

Article

Spreading Uniformity and Parameter Optimization of Multi-Rotor UAVs for Granular Fertilizer Application

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Abstract

Unmanned Aerial Vehicle (UAV) fertilization is important for precision agriculture. However, multi-rotor UAVs show a lot of inconsistencies in homogeneity and unclear deposition patterns when they spread granular fertilizer in different operational situations. This study utilized the DJI T40 UAV to measure discharge rates and create a correlation model. An orthogonal design combined DEM simulation with field experiments to look at how flight height and disc speed affected spreading uniformity and effective swath for single and overlapping flight paths. The discharge rate has a strong linear relationship with control parameters ($R^2 > 0.94$), which means that it is very easy to predict for all particle sizes. Single-pass deposition shows an “M-shaped” bimodal profile with particles of different sizes arranged in a radial pattern. The best values for H and n were found to be 7 m and 1200 rpm, respectively, and gave a 10 m effective swath width and a coefficient of variation (CV) of 13.79%. Deposition patterns change nonlinearly with flight height and disc speed. Particle size consistency is critical for distribution stability, with flight height being the key quality determinant and particle size variation the primary source of instability.

Keywords: broadcast pattern characterization; swath width; flight dynamics; centrifugal spreading; precision nutrient management

1. Introduction

Achieving precise spatial uniformity in granular fertilizer application is a fundamental prerequisite for maximizing fertilizer use efficiency and ensuring sustainable crop yields [1–4]. Compared to manual broadcasting and conventional ground-based machinery, UAVs demonstrate pronounced advantages in operational efficiency, application quality, and agro-ecological conservation. UAVs substantially accelerate field operation rates [5], enabling the precise capture of agronomic windows for topdressing [6]. Furthermore, they mitigate the risks of localized over-fertilization and enhance fertilizer use efficiency, while operating entirely unconstrained by terrain limitations and effectively eliminating mechanical trampling damage to crops [7,8]. The overarching agronomic efficacy of UAV application is fundamentally dictated by its spreading quality. Specifically, the spatial distribution uniformity of granular fertilizer significantly impacts fertilizer use efficiency, which is directly correlated with crop growth consistency and final yield [9,10].



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While previous research has primarily focused on the structural design of spreading equipment to ensure reliable fertilizer discharge, the operational optimization required for precise application under dynamic flight conditions remains largely unresolved. Driven by the need for maximum operational efficiency, UAVs increasingly operate at high speeds and large mass flow rates. In liquid spraying, the strong downward airflow primarily serves to drive fine droplets through the crop canopy, enhancing penetration and mitigating wind drift [11–13]. In granular spreading, the initial velocity vectors of the granules are significantly perturbed by the rotor downwash airflow upon ejection from the centrifugal spinner disk. The intensity of this aerodynamic interference is highly dependent on key operational parameters, notably flight altitude and disk rotational speed [14]. Granules are initially accelerated horizontally by the centrifugal disc; immediately upon detachment, their ballistic trajectories are intercepted by the rotor downwash airflow. This fluid–solid interaction significantly alters the particles’ aerial trajectories, often affecting their lateral flight distance or causing severe central accumulation if the centrifugal kinetic energy is insufficient to overcome the downwash suppression. Such non-uniform application creates zones of localized nutrient deficiency alongside areas of excessive nitrogen accumulation, which can induce severe crop lodging and destabilize overall grain quality [15,16]. Therefore, systematically quantifying the interactive effects of these dynamic operational parameters (e.g., flight velocity, altitude, and spinner speed) on spreading uniformity remains a critical knowledge gap. To bridge this gap, establishing the optimal parameter combinations is crucial for ensuring uniform deposition and high fertilizer utilization. This optimization not only enhances the precision performance of plant protection UAVs but also serves as a fundamental step toward achieving sustainable fertilization with reduced inputs and increased efficiency.

While considerable research efforts have been devoted to optimizing the structural design of UAV spreading devices to ensure reliable fertilizer discharge, a critical knowledge gap remains regarding their dynamic operational performance. Specifically, the complex interactive effects of multiple operational parameters on spatial spreading uniformity have not been systematically quantified. Liu et al. [17] created a centrifugal disc with an involute spiral guide rail. They used discrete element analysis to look at how the disc’s speed and feed rate affected the structure of the spreading system, which made the spreading more even. Cen Haiyan et al. [18] developed a UAV system and methodology for variable-rate fertilization, utilizing a centrifugal disc mechanism that adjusts the distribution rate by changing the disc’s rotational speed and the number of slots along its edge to achieve different levels of fertilization efficiency. Wang et al. [19] demonstrated that a multi-channel pneumatic UAV spreader, when optimized with partitions to stabilize the airflow, could mitigate discharge inconsistencies and achieve a highly uniform banded deposition with a CV as low as 8.69%. In terms of the centrifugal spreader design, Wang et al. [20] employed a horizontal auger alongside a centrifugal disc, achieving continuous and stable quantitative distribution with an operational width of 8 m and a CV of 14.04%. Song et al. [21] evaluated several commercial UAV-based spreaders and revealed that their transverse deposition patterns differ drastically, ranging from typical M-shapes with two peaks to more uniform trapezoidal shapes. Their study emphasized that spreaders producing trapezoidal distributions are fundamentally more conducive to achieving high overall uniformity during overlapping parallel flights. According to the ASAE S341.5 standard for granular broadcast spreaders, an ideal transverse distribution pattern should typically approximate a trapezoidal or triangular shape to ensure a low CV during adjacent swath overlaps [22]. However, for UAV-based topdressing, the morphology of granule deposition curves often deviates into suboptimal patterns (such as bimodal or M-shaped curves) due to inconsistencies between the spreading process, operational parameters, and route plan-

ning [23,24]. These deviations disrupt the ideal overlap, directly leading to strip-shaped zones of “skipped application” or “overlapping application” in the field. To mitigate these issues, it is essential to analyze the granular deposition patterns and establish the optimally matched operational parameters before practical application.

The primary objective of this study was to systematically evaluate and optimize the interactive effects of dynamic operational parameters on the spatial spreading uniformity of a UAV centrifugal spreader. This research lies in its multi-variable field assessment of how these dynamic factors alter the fluid–solid coupling and spatial deposition. Specifically, the discharge system was evaluated to determine the influence of varying particle sizes on mass flow characteristics. And we quantitatively analyzed how flight altitude and disc speed interactively dictate lateral diffusion, spatial deposition patterns, and the spatial segregation of particles by size. By examining variations in singular spreading swaths and simulating overlapping flight trajectories, we identified the optimal operational parameter combinations designed to minimize the CV and maximize the effective swath width. This study proposes a parameter optimization strategy for UAV-based granular fertilizer spreading. This strategy transitions UAV granular spreading from empirical, trial-and-error estimations to predictable, precision applications, providing actionable guidelines for operators to minimize fertilizer waste, prevent extreme local misapplication, and maximize overall agronomic efficiency.

2. Materials and Methods

2.1. UAV Spreading System

2.1.1. Operational Platform and Material Parameters

This research employed the DJI T40 eight-rotor electric UAV operational platform, manufactured by Shenzhen DJI Innovation Technology Co., Ltd. (Shenzhen, China), as seen in Figure 1. The fertilizer spreading system is located under the UAV’s main body. At its core are four components: a hopper, a weighing sensor, a control gate, and a centrifugal spreading disc. A weighing sensor is incorporated at the base of the spreading system, facilitating accurate display of remaining inventory and closed-loop regulation of the application rate by tracking real-time fluctuations in hopper weight. The discharge control mechanism regulates the mass flow rate by adjusting the discharge aperture at the bottom of the hopper. Upon exiting the discharge aperture, the fertilizer granules fall onto the rapidly rotating centrifugal disc. The disc geometry and its rotational speed dictate the initial centrifugal kinetic energy and horizontal ejection velocity imparted to the particles. Upon ejection from the centrifugal disc, the spatial trajectories of the granules are subjected to the rotor downwash generated by the multi-rotor system. The centrifugal disc possesses a diameter of 24 cm and exhibits a 3° conical angle in relation to the horizontal plane. The disc is equipped with 8 symmetrically distributed straight blades, and its body is manufactured from lightweight engineering plastic to minimize overall rotational inertia, whereas the blades are constructed from corrosion-resistant metal. This metallic blade surface provides superior wear resistance against high-speed granular impacts and a low coefficient of kinetic friction, effectively reducing particle degradation. The detailed specifications of the UAV are listed in Table 1. Fertilizer granules are distributed around the disc, creating an annular dispersion zone [25].



Figure 1. DJI T40 UAV Centrifugal Spreading System. (a) DJI T40 UAV Complete Machine Schematic; (b) Spreading System Component Decomposition; (c) Centrifugal Disc Structure.

Table 1. Specifications and Technical Parameters of the UAV Spreading System.

Parameter	Technical Indicator	Notes
Applicable Diameter	0.5–5.0 mm	Suitable for dry solid granules
Hopper Rated Volume	70 L	/
Hopper Rated Load	50 kg	Total transport weight about 101 kg when fully loaded
Load Cell Capacity	0–60 kg	For real-time flow monitoring and auxiliary regulation
IP Rating	IP6X	Core components feature anti-corrosion coatings and support washing

This experiment used Kunlun-brand urea as the sample material (Figure 2). Urea is a type of fertilizer made from ammonia and carbon dioxide. It has 1.5% biuret, 1.0% moisture, and at least 46.0% nitrogen. The urea was sorted into big granules (2–4.75 mm) and small granules (0.85–2.80 mm). The particle densities of the large-granule and small-granule urea were determined to be 1.25 g/cm³ and 1.28 g/cm³, with sphericities of 94% and 96%, respectively. The equivalent diameter was used to describe the size of the particles because urea particles do not have a regular shape [26]. Figure 2 shows how the urea particles were sorted by size using standard mesh sieves with openings of 4 mm, 3 mm, 2 mm, and 1 mm.

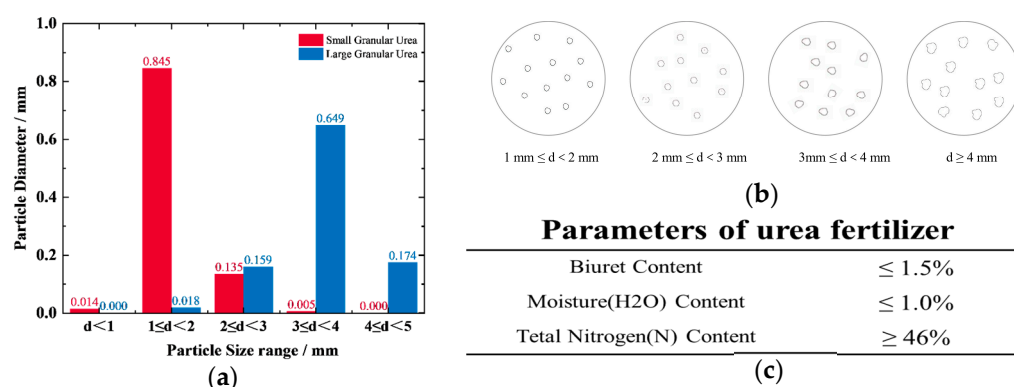


Figure 2. Parameters of the Granular Fertilizer Used in the Experiment. (a) Proportion of different particle size ranges in large granular urea and small granular urea. (b) Classification into Four Different Particle Size Ranges. (c) Parameters of urea fertilizer.

2.1.2. Fertilizer Spreading Model

This work uses the Discrete Element Method (DEM) and EDEM 2022 (Altair Engineering Inc., Troy, MI, USA) to create a model for completely obtaining and analyzing the motion information and deposition distribution of fertilizer granules during UAV spreading operations. Before executing the DEM simulation, it was essential to create

the structural model of the fertilizer granules in the pre-processing interface. The actual form and size of fertilizer granules diverge from ideal spherical particles under optimal conditions; thus, simulating them precisely would achieve great simulation accuracy but lead to prolonged calculation durations and diminished efficiency. Consequently, this work employs a singular spherical particle model. But utilizing perfectly spherical models tends to underestimate the inter-particle friction and rolling resistance, to mitigate these shape-induced discrepancies, the rolling friction coefficient between the particles and the contact geometries was appropriately calibrated and increased in the simulation model. The components of the UAV dispersal system, acquired using 3D point cloud scanning, along with the 3D solid model of the spreader created in SolidWorks 2021 (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA), were loaded into EDEM (Figure 3) and constructed based on their coordinates.

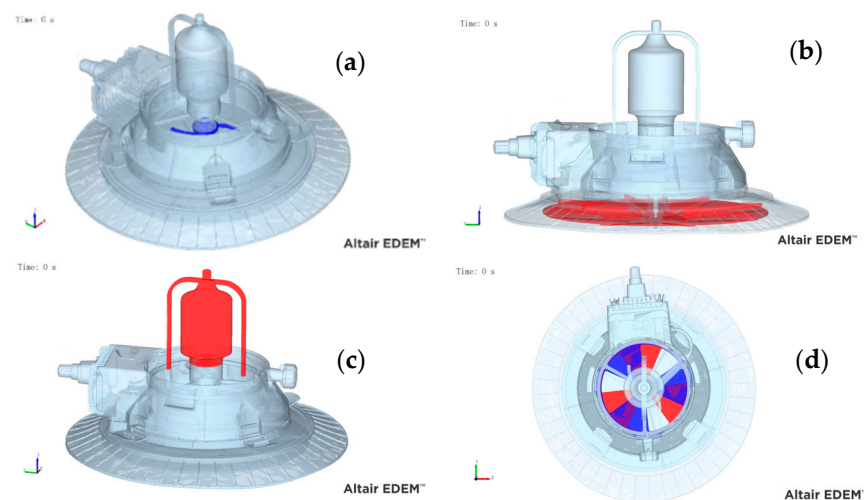


Figure 3. Structure of the DJI T40 UAV Spreading Disc. (a) Stirring rod. (b) Centrifugal disc. (c) Stirring device. (d) Adjustable baffle.

A model of the spreading system was developed utilizing the Discrete Element Method (DEM) in EDEM software (DEM-Solutions, UK) to acquire more precise motion data of granular fertilizer during operation. This model was employed to simulate and analyze the motion dynamics of granular fertilizer and to investigate the impact of fertilizer distribution and the UAV spreading apparatus on enhancing fertilization uniformity. The standard no-slip Hertz-Mindlin contact model incorporated in EDEM software was utilized for the simulation research [27,28]. A particle factory was established to dynamically produce 50 kg of particles. The rotational velocity of the centrifugal spreading disc was established between 400 and 1200 rpm, while the aperture angle of the fertilizer flow control baffle was modified from 0° to 60°. The duration of the simulation for each distinct scenario was established at 10 s. To guarantee simulation accuracy, contact parameters were calibrated experimentally. Baseline parameter ranges were first derived from literature [29,30]. Precise values were then determined through iterative calibration against physical measurements, specifically the static angle of repose. The final calibrated values used in all simulations are listed in Tables 2 and 3.

Table 2. Material Parameters in EDEM.

Materials	Poisson's Ratio	Density (kg/m ³)	Shear Modulus
ABS	0.394	1060	8.9×10^8 Pa
Urea	0.25	1330	100 MPa

Table 3. Contact Parameters between Materials in EDEM.

Interaction Pair	Coef. of Restitution	Static Friction Coef.	Rolling Friction Coef.
Urea-ABS	0.6	0.33	0.41
Urea-Urea	0.35	0.5	0.22
Urea-Soil	0.15	0.4	0.75

After setting the relevant parameters, the UAV spreading system was simulated as shown in Figure 4a. The ground material parameters were modified to cohesive soil to reduce particle bouncing during simulation, thereby improving simulation accuracy and reference value. The spreading results under different operational parameters were analyzed through EDEM post-processing. Taking the experimental results in Figure 4 as an example, the simulation parameters for Figure 4b were set as follows: UAV flight altitude of 3 m, flight speed of 5 m/s, spreading disc speed of 600 rpm, flow control baffle opening of 100%, and particle diameter of 4 mm. For Figure 4c, the simulation parameters were: UAV flight altitude of 3 m, flight speed of 5 m/s, spreading disc speed of 1200 rpm, flow control baffle opening of 100%, and particle diameter of 4 mm. Clearly, the rotational speed of the spreading disc significantly influences the effective swath width and spreading uniformity of the UAV application.

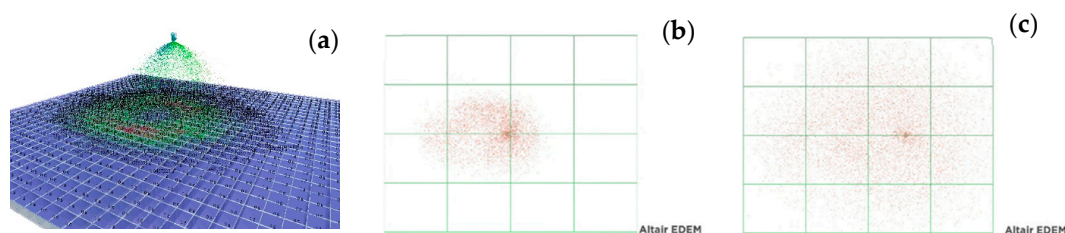


Figure 4. UAV Spreading Simulation under Different Parameters in EDEM. (a) Schematic diagram of the EDEM simulation process. (b) Simulation results under the conditions of UAV altitude 3 m, flight speed 5 m/s, and spreading disc speed 600 rpm. (c) Simulation results under the conditions of UAV altitude 3 m, flight speed 5 m/s, and spreading disc speed 1200 rpm.

2.2. Experimental Design

2.2.1. Calibration Experiment for the Discharge Rate of the Spreading System

To systematically calibrate the system's discharge rate and evaluate the influence of centrifugal disc rotational speed, baffle opening, and particle diameter, a mixed-level orthogonal array was implemented. Rather than conducting an exhaustive 80-run full factorial matrix, this statistical approach was strategically chosen to maximize experimental efficiency while ensuring robust evaluation under diverse working conditions [31–33]. The specific operational parameters and their corresponding levels evaluated in this study are detailed in Table 4. To ensure the practical relevance of the spreading tests, the selected particle sizes reflect the typical size distribution of commercially available granular fertilizers, while the disc speeds and baffle openings encompass the effective adjustable range of the equipment during standard topdressing operations. The DJI T40 multi-rotor UAV, outfitted with the dispersal system, was secured to a test stand. The centrifugal disc rotational speed was established in five increments within the typical operational speed range: 400 rpm, 600 rpm, 800 rpm, 1000 rpm, and 1200 rpm. The Baffle opening was established at four gradients: 40%, 60%, 80%, and 100%. The particle diameter was established at four intervals: 1–2 mm, 2–3 mm, 3–4 mm, and greater than 4 mm. The experiment was performed on a stationary test bench established in the laboratory. The discharge rate was ascertained using timed measurements utilizing the UAV spreading system and its

integrated weighing sensor, which monitored the residual material mass in the hopper in real time. The mass of the fertilizer was measured using a high-precision electronic scale with an accuracy of 0.001 g.

Table 4. Experimental Factors and Levels.

Factors	Levels				
	1	2	3	4	5
A: Centrifugal disc speed/rpm	400	600	800	1000	1200
B: Baffle opening/%	40	60	80	100	/
C: Particle size/mm	1~2	2~3	3~4	>4	/

2.2.2. Optimization Experiment of UAV Operation Parameters

To investigate the effects of UAV flight height and centrifugal disc rotational speed on the spreading width of UAVs, field single-factor experiments were conducted combined with calibrated discharge rates to obtain the weight and quantity of samples at sampling points under different operation parameters. The specific experimental design is shown in Figure 3. Previous studies [14,25,34–36] have demonstrated that within the typical operational speed envelope of agricultural UAVs (e.g., 3–6 m/s), flight speed predominantly affects the longitudinal distribution of the granules. In contrast, the transversal spreading uniformity—the primary optimization objective of this study—is fundamentally dominated by the centrifugal disc speed and the flight altitude. From an operational perspective, UAV flight controllers typically couple the flight speed with the metering gate aperture to achieve precise, variable-rate matching. Consequently, maintaining a constant flight speed was a necessary experimental control to isolate the interactive effects of the mechanical discharge settings and altitude, ensuring the reliability of the established spreading model. Therefore, in this study, the flight speed was fixed at 5 m/s to focus on exploring the influences of the pneumatic flow field and centrifugal force on the deposition mechanism. When the spreading disc speed and UAV flight speed were constant, six different gradients of UAV flight height were set: 2 m, 3 m, 4 m, 5 m, 6 m, and 7 m. When the UAV flight speed and flight height were constant, five different gradients of spreading disc speed were set: 400 rpm, 600 rpm, 800 rpm, 1000 rpm, and 1200 rpm.

The field experiment was conducted in November 2024 at the National Precision Agriculture Research and Demonstration Base, Xiaotangshan Town, Changping District, Beijing, China (40°10′42.99″ N, 116°27′0.61″ E). To minimize the interference of dynamic environmental factors on the spatial trajectories of the fertilizer granules, all field tests were conducted under relatively stable meteorological conditions. Ambient wind speed was strictly monitored in real-time using an anemometer, and all spreading operations were restricted to periods with wind speeds below 2 m/s. The UAV spreading fertilizer operation scene is shown in Figure 5. Sample collection bags were arranged in the test area with a length of 26.8 m and a width of 12 m, and the application rate was determined to be 10 kg per mu. A total of 60 circular collection bags with a diameter of 30 cm were placed in a 6-row × 10-column arrangement. To precisely characterize the lateral distribution profile and effective swath width, collection trays were deployed transversally (perpendicular to the flight path) at 1 m intervals, ensuring localized deposition variations were fully resolved. Furthermore, to obtain statistically independent replicates and validate discharge consistency, these transversal lines were arrayed longitudinally at 5 m intervals. This 5 m longitudinal spacing guarantees the stabilization of the aerodynamic downwash and granular mass flow, effectively eliminating spatial autocorrelation. Figure 5 shows the schematic diagram of the UAV flight route and the layout of sampling points. The data from the single-factor experiment were used to figure out the spreading uniformity. This study

used a two-factor, four-level orthogonal experimental design ($L_{16}(4^2)$) to systematically look into how the laws of flight height and the speed of the centrifugal disc affect the uniformity of the spreading, as shown in Table 5. The ASABE S341.5 standard was used to judge the experimental indicators [22]. Range analysis was used to find the first and second order of how each factor affected the CV and the best operating conditions for UAV spreading.

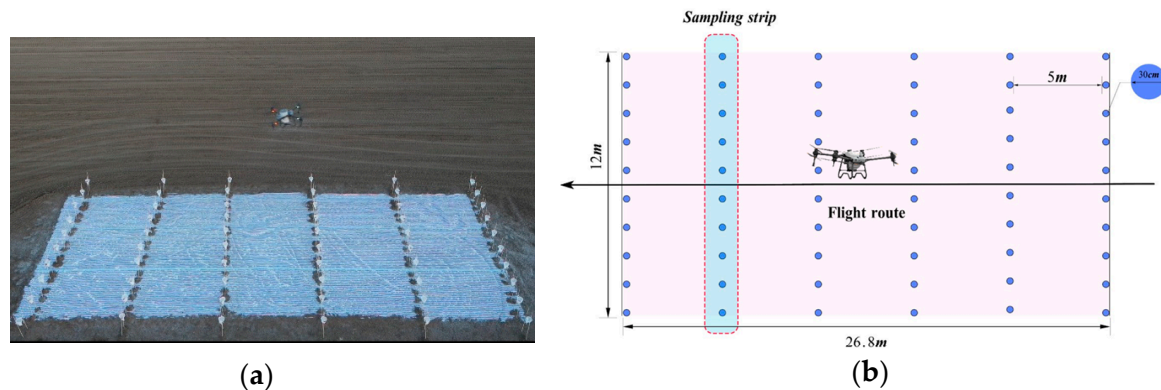


Figure 5. UAV Parameter Optimization Experiment. (a) Operation Process in Field Test Site. (b) Sampling Point Layout Scheme.

Table 5. Orthogonal Experiment Design.

Factors	Levels			
	1	2	3	4
A: Flight height/m	4	5	6	7
B: Centrifugal disc speed/rpm	600	800	1000	1200

2.3. Data Processing and Evaluation Indicators

According to the specific requirements for agricultural machinery performance in GB/T 5262-2008 General Provisions for Determining Test Conditions of Agricultural Machinery [37] and the test method for centrifugal spreaders specified in ISO 5690 [38], each treatment was repeated three times, and the average value of the three tests was taken. The CV of particle distribution was used as evaluation indexes for system performance. The CV was adopted to characterize the fertilizer application uniformity of the spreading system; the smaller the CV, the more uniform the spreading effect [39].

The CV can be calculated by the following formula [40,41]:

$$C_V = \frac{SD}{\bar{X}} \times 100\% \quad (1)$$

$$D = \left\{ \sum_{i=1}^n \left[(X_i - \bar{X})^2 \right] / (n - 1) \right\}^{\frac{1}{2}} \quad (2)$$

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i (i = 1, 2, 3, \dots, n) \quad (3)$$

where SD is the sample standard deviation, and $\bar{X}$ is the average mass of particles at sampling points.

The difference between the round-trip mode and the one-way mode is that the distribution patterns of adjacent flight paths are mirror-inverted. This can effectively offset the asymmetry caused by the rotation direction of the centrifugal spreading disc, as shown in Figure 6. According to the ASABE S341.4 standard and the common data processing logic

for agricultural machinery, the deposition rates from each flight path at the same coordinate point are accumulated in the overlap region:

$$M(x) = \sum_{n=0}^N f_n(x - nW) \quad (4)$$

where W is the set flight path spacing; the distribution of the first path is $f(x)$; the distribution of the second path is the left-right mirror-inverted pattern of $f(x - W)$; mirror inversion shall be performed for f_n when n is odd.

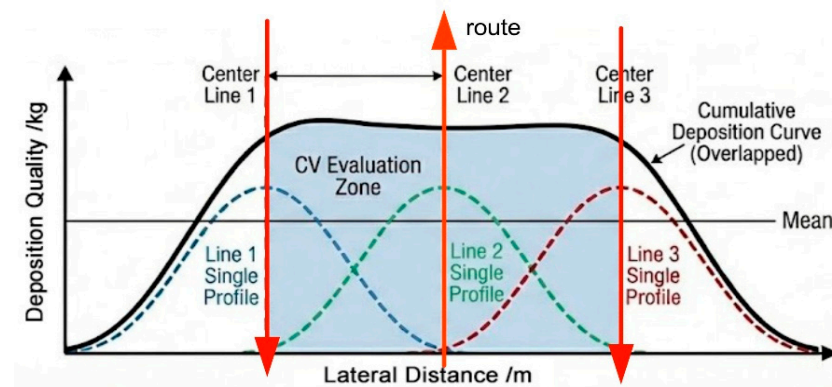


Figure 6. Schematic Diagram of Round-trip Flight Path Simulation and Superposition. The red arrows represent the flight route of the UAV.

It should be noted that this study primarily focused on evaluating and optimizing the transversal (side-to-side) spreading uniformity and swath overlap. To ensure the statistical reliability of the transversal data, multiple deposition sampling bands were arranged along the longitudinal flight path. The longitudinal spacing between these front-to-back sampling bands was sufficiently long to eliminate spatial autocorrelation, allowing each band to be treated as an independent replicate for statistical analysis.

A fertilizer application error represents the precision of spreading. The lesser the fertilizer application mistake, the more accurate the particle material distribution. The specific calculating formula is as follows:

$$\lambda = \frac{|M - G|}{G} \times 100 \quad (5)$$

where λ is the fertilizer application error per unit area, %; M is the total mass of fertilizer particles per unit area, g/m^2 ; G is the theoretical fertilizer application rate per unit area, g/m^2 .

This study uses Grey Relational Analysis (GRA) to look at the main factors that affect fertilizer application error and how they change, as well as to look at the influence weights of different operational parameters on fertilizer application error. The main idea is to figure out how close relationships are between different sequences by looking at how similar their geometric shapes are. The grey relational coefficient $\zeta(X_i)$ between each comparison sequence and the reference sequence can be calculated by the following formula:

$$\zeta_{0i} = \frac{\Delta(\min) + \rho\Delta(\max)}{\Delta_{0i}(k) + \rho\Delta(\max)} \quad (6)$$

where ρ is the distinguishing coefficient, which generally ranges from 0 to 1, and is usually taken as 0.5. $\Delta_{\min}$ denotes the second-stage minimum difference. $\Delta_{\max}$ denotes the two-stage maximum difference. $\Delta_{0i}(k)$ is the absolute difference between each point on the comparison sequence X_i curve and each point on the reference sequence X_0 curve.

The relational coefficient reflects the degree of correlation between each point in the comparison sequence and the reference sequence. However, the information is too scattered to facilitate an overall comparison. The formula for the relational degree r_i is as follows:

$$r_i = \frac{1}{N} \sum_{k=1}^N \zeta_i(k) \quad (7)$$

where r_i represents the grey relational degree of the comparison sequence X_i relative to the reference sequence X_0 .

Analysis of variance (ANOVA) was used to process the data for evaluating the CV and fertilizer application error. The overall mean was calculated first, followed by the sum of squares of between-group, within-group, and total variation. The degrees of freedom, mean square, and F-value were also calculated. Combined data analysis was performed using IBM SPSS Statistics 27.0 (IBM Corp., Armonk, NY, USA) and Origin 2021 (OriginLab Corporation, Northampton, MA, USA), including the establishment of orthogonal experimental tables and ANOVA. Specifically, the Shapiro–Wilk test was employed to verify the normality of the residuals, and Levene’s test was conducted to confirm the homoscedasticity (equality of variances) across the treatment groups. The results indicated that all data satisfied these prerequisite assumptions ($p > 0.05$). These statistical methods can effectively evaluate the significance of experimental results, help ensure rigorous scientific research, and improve the reliability and validity of the findings.

3. Results

3.1. Discharge Calibration and Rate Analysis of the Spreading System

To explore the dominant factors affecting the discharge rate of the spreading system and quantify the parameter weights, a multiple linear regression analysis was conducted. Initially, particle size, the percentage of baffle opening, and centrifugal disc speed were incorporated into the evaluation. However, centrifugal disc speed was subsequently excluded from the final regression equation due to its statistical insignificance. The established multiple linear regression model was statistically significant, with a highly significant regression equation ($F = 496.552$, $p < 0.001$). Ultimately, the particle size and the percentage of baffle opening collectively accounted for 94.0% of the variation in the dependent variable. As detailed in Table 6, this high explanatory power indicates excellent consistency between the empirical measurements and the fitted model, confirming the robust predictability of the system’s output.

Table 6. Results of Multiple Linear Regression Analysis.

	B	Beta	p	F	Adjusted R²	DW
Particle size	−0.156	−0.426	0.000	496.552 ***	0.940	2.048
Baffle opening	0.016	0.872	0.000			
Centrifugal Disc speed	2.661×10^{-5}	0.022	0.381			

Note: *** indicates an extremely significant difference at $p < 0.001$.

Statistical diagnostics confirmed residual independence (Durbin-Watson = 2.048) and no multicollinearity (Tolerance > 0.1). The analysis revealed that metering gate opening ($b = -0.156$, $\beta = -0.426$, $p < 0.001$) positively influenced the discharge rate, while particle size ($b = 0.016$, $\beta = 0.872$, $p < 0.001$) exerted a negative effect; centrifugal disc speed was statistically non-significant. As shown in Table 7, while larger particles generally resulted in a lower baseline mass flow rate compared to smaller particles, this size-induced difference did not disrupt the dominant increasing trend of the discharge rate driven by the enlarged gate opening. To quantitatively establish the mathematical relationship between

the operational parameters and the spreading performance, a multiple regression model was developed to assess the influence of each element on the discharge rate, incorporating opening degree, rotating speed, and average particle size. Designate the independent variables as particle size x_1 , baffle opening x_2 , and centrifugal disc velocity x_3 . According to the above multiple linear regression analysis, the opening degree had the most significant effect on the discharge rate, followed by particle size, while the effect of rotational speed was not statistically significant. Specifically, the variable of centrifugal disc speed was excluded from the final equation due to its statistical insignificance ($p = 0.381 > 0.001$) and negligible partial correlation ($B = 2.661 \times 10^{-5}$). Consequently, the final optimized regression model retained only particle size and metering gate opening as the significant predictors. The ultimate calibrated prediction equation for the discharge rate is as follows:

$$y = -0.156x_1 + 0.016x_2 + 0.181 \quad (8)$$

Table 7. Discharge Rate of Spreading System by Particle Size Range.

Baffle Opening%	The Spreading System Discharge Rate kg/s			
	1–2 mm	2–3 mm	3–4 mm	>4 mm
40	0.45	0.4	0.3	0.23
60	0.8	0.8	0.5	0.5
80	1.34	1.27	0.95	0.8
100	1.58	1.5	1.1	0.9

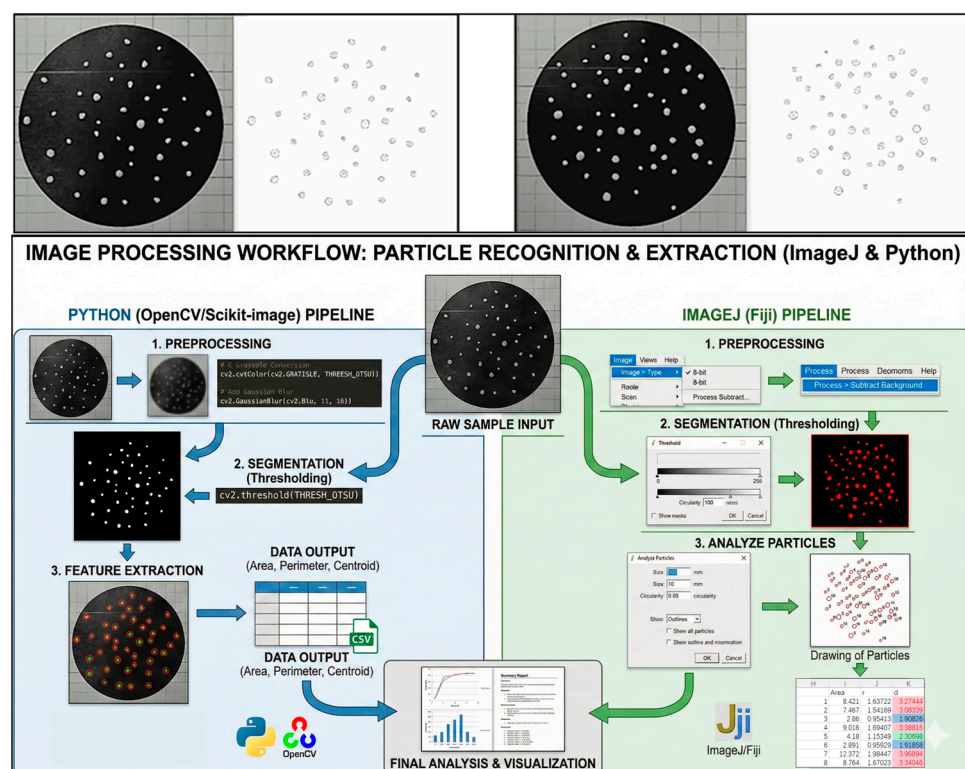
3.2. Analysis of Relative Error in Fertilizer Application Rate

To analyze the factors influencing fertilization error, we examined particle deposition from UAV spreading experiments. Collected samples were categorized by size (1–2, 2–3, 3–4, and >4 mm) and quantified using image recognition. To mitigate the adverse effects of variable ambient field lighting, granules from all sampling points were photographed under uniform indoor illumination. A total of 1800 sample images were acquired, and a dynamic thresholding technique was applied for image binarization to accommodate minor variations in particle size and color. Crucially, to address the challenges of particle occlusion and overlapping, the Hough transform and Watershed segmentation algorithm were implemented to effectively identify contours and separate adjacent granules. Evaluation results demonstrated a high average counting accuracy of 96.8%. Consequently, although residual image recognition errors inherently propagate into the calculation of the target application rate, this minor systematic uncertainty is strictly bounded and does not compromise the macroscopic evaluation of the application error.

The numerical proportion of particles of different sizes at each sampling point was calculated to characterize the spatial heterogeneity of particle size distribution in the deposition area, as shown in Table 8. Utilizing an automated image processing workflow in ImageJ 1.x and Python 3.12 (Figure 7), particle size distributions were quantified with a 97% recognition accuracy through standardized thresholding and macro batch processing. The target fertilizer application rate was then calculated by combining these size proportions with the calibrated discharge rates for each size range, whereas the actual application rate was directly monitored via the hopper-mounted weight sensor. The relative error of fertilizer application was then calculated using the fertilizer error formula, as shown in Figure 8.

Table 8. Proportions of particle size fractions under different operational parameters.

Height/m	Disc Speed/rpm	The Range of Particle Size			
		1–2 mm	2–3 mm	3–4 mm	>4 mm
2	800	4.673%	21.896%	8.011%	65.421%
	1000	0.852%	26.354%	53.743%	19.051%
	1200	1.824%	40.126%	46.352%	11.698%
3	800	4.618%	17.470%	7.229%	70.683%
	1000	1.033%	25.000%	55.096%	18.871%
	1200	2.583%	43.964%	41.550%	11.903%
4	800	2.208%	22.240%	8.044%	67.508%
	1000	1.344%	23.477%	53.763%	21.416%
	1200	2.413%	40.259%	44.379%	12.949%
5	800	4.409%	18.220%	61.065%	16.306%
	1000	1.114%	23.607%	51.976%	23.303%
	1200	1.855%	27.829%	51.484%	18.831%
6	800	0.543%	11.957%	67.174%	20.326%
	1000	0.528%	20.169%	54.065%	25.238%
	1200	1.154%	23.190%	51.626%	24.029%
7	800	1.111%	24.921%	55.635%	18.333%
	1000	0.703%	18.373%	52.610%	28.313%
	1200	4.643%	26.225%	50.215%	18.917%

**Figure 7.** Process of Particle Deposition Statistics and Analysis at Sampling Points.

While standard inferential statistics establish the primary significance of the operational parameters, Grey Relational Analysis (GRA) was employed as a supplementary non-parametric evaluation to quantify the geometric sequence similarity between these independent variables and the fertilizer application error, as shown in Table 9. To ensure analytical robustness and completely eliminate the dimensional discrepancies among the factors, range normalization (Min-Max scaling) was strictly applied to preprocess the raw data. Based on the range-normalized sequences, the calculated grey relational degrees were

0.724 for particle size, 0.573 for flight height, and 0.523 for rotational speed. These results indicate that, within the geometric bounds of the tested sequences, particle size exhibited the highest relational coupling with the application error. Consequently, while all three operational parameters contribute to the spreading accuracy, controlling the uniformity of the fertilizer particle size represents a critical pathway to mitigating severe fluctuations in application error during UAV operations.

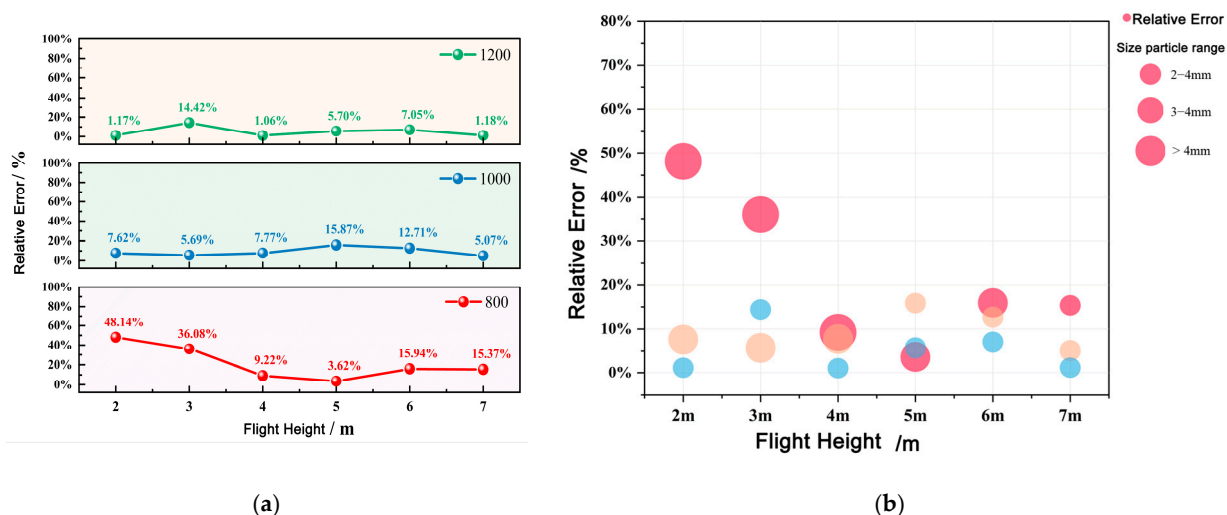


Figure 8. Influences of Various Factors on Relative Error in the Fertilization Process. (a) Fertilization Errors at Different Flight Heights and Centrifugal Disc Speeds. (b) Relationship Between Particle Size Range and Fertilization Error.

Table 9. Grey Relational Analysis Results of Different Calculation Methods.

Factors	Mean Normalization		Range Normalization	
	Relational Degree	Rank	Relational Degree	Rank
Flight Height	0.765	1	0.573	2
Particle Size	0.755	2	0.724	1
Centrifugal Disc Speed	0.749	3	0.523	3

3.3. Analysis of Particle Deposition Distribution Patterns

To further investigate deposition patterns and particle size segregation during UAV spreading, field experiments evaluated the deposition distributions across varying flight heights, centrifugal disc speeds, and size fractions, as shown in Figure 9. Crucially, the shape of the single-pass deposition curve dictates the uniformity of subsequent overlapping round-trip operations. Our findings reveal that the interactive effects of disc speed and flight height significantly alter the overall deposition profile. As UAV disc speed increases, the lateral deposition exhibits a symmetrical “M-shaped” double-peak. This central “hollow” phenomenon is likely exacerbated by rotor downwash and feeding port positioning [42,43], which create a divergence zone that limits particle deposition directly beneath the flight path. As UAV flight height increases, particle deposition transitions from a triangular to an M-shaped distribution, significantly expanding coverage. At flight heights of 6 m and above, a W-shaped curve emerges. While low speed and height can mitigate the “hollow” effect, they fail to meet the high-efficiency requirements of practical agriculture.

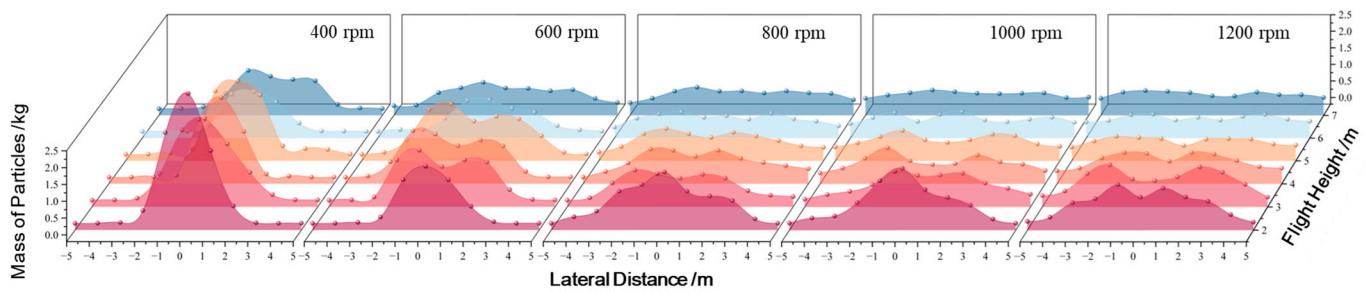


Figure 9. Particle deposition distribution curve for single-pass UAV operation.

As illustrated in Figure 10, a distinct radial size gradient characterizes the deposition area: smaller particles inherently concentrate near the central axis, whereas larger particles are propelled further outward. Particle spatial distribution is highly parameter-dependent. Initially, low altitudes and speeds yield a centrally dense distance-decay pattern across all size fractions. As altitude (5–7 m) and disc speed (>800 rpm) increase, the deposition profiles broaden laterally. Notably, while elevated parameters disperse smaller particles (1–2 mm), extreme speeds (1200 rpm) compromise their uniformity. Conversely, larger particles (>2 mm) develop multi-peak or banded distributions under these intensified settings, significantly improving spatial consistency and flattening the radial gradient.

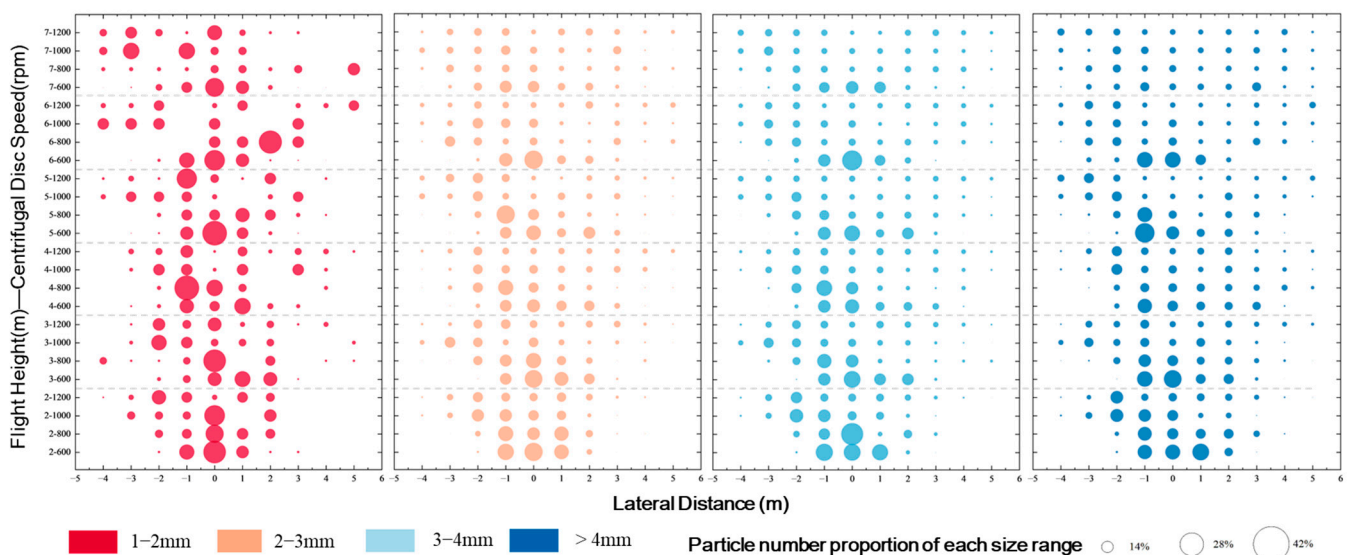


Figure 10. Distribution Proportion Chart of Particle Quantity in Different Size Ranges.

3.4. Operation Uniformity Analysis and Parameter Optimization

To quantify the interactive effects of flight altitude (H) and disc speed (n) on spreading uniformity, a quadratic polynomial regression model for the CV was established. The predictive equation is expressed as follows:

$$CV = 309.16 - 6.04H - 0.394n + 0.053H^2 + 0.0002n^2 - 0.0064(H \times n) \quad (9)$$

Statistical analysis indicated that the coefficient of determination R^2 and the adjusted R^2 (R^2_{adj}) were 0.93 and 0.91, respectively, suggesting that the model possesses high fitting precision and can explain 93% of the total variance in the experimental data. In the global significance test, the p -value of the F-test was significantly lower than 0.001, demonstrating that the joint effect of flight height and spreader speed on spreading uniformity is highly significant. To further evaluate the model's adequacy, a Lack-of-Fit test was conducted. The results yielded a p -value of 0.158 ($p > 0.05$) for the Lack-of-Fit term, indicating that

the lack-of-fit effect is non-significant. This confirms that the experimental error primarily stems from random fluctuations rather than structural deficiencies in the model; thus, the quadratic polynomial model is sufficient for accurately characterizing the nonlinear interaction between the operating parameters. Furthermore, at a 95% confidence level, the confidence intervals for all model coefficients did not encompass zero. Consequently, this model serves as an effective theoretical framework to guide the precise matching of broadcasting parameters in practical field operations.

To precisely determine the optimal UAV spreading parameters, an orthogonal experimental design was implemented using flight altitude (Factor A: 4–7 m) and disc rotational speed (Factor B: 600–1200 rpm). As detailed in Table 10, the range analysis (R) revealed that disc speed exerted a more dominant influence on the lateral spreading CV than flight altitude ($R_B > R_A$). Trend analysis of the mean evaluation indices (k_i) demonstrated that the CV decreased significantly with elevated rotational speeds, while exhibiting a milder downward trend alongside increasing flight altitude. Consequently, the optimal operational combination was identified as A_4B_4 , with altitude of 7 m and disc speed of 1200 rpm. Field validation under these specific conditions yielded a CV of 16.59%, which strictly satisfies the ASABE S341.4 standard for spreading uniformity.

Table 10. Range Analysis of Orthogonal Tests on Spreading Uniformity in Single Pass.

Factors	k1	k2	k3	k4	R	Rank
A: Flight Height (m)	61.45	51.18	49.09	28.7	32.75	2
B: centrifugal Disc Speed (rpm)	86.67	44.33	33.36	26.05	60.62	1

Note: k_i is the mean coefficient of variation (CV) at the i -th level of each factor. A smaller CV indicates more uniform spreading.

Following the ASABE S341.4 standard [22], round-trip fertilization was simulated to determine the CV and effective swath width (W_{eff}). Single-pass deposition patterns were mathematically overlapped across various route spacings, with W_{eff} defined as the maximum spacing that maintains a CV below 20% for agronomic viability (Figure 11). Furthermore, the 3D response surface (Figure 12) reveals significant interactions among flight height, disc speed, and deposition uniformity, showing that W_{eff} generally increases with both UAV flight height and centrifugal disc speed. At a 10 m spacing, the optimal overlapped distribution was achieved at a flight height of 7 m and a disc speed of 1200 rpm, yielding a CV of 13.79%. Under these conditions, the central deposition curve remains highly stable (CV < 15%), demonstrating strong anti-interference capability and confirming that edge overlapping effectively offsets declining single-pass margins.

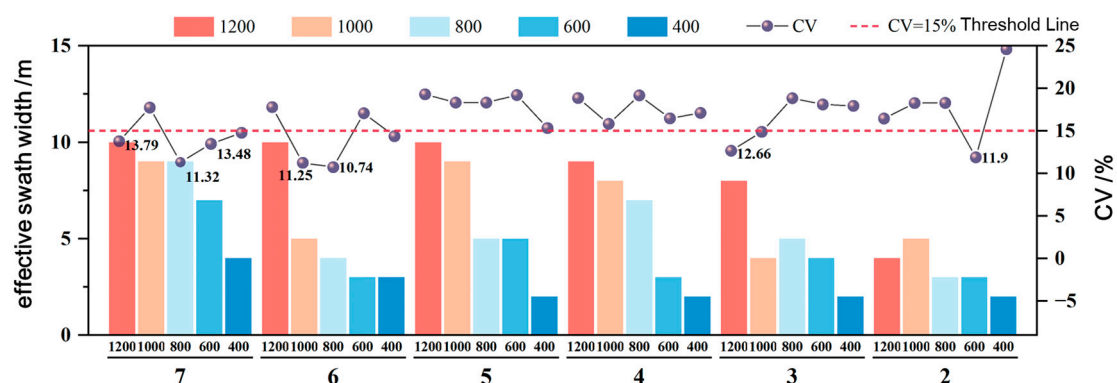


Figure 11. The effective swath width and CV of tested UAVs in different work parameters.

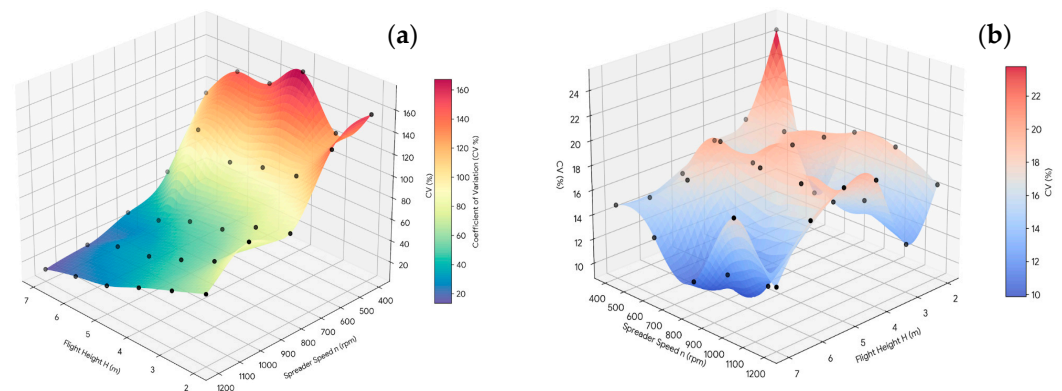


Figure 12. 3D response surface plots of CV for single route and multiple routes of UAV operations. (a) Single route; (b) Multiple routes. The black points indicate the actual experimental values of the coefficient of variation (CV) for UAV granular fertilizer application under various parameters.

4. Discussion

The motion behavior of granular fertilizer during spreading directly determines the distribution of deposition points, thereby affecting the effective swath width and uniformity of operation. For a multi-rotor UAV spreading system, the particle movement process is complex and can be divided into three measurable stages: (1) the acceleration stage on the spreading disc, quantified by particle initial velocity and contact forces extracted from DEM simulations; (2) the aerial flight stage after leaving the disc, characterized by the lateral dispersion radius and particle trajectories in the DEM model; and (3) the deposition stage disturbed by the rotor downwash, directly evaluated through the deposition density, effective swath width (W_{eff}), and coefficient of variation (CV) measured in field experiments [44]. The complex, nonlinear dependence of spreading uniformity on centrifugal disc speed and UAV flight height is fundamentally governed by the dynamic force balance of particles on the disc and their subsequent aerial trajectories. Beyond these internal operational parameters, external aerodynamic conditions also significantly influence deposition. To isolate the system's performance, ambient wind speeds in this study were strictly maintained below 2 m/s—conforming to standard UAV operational protocols—thereby minimizing environmental interference. Consequently, the rotor-induced downwash exerts a substantially greater impact on field deposition dynamics than ambient crosswinds [14]. This conclusion is corroborated by recent empirical investigations into UAV airflow interactions, which demonstrate that application deposition patterns are primarily dictated by operational parameters and canopy architecture, whereas terrain and ambient meteorological factors exert only a secondary influence [45]. Figure 13 illustrates the dynamic behavior of fertilizer particles on the rotating disc. The fertilizer particles were assumed to be homogeneous spherical particles, and inter-particle forces were neglected. Particles on the disc are subjected to gravity, the normal force from the disc, the friction force F_{fd} between the particle and the disc, the normal force from the vane, the friction force F_{fv} between the particle and the vane, centrifugal force F_{ce} , and Coriolis force F_{cor} . The force balance equation of particles along the vane direction was established as follows:

$$a = \omega^2 r (\cos(\beta) - \mu(\sin(\alpha) + \sin(\beta))) - \mu(g \cos(\alpha) + 2\omega v) \quad (10)$$

where a is the acceleration, β is the angle between the direction of motion and the centrifugal force, ω is the angular velocity, r is the distance from the particle to the center of the disc, and μ is the friction coefficient between the particle and the disc.

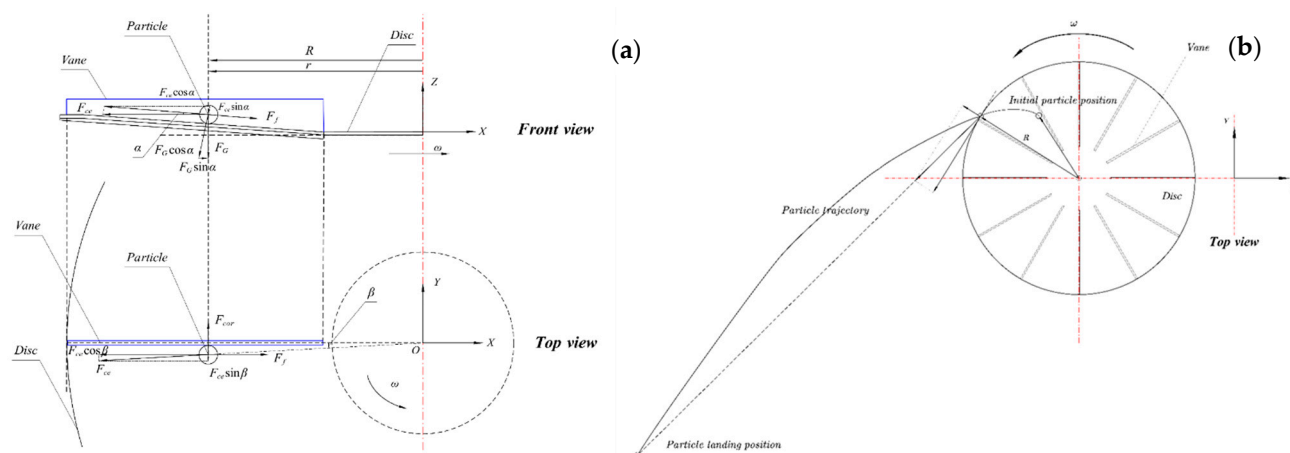


Figure 13. Mechanical analysis of fertilizer particles on the centrifugal spreading disc and kinematic analysis of their movement in the air after leaving the disc. (a) Motion of particles on the centrifugal disc; (b) Movement of particles in the air after leaving the centrifugal disc.

According to the equation of motion of particles on a rotating horizontal disc, the radial velocity v_r and tangential velocity v_t of particles at the instant they leave the disc can be expressed as: $v_r = \omega \sqrt{R^2 - R_0^2}$, $v_t = \omega R$, where ω is the angular velocity of the disc, and R is the radius of the disc. The resultant initial velocity of the particle $v_0 = \sqrt{v_r^2 + v_t^2}$ is directly dependent on the rotational speed n . This study discovered that as the rotating speed escalates from 400 rpm to 1200 rpm, the initial kinetic energy of the particles $E_k = \frac{1}{2}mv_0^2$ grows quadratically. At low altitudes, this substantial horizontal kinetic energy effectively overcomes air resistance, enabling particles to penetrate the intense rotor downwash. This mechanism mitigates the central accumulation that typically degrades uniformity, explaining the more stable and gradual decline in CV values at higher rotational speeds as altitude increases. The shift of the deposition curve from a triangular shape to “M-shaped” and “W-shaped” profiles reflects the dynamic interaction among the centrifugal force field, gravity field, and airflow field. When the height is low, the particle residence time in the air is short, and its lateral displacement $x = \int_0^t v_x(t)dt$ is limited, resulting in concentrated deposition. As the height increases to above 6 m, the modulation effect of the downwash airflow on the particle trajectory becomes more significant. In this study, we hypothesize that the “W-shaped” particle deposition distribution observed at an operating height of 6 m may be attributed to the classification effect of rotor downwash airflow on particles of different masses. At 6 m of flight height, the converging central airflow generated by the rotor might re-transport small particles with lower initial velocity back to the central area of the flight path, forming a third deposition peak. However, as no direct airflow measurements or CFD simulations were conducted, this aerodynamic interaction remains a theoretical proposition. When the operating height is increased to 7 m, the dissipation effect of airflow near the ground is enhanced, and the constraining effect of downwash airflow is relatively weakened. Particles achieve more uniform lateral spreading dominated by gravity, resulting in the minimum coefficient of variation of 16.59% at 1200 rpm. The 3D surface response plot (Figure 12) obtained using the response surface methodology (RSM) intuitively reveals the coupling relationship among operating parameters. Physically, the particle deposition pattern is mainly determined by the interaction between the centrifugal force field and the rotor downwash airflow. At low rotational speeds (<800 rpm), the instantaneous radial velocity of particles leaving the disc is relatively small, and their ability to overcome air resistance is weak. Particles tend to accumulate directly beneath the UAV under the vertical suppression of downwash airflow, forming a “central accumulation” and

thus leading to a significant increase in the coefficient of variation (CV). When the rotational speed is increased to approximately 1200 rpm, the initial kinetic energy acquired by the particles is substantially improved, and the horizontal throwing distance and effective coverage area are correspondingly increased. However, the relationship between disc speed and spreading quality is not monotonically linear. As statistically evidenced by the significant quadratic term of rotational speed in our regression model, excessively high speeds exacerbate the variance in particle kinetic energy and flight trajectory fluctuations, which ultimately degrades deposition uniformity. Therefore, an optimum speed range exists rather than a continuous improvement. Flight height also provides a compensation mechanism for this deposition uniformity. At higher operating heights of 6–7 m, the particle residence time in the air is prolonged, providing a sufficient physical buffer for trajectory redistribution after aerodynamic disturbance, perfectly balancing the high centrifugal kinetic energy. Compared with low-altitude operation at 2–4 m, high-altitude operation can effectively alleviate the sudden disturbance of the strong turbulent flow field of the rotor on the particle landing distribution.

Fertilizer particle size exerts a significant influence on both fertilizer discharge rate and deposition distribution. The rotational speed of the centrifugal disc determines the initial momentum of particles as they depart from it, while the flight height governs the residence time of particles in the air and the extent to which they are disturbed by the airflow field. Under identical outlet opening and rotational speed conditions, the discharge rate of small-sized fertilizer is generally higher than that of large-sized fertilizer. The higher discharge rate of small particles is primarily governed by their geometric interaction with the discharge orifice rather than intrinsic material flowability. Compared to larger granules, smaller particles experience less spatial restriction and have a significantly lower probability of mechanical interlocking or arching at the hopper gate. Consequently, smaller particles can pass through the fixed valve opening more efficiently, leading to a higher mass flow rate under the same gate opening conditions [46]. At small hopper openings, large particles experience significant discharge fluctuations due to transient bridging and clogging, caused by a low outlet-to-particle size ratio. Upon discharge, massive particles maintain stable trajectories due to their high inertia, effectively resisting rotor-induced turbulence. During low-altitude flights, strong rotor downwash restricts the deposition swath inward, concentrating the peak near the centerline. However, elevating the disc rotational speed imparts greater radial kinetic energy, enabling particles to overcome aerodynamic drag. This expands the lateral spread, transforming the deposition profile from a single central peak to a broad double peak. This dynamic induces distinct spatial segregation: large particles dominate the swath edges, whereas fine particles concentrate centrally, confirming the profound impact of particle size on deposition patterns [47]. Furthermore, increasing flight height prolongs aerial residence time, facilitating lateral diffusion and widening the effective swath. Although single-pass deposition is generally symmetric, a slight leftward skew is observed, likely driven by the coupled effects of disc rotation direction and crosswinds. In simulated overlapping round-trip operations, raising the flight height to 7 m reduced the coefficient of variation (CV) by 22.5% (yielding a CV of 13.79%) while strictly maintaining a 10 m working width. This optimized height enhances the uniform superposition of asymmetric patterns, confirming that appropriate rotor airflow clearance improves overall spreading performance [48]. Ultimately, these mechanisms reveal the root causes of fertilization errors: flight height acts as a fundamental threshold governing spreading quality—where insufficient height dictates systematic non-uniformity—while particle size discrepancies primarily drive extreme application errors. From a practical operational perspective, these statistical outcomes provide targeted guidance for UAV application. The result under mean normalization suggests that for routine pre-flight calibration, optimizing

and stabilizing the flight height is the most effective operator decision to improve the baseline, average spreading quality across the entire target area. Conversely, the result under range normalization highlights the critical risk posed by particle size variability. In actual field conditions, commercially available granular fertilizers often exhibit inconsistent physical properties. The range normalization indicates that such variability is the primary trigger for severe local errors. Therefore, to prevent extreme local misapplication, it is highly recommended that operators screen the fertilizer batch for size consistency prior to loading or implement adaptive adjustments to the metering mechanism when handling highly variable materials. Given that the central hollow phenomenon commonly occurs in field operations and that flight height is restricted in practice, relying solely on the adjustment of operating parameters presents certain limitations. Future studies may concentrate on the structural enhancement of the centrifugal disc. By improving the blade assembly scheme or designing a non-zero feeding angle, the challenge of spreading uniformity under low-altitude operation can be addressed from a hardware perspective.

Despite systematically optimizing UAV spreading parameters, this study has two main limitations. First, without direct airflow measurements or DEM-CFD simulations, specific micro-aerodynamic mechanisms (e.g., wake vortex re-transportation) remain hypotheses inferred from field deposition. Second, field trials were limited to optimal conditions (ambient wind < 2 m/s), leaving the impacts of variable crosswinds, complex terrains, and diverse fertilizer properties (e.g., irregular shapes) unexplored. Future research must integrate rigorous CFD modeling with multi-environment trials to develop a universally adaptable spreading system.

5. Conclusions

This study investigated the granular fertilizer spreading performance of a multi-rotor UAV. By integrating DEM simulations with field experiments, we systematically evaluated the effects of flight height, centrifugal disc speed, and particle size on deposition patterns. Based on application error and the coefficient of variation (CV) across single and overlapping swaths, the operational parameters were comprehensively optimized. The main conclusions are as follows:

(1) The deposition distribution of particles spread by UAV exhibits a nonlinear variation with flight height and centrifugal disc rotational speed. At constant flight speeds, low-altitude operations produce a distinct “M-shaped” bimodal distribution, causing a severe deposition deficit along the central flight path. Mechanistically, higher disc speeds exacerbate this central void by increasing the particles’ initial horizontal kinetic energy, whereas flight height dictates spreading uniformity by modulating aerial residence time and the extent of rotor-induced airflow disturbance.

(2) The influence of particle size on spreading stability was revealed. Large particles have greater inertia and more stable movement trajectories, leading to more uniform deposition; small particles are susceptible to airflow disturbance and tend to drift toward the central axis. Particle size uniformity is critical to ensuring spreading stability, and future research should focus on the development of adaptive compensation algorithms for particles of different sizes.

(3) This study identified the primary drivers of application error and established optimal operating parameters for the DJI T40 UAV. Flight height predominantly governs spreading uniformity, whereas particle size dictates system stability. The optimal operating parameters were determined in this study as a flight speed of 5 m/s, flight height of 7 m, and centrifugal disc speed of 1200 rpm. During overlapping swath operations, increasing the operating height from 6 m to 7 m at 1200 rpm can maintain a constant 10 m working width while reducing the CV from 17.8% to 13.79%.

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