considering the particle size distribution of actual Imidacloprid pesticide particles, the spherical particle modeling method in EDEM software was employed to construct simulation models of particles with various shapes (Fig. 4). The experimental design included single-sphere, double-sphere, three-sphere, four-sphere, and irregular multi-sphere models, based on the actual particle distribution ratio to ensure the simulated morphology closely matched real particle characteristics (*Xie K. et al., 2024*). The simulation model parameters are listed in Table 2. This approach effectively characterizes particle morphology and simulates their motion within the equipment, providing a reliable basis for particle flow analysis and optimization of drug application equipment. Model parameters were set based on experimentally measured data, improving the accuracy and reliability of the simulation results.

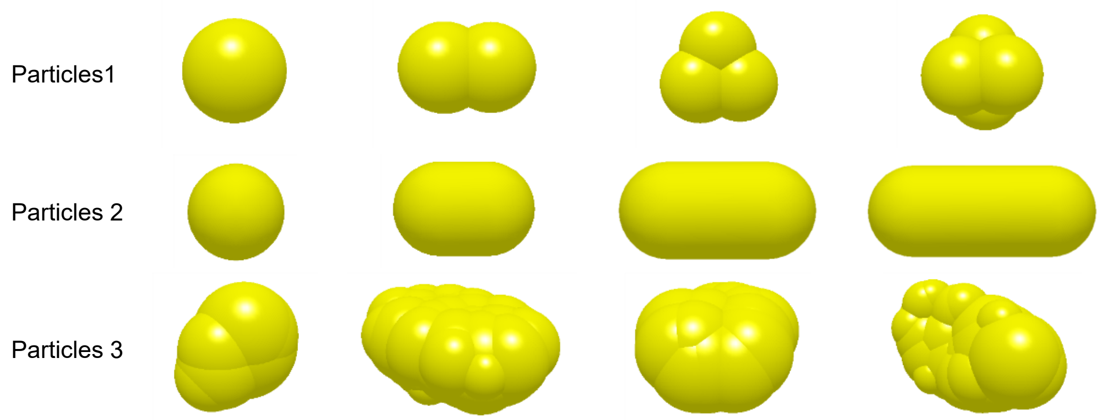


Fig. 4 - Simulation particle model

Table 2

Discrete element simulation model parameters

Item	Parameter	Value		
		Particles 1	Particles 2	Particles 3
Particles	Poisson's ratio	0.35	0.20	0.25
	Shear modulus /Pa	9×10^{10}	5×10^{9}	3×10^{10}
	Number of particles	100000	100000	100000
	Gravity acceleration / $m\cdot s^{-2}$	9.81	9.81	9.81
Steel	Poisson's ratio	0.30		
	Shear modulus /Pa	1.1×10^{11}		
	Density /$kg\cdot m^{3}$	7850		
Particle-Particle	Coefficient of restitution	0.30	0.4	0.30
	JKR surface energy /$J\cdot m^{2}$	13.50	18.55	12.40
	Static friction coefficient	0.30	0.40	0.30
	Dynamic friction coefficient	0.01	0.05	0.01
Granules-Stainless Steel	Coefficient of restitution	0.30	0.50	0.30
	JKR surface energy /$J\cdot m^{2}$	14.50	20.20	15.00
	Static friction coefficient	0.25	0.35	0.30
	Dynamic friction coefficient	0.01	0.05	0.01

Simulation Experiment Design

To verify the design rationality of the spraying mechanism, to further explore the interaction between the spraying mechanism and pesticide particles, and to provide a scientific basis for the design of key parameters of the spraying machine, a simulation experiment was conducted using EDEM software. Based on typical spraying operation conditions in hilly and mountainous areas, the rotation speed of the spraying machine's material plate was set to 60 r/min, the material port diameter was set to 7 mm, and the spraying angle was maintained at 0° to ensure the uniformity of the testing process. Three types of pesticide particles with different material properties were selected for the experiment, covering various particle sizes, densities, and surface morphologies to simulate common pesticide formulations. By keeping the spraying machine's operating parameters constant and adjusting only the particle characteristics, the adaptability and reliability of the spraying machine under different particle types were studied (*Yin Y.S. et al, 2018*).

Field trials

To verify the operational performance of the precision quantitative solid particle sprayer, the experimental design followed industry standards, including the "JB/T 9782-2014 General Test Methods for Plant Protection Machinery" and the "GB/T 21157-2007 Test Methods for Granular Pesticide or Herbicide Spreaders." The focus was on evaluating the performance stability and uniformity of the sprayer. The experiment used the Box-Behnken experimental design method, with operating speed, feed port diameter, and spraying angle as the main influencing factors, and coefficient of variation and relative deviation as response variables.

Design-Expert 13 was used to conduct a three-factor, three-level experimental design, construct a response surface model, and optimize the operating parameters of the precision spraying equipment. Operating speed directly affects the uniformity and efficiency of spraying; feed port diameter determines the unit spraying amount of solid drug particles and is the core parameter of precision spraying; spraying angle, i.e., the vertical angle between the feed port and the crop to be sprayed, affects the distribution range and uniformity of the particles.

This study uses the coefficient of variation and relative deviation as key evaluation indicators to fully reflect the spraying performance of the equipment. By optimizing the combination of various factor levels, data support was provided for the parameter optimization of precision pesticide application equipment, laying a theoretical foundation for reducing pesticide usage, improving pesticide utilization, and promoting the application of precision pesticide technology. The test factors and levels are shown in Table 3, and the field test is shown in Fig. 5.

Table 3

Response surface test factors and levels

Level	Factor		
	Operation speed	Feeding port diameter	Spraying angle
	[km/h]	[mm]	[°]
-1	0.6	5	0
0	1.2	7	30
1	1.8	9	60

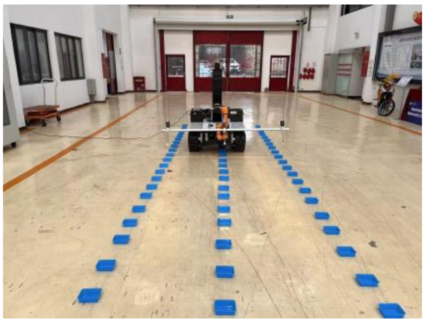


Fig. 5 - Field test of pesticide sprayer

RESULTS

Evaluation indicators

According to the "Test Method for Granular Pesticide or Herbicide Spreader GB/T 21157-2007," this study selected the coefficient of variation (CV) and relative deviation (RD) as evaluation indicators to quantitatively analyze the spreading uniformity and application accuracy of granular spraying equipment. The coefficient of variation (CV) reflects the uniformity of the granule spreading amount in different areas; the smaller the value, the higher the uniformity. The relative deviation (RD) evaluates the degree of deviation between the actual application amount and the target application amount, which is an important indicator for measuring the performance of precision spraying. Through rigorous experimental design and data analysis, this study comprehensively evaluates the performance of equipment spraying and provides a scientific basis for optimizing spraying parameters and improving spraying accuracy.

The average mass $\overline{M_n}$ of a single row of pellet boxes is calculated as follows:

$$\overline{M_n} = \frac{1}{n}\sum M_i \tag{1}$$

where n is the number of particle collecting boxes; M_i is the mass of granules collected by the ith particle collecting box.

The coefficient of variation (*CV*) calculation formula is:

$$CV_n = \frac{s}{\overline{M_n}} \tag{2}$$

where s is the standard deviation, calculated as follows:

$$s = \sqrt{\frac{1}{n-1}\sum (M_i - \overline{M_n})^2} \tag{3}$$

The relative deviation (*RD*) of each row is calculated as:

$$RD_n = \frac{M_{i,\max} - M_{i,\min}}{\overline{M_n}} \times 100 \tag{4}$$

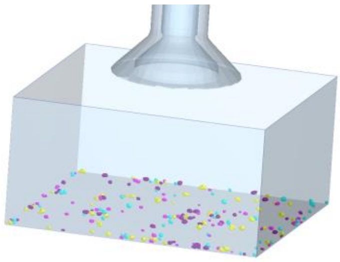
Simulation Results Analysis

The simulation test of the pesticide applicator was carried out based on EDEM software, and the results are shown in Figure 6. The simulation analysis shows that the spreading uniformity and stability of the pesticide applicator are greatly affected by the characteristics of the pesticide granule material. The coefficients of variation of granule 1, granule 2, and granule 3 are 4.25%, 4.63%, and 5.57%, respectively, and the relative deviations are 8.51%, 9.28%, and 11.33%, respectively (Fig. 7), all of which meet the industry standard requirements specified in the "Technical Specifications for Quality Evaluation of Fertilizer Machinery NY/T1003-2006." The simulation results show that the increase in particle size, density, surface profile, and friction coefficient will lead to a decrease in spreading uniformity and stability. Among them, the coefficient of variation of particle 3 is relatively high, indicating that its spreading distribution is more discrete, which may be related to the increase in the friction coefficient between particles leading to a decrease in fluidity.

Under fixed operating parameters, the pesticide applicator has the best adaptability to particle 1, and its coefficient of variation and relative deviation are both low, indicating that the pesticide applicator is suitable for particles with small particle size, smooth surface, and low friction coefficient.

In comparison, the simulation results of particle 3 reveal the limitations of the existing design when dealing with high-density, large-size particles. It is difficult to effectively overcome the inertia and friction resistance of the particles by relying solely on the particle gravity and the material inlet diameter, resulting in a decrease in spreading uniformity.

a)



b)

Fig. 6 - Simulation analysis of pesticide application device

a) Overall sprayer; b) Sprayer drop

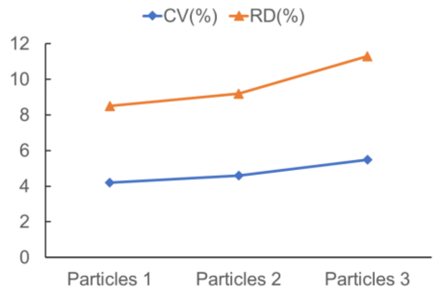


Fig. 7 - Simulation results

Analysis of field test results

According to the Technical Specifications for Quality Evaluation of Fertilizer Machinery (NY/T 1003-2006), the coefficient of variation for granular sprayers should be ≤13% (MARA., 2006). The maximum coefficient of variation was 8.25%, and the average relative deviation was 18.07%, both of which met the industry standard requirements (Table 4). The test data were imported into Design-Expert13 software for variance analysis (Table 5) and response surface analysis (Fig. 8, Fig. 9). From the univariate analysis, operating speed, feed port diameter, and application angle all had a significant effect on the coefficient of variation. Operating speed had the most significant effect, followed by feed port diameter, while the effect of the application angle was relatively small but still statistically significant. This indicates that the variation in the coefficient of variation is primarily affected by operating speed, while feed port diameter and application angle also influence spraying uniformity to some extent. The interaction analysis showed that the interaction effects of operating speed × feed port diameter and feed port diameter × application angle were not significant, while the interaction effect of operating speed × application angle was significant. The response surface analysis showed that at low operating speeds, increasing the feed opening diameter significantly reduced the coefficient of variation, indicating that appropriately increasing the feed opening diameter could improve uniformity. However, at high operating speeds, the effect of increasing the feed opening diameter on the coefficient of variation tended to stabilize. The effect of application angle on the coefficient of variation was more significant at high operating speeds, indicating that optimizing the application angle could improve spreading uniformity at high-speed operation. At low operating speeds, the effect of the application angle was relatively small. Under conditions of extreme application angles and larger feed opening diameters, the coefficient of variation increased slightly, indicating that excessively large application angles may lead to decreased spraying uniformity.

Table 4

Response surface experimental design and results

Test No.	Operation speed [km/h]	Feeding port diameter [mm]	Spraying angle [°]	Evaluation indicators *CV*	Evaluation indicators *RD*
1	0.6	5	30	6.42	15.61
2	1.8	5	30	8.25	21.32
3	0.6	9	30	6.27	18.59
4	1.8	9	30	7.06	16.64
5	0.6	7	0	4.81	15.38
6	1.8	7	0	6.85	20.26
7	0.6	7	60	5.91	17.45
8	1.8	7	60	5.36	16.96
9	1.2	5	0	7.47	22.28
10	1.2	9	0	6.73	16.67
11	1.2	5	60	7.16	19.24

Test No.	Operation speed	Feeding port diameter	Spraying angle	Evaluation indicators	
	[km/h]	[mm]	[°]	*CV*	*RD*
12	1.2	9	60	6.16	19.51
13	1.2	7	30	5.92	16.58
14	1.2	7	30	5.16	16.65
15	1.2	7	30	5.53	18.48
16	1.2	7	30	6.32	17.19
17	1.2	7	30	6.15	18.38

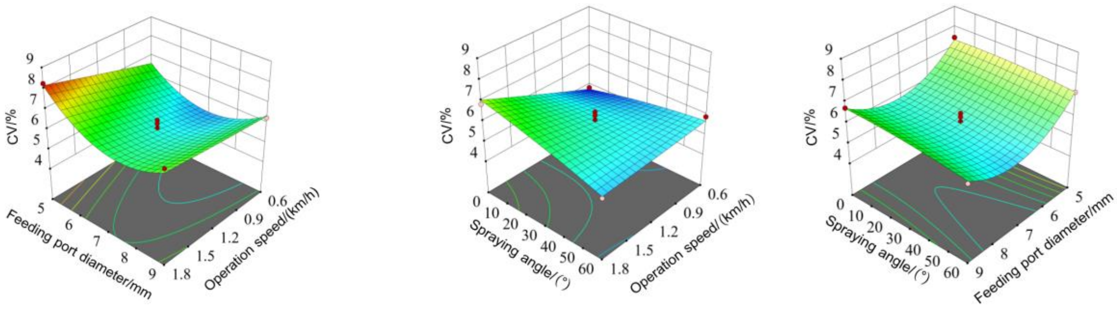
As shown in Table 5 and Fig. 9, the effects of operating speed, orifice diameter, and application angle on relative deviation are statistically significant, with P values of 0.0125, 0.0237, and 0.0342, respectively. From the perspective of the F-value, operating speed has the most significant effect, followed by orifice diameter, while the effect of application angle is relatively small. The two-factor interaction analysis showed that operating speed × orifice diameter and orifice diameter × application angle significantly affected relative deviation (P values of 0.0030 and 0.0114, respectively).

Table 5

Analysis of variance

Sources of variance	*CV*				*RD*			
	sum of squares	DOF	*F-value*	*p-value*	sum of squares	DOF	*F-value*	*p-value*
Model	11.22	9	7.94	0.0061	55.75	9	8.29	0.0054
A	2.11	1	13.46	0.0080	8.30	1	11.12	0.0125
B	1.19	1	7.56	0.0285	6.20	1	8.29	0.0237
C	0.2016	1	1.29	0.2943	0.2556	1	0.3422	0.5769
AB	0.2704	1	1.72	0.2306	14.67	1	19.64	0.0030
AC	1.68	1	10.69	0.0137	7.21	1	9.65	0.0172
BC	0.0169	1	0.1077	0.7523	8.64	1	11.57	0.0114
A^2	0.0014	1	0.0089	0.9273	1.86	1	2.49	0.1588
B^2	5.72	1	36.47	0.0005	6.56	1	8.78	0.0210
C^2	0.0436	1	0.2779	0.6144	2.19	1	2.93	0.1308
Residual	1.10	7			5.23	7		
Lack of Fit	0.2096	3	0.3146	0.8154	1.84	3	0.7231	0.5887
Pure Error	0.8885	4			3.39	4		
Total	12.32	16			60.98	16		
R^2	0.9108				0.9143			
R^2_{adj}	0.7962				0.8040			
Adeq Precision	11.287				9.9928			
Regression Equation	CV=5.82+0.5138A-0.385B-0.1587C-0.26AB-0.6475AC-0.065BC+0.0182A^2+1.17B^2-0.1017C^2				RD=17.46+1.02A-0.88B-0.1788C-1.91AB-1.34AC+1.47BC-0.6643A^2+1.25B^2+0.7208C^2			

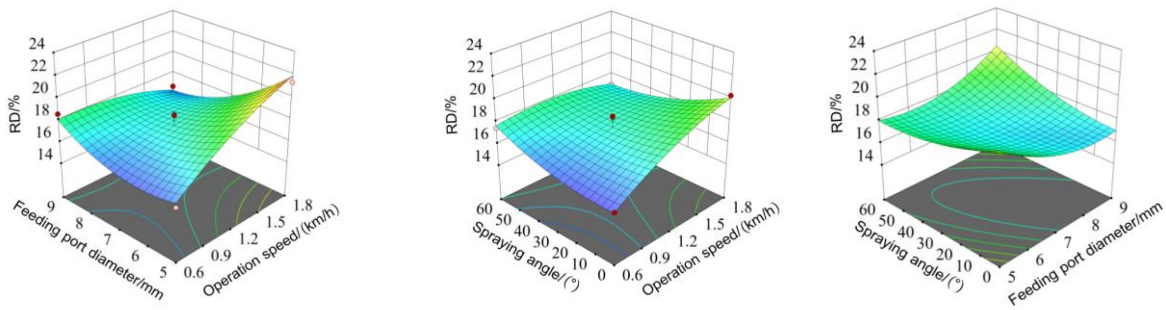
Note: p<0.05 shows this term is significant; p<0.01 shows this term is very significant.



a) *b)* *c)*

Fig. 8 - Response surface plot of the effect of two-factor interaction on the coefficient of variation
a) Feeding port diameter × Operating speed; b) Spraying angle × Operation speed; c) Spraying angle ×Feeding port diameter

The response surface analysis showed that at low operating speeds, increasing orifice diameter had a greater effect on relative deviation, while at high operating speeds, the effect of increasing orifice diameter on relative deviation gradually weakened. This indicates a synergistic effect between the two, but the intensity of the effect is influenced by operating speed. In addition, the interaction between orifice diameter and application angle on relative deviation shows a nonlinear relationship. When the orifice diameter is small, adjusting the application angle has a smaller effect on relative deviation, while when the orifice diameter is large, the effect of changing the application angle on relative deviation becomes more significant. This indicates that when optimizing application parameters, the matching relationship among operating speed, feed port diameter, and application angle should be considered comprehensively to improve application accuracy and reduce deviation.



a) *b)* *c)*

Fig. 9 - Response surface plot of the effect of two-factor interaction on relative deviation

a) Feeding port diameter × Operating speed b) Spraying angle × Operation speed c) Spraying angle ×Feeding port diameter

CONCLUSIONS

This study provides a theoretical basis for the research and development of precision pesticide application equipment in hilly areas, as well as technical support for reducing pesticide use, reducing environmental pollution, and promoting the development of precision agriculture. Discrete element method (DEM) was used to design and optimize a crawler-type precision pesticide applicator. Through simulation and field tests, the effects of pesticide particle characteristics and key operating parameters on application uniformity and accuracy were evaluated. The main findings are:

1. Particle material properties significantly affect application performance. The coefficients of variation for different particles were 4.25% (Particle 1), 4.63% (Particle 2), and 5.57% (Particle 3), with corresponding relative deviations of 8.51%, 9.28%, and 11.33%. Small-size, low-density, and smooth-surfaced particles exhibited good fluidity within the applicator and high spreading uniformity. In contrast, larger and denser particles were more significantly affected by gravity and friction, leading to accumulation at the material port, resulting in uneven spreading and affecting the accuracy of pesticide application.

2. Response surface analysis optimized key parameters such as operating speed, material port diameter, and application angle. Operating speed had the most significant effect on uniformity and accuracy, followed by material port diameter, with application angle having a smaller effect. At low speeds, increasing port diameter improved uniformity, while at higher speeds, optimizing the application angle reduced deviation and improved precision.

3. Field tests showed a maximum coefficient of variation of 8.25% and an average relative deviation of 18.07%, both meeting industry standards. The consistency between simulation and test data confirms the feasibility and stability of the designed applicator for precise pesticide application.

ACKNOWLEDGEMENTS

The study was funded by Chongqing Education Commission Science and Technology Research and Technology Youth Fund Project (KJQN202400208), Chongqing Beibei District Industry-University-Research Cooperation Guidance Program Project (2024cxyhz-04) and Chongqing Beibei District Science and Technology Bureau Science and Technology Talent and Independent Innovation Special Project (2024-30).

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