

Article

Design and Test of a UAV-Based Oscillating-Tube Broadcasting Device

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Abstract

A multi-rotor UAV-based oscillating-tube broadcasting device incorporating replaceable material-specific screw metering units was developed for low-rate seed and granular-fertilizer application. The key structural parameters of the oscillating tube were screened through theoretical analysis and single-factor experiments using pre-germinated conventional Huanghuazhan rice. An L16(4³) orthogonal experiment was then conducted solely for exploratory screening of the main effects of flight height, forward speed, and broadcasting material on the single-pass broadcasting-uniformity coefficient of variation (CV_b) and effective spreading width (We). Forward speed significantly affected CV_b, whereas all three factors significantly affected We, with flight height showing the strongest effect. Separate two-factor central composite design experiments were subsequently conducted for conventional Huanghuazhan rice, hybrid Yongyou 12 rice, Yangguang 131 rapeseed, and Stanley compound fertilizer. Material-specific quadratic models were established, yielding model-recommended flight height and forward speed combinations of 3.04 m and 2.35 m s⁻¹, 2.79 m and 1.70 m s⁻¹, 3.00 m and 1.80 m s⁻¹, and 3.20 m and 2.25 m s⁻¹, respectively. These combinations represent constrained model-based recommendations rather than global or independently verified optima. In a limited consecutive-pass field demonstration, the field-sample coefficient of variation (CV_f) ranged from 13.76% to 20.34%, and the mean absolute pointwise deviation from the target count ranged from 15.11% to 19.05%. The results demonstrate the preliminary mechanical and operational feasibility of the prototype under the tested materials, operating settings, site, and environmental conditions.

Keywords: UAV; broadcasting device; rice; rapeseed; fertilizer; oscillating tube



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1. Introduction

Rice and rapeseed are important grain and oil crops in China and are widely cultivated in the middle and lower reaches of the Yangtze River. Sowing and fertilization for these crops traditionally require substantial field labor. With rapid economic development, however, the migration of rural workers to urban areas has led to severe labor shortages and increased labor costs during peak seasons, such as double-cropping and summer planting periods [1–3]. Farmers have therefore become increasingly interested in simplified direct-seeding techniques. Although mechanical direct seeding can substantially improve

operational efficiency, the adaptability of existing agricultural machinery remains insufficient under diverse topographical and soil conditions. In southern hilly and mountainous regions in particular, conventional mechanized operations are still constrained by high labor intensity, low operational efficiency, and inefficient resource use [4–6].

Recent advances in unmanned aerial vehicle (UAV) technology offer a practical way to ease these constraints. UAV-mounted broadcasting devices used in different agricultural production stages can overcome terrain and field constraints, thereby reducing operating costs and improving efficiency [7–10]. Owing to their high operational efficiency and relatively simple structural requirements, UAV-based broadcasting devices have therefore been studied more frequently [11,12].

Wu et al. designed a UAV-based centrifugal direct-seeding device for rice using a concave perforated disc and double-arc seed-pushing blades [13,14]. Zhou et al. developed a UAV-based fertilizer-spreading device and analyzed the effects of spreading-disc rotational speed and flight height on spreading performance; their results showed that UAV rotor airflow affected the spreading pattern [15]. Wang et al. designed a UAV-based pneumatic rice metering system that integrated a variable-pitch screw conveyor with a seed-metering device [16]. Shi et al. investigated the effects of forward speed, disc rotational speed, and vane inclination angle on the operational performance of disc broadcasting devices [17]. Song et al. developed a UAV-based rice broadcasting device and showed that flight height and forward speed significantly affected the effective spreading width [18]. In addition, Ren et al. investigated a fertilizer-compatible broadcasting device [19], Chen et al. designed a centrifugal broadcasting device equipped with a vertical screw [20], and Gao et al. developed a UAV-based centrifugal spinner-disc device for broadcasting green manure seeds [21].

Commercial UAV broadcasting systems commonly employ spinner-disc architectures. Such systems generally provide mature route automation, high payload capacity, and high operational throughput, although metering and calibration at very low application rates may remain dependent on material properties and the feeding mechanism [22–24]. The present study therefore evaluates an alternative metering-and-spreading architecture rather than claiming overall superiority over commercial equipment. A direct side-by-side comparison under the same UAV platform, broadcasting material, target application rate, and environmental conditions was beyond the scope of this study.

To investigate the feasibility of combining replaceable, material-specific screw metering with an oscillating tube for broadcasting rice, rapeseed, and granular fertilizer, a two-stage experimental procedure was adopted. First, the structural parameters of the key components were screened through theoretical analysis and single-factor experiments, and a three-factor $L_{16}(4^3)$ orthogonal experiment was conducted for exploratory main-effect screening. Subsequently, separate two-factor central composite design experiments were conducted for each broadcasting material using flight height, h , and forward speed, v , as quantitative factors, with the coefficient of variation, CV, and effective spreading width, W_e , as responses. The scope of inference is restricted to the tested materials, factor ranges, and operating conditions.

2. Materials and Methods

2.1. Overall Structure and Working Principle

The UAV-based oscillating-tube broadcasting device is illustrated in Figure 1a. The device consists mainly of a UAV platform (Xinhelike LT-15D Intelligent Agricultural Hexarotor UAV; Jiangxi Xinhe Lite Technology Collaborative Innovation Co., Ltd., Nanchang, China), a seed/fertilizer hopper, a screw trough, and a seed/fertilizer conveying screw. Its working principle is shown in Figure 1b. Seeds or granular fertilizer are stored in the hopper and

descend under gravity through the inlets on both sides of the screw trough. The conveying screw then transports the materials quantitatively from both sides to the rotating base. Subsequently, the seeds or fertilizer flow into the oscillating tube and are accelerated under the combined effects of gravity and oscillating inertial forces. Finally, the materials strike the particle-evening strip at the end of the oscillating tube and are broadcast into the field. Because the required application rates differ substantially among rice, rapeseed, and granular fertilizer, replaceable conveying screws were used to ensure stable delivery [25,26].

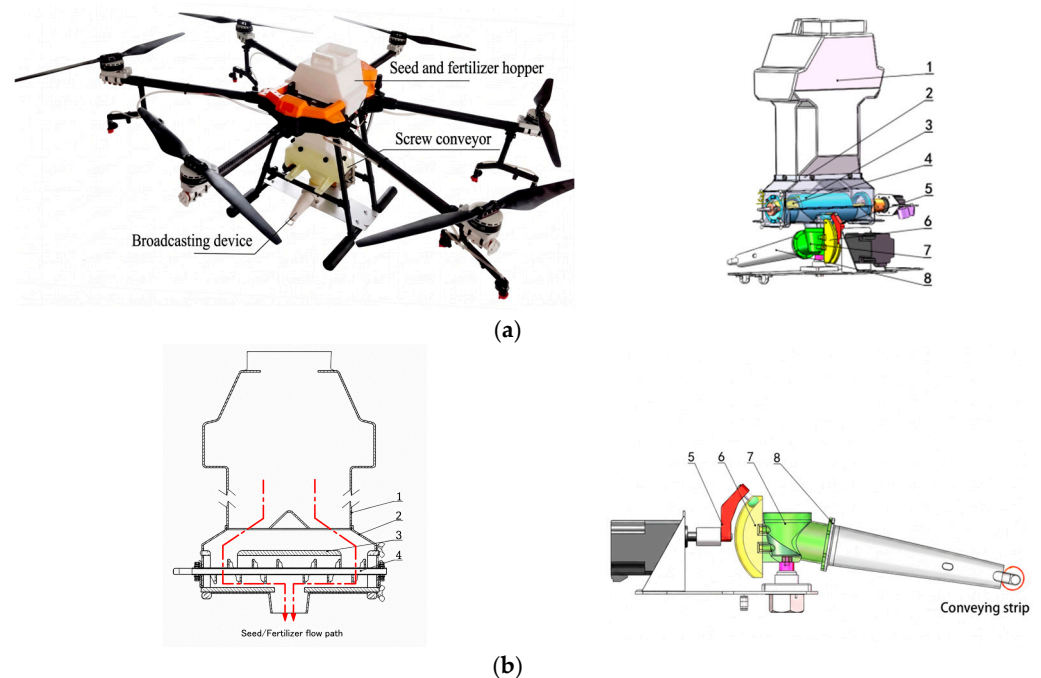


Figure 1. Structure and working principle of the UAV-based oscillating-tube broadcasting device: (a) overall structure; (b) working principle. 1. Seed/fertilizer hopper; 2. outer casing; 3. screw trough; 4. seed/fertilizer conveying screw; 5. crank arm; 6. arc-shaped slide rail; 7. rotating base; 8. oscillating tube. The red circle indicates the connection between the oscillating tube outlet and the conveying strip.

2.2. Design of Key Components

2.2.1. Design of the Conveying Screw

Based on the agronomic requirements for UAV broadcasting operations, the target application rates were 52.5 kg ha^{-1} for conventional rice, 30.0 kg ha^{-1} for hybrid rice, 7.5 kg ha^{-1} for rapeseed, and 300 kg ha^{-1} for basal compound fertilizer. These values correspond to the original local recommendations of 3.5, 2.0, 0.5, and 20.0 kg mu^{-1} , respectively ($1 \text{ mu} \approx 0.0667 \text{ ha}$). To meet the substantially different application-rate requirements, three types of screws and screw troughs were designed for combined use, as shown in Figure 2.

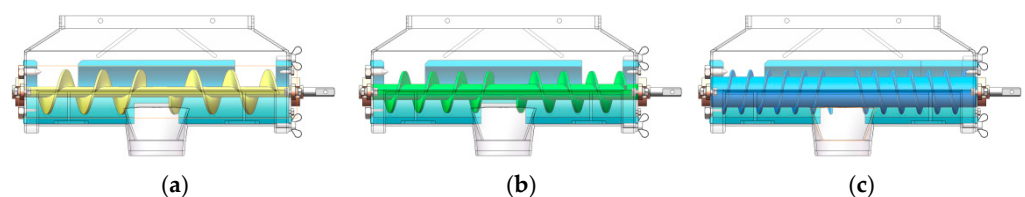


Figure 2. Schematic diagrams of the screw conveyors: (a) fertilizer conveying; (b) rice conveying; (c) rapeseed conveying.

Within the tested rotational-speed range, the discharge amount per revolution of the conveying screw varied only slightly, and the discharge amount was expected to maintain

a linear relationship with screw rotational speed. The theoretical formula for the discharge amount per revolution q is expressed as follows [27]:

$$\begin{cases} q = [\pi(D^2 - d^2)s/4 - bh_sL_p]\rho\varphi\eta \\ h_s = (D - d)/2 \\ L_p = \sqrt{[\pi(D + d)/2]^2 + s^2} \end{cases} \quad (1)$$

The areal application rate in SI units is calculated as follows:

$$Q_A = \frac{10^4 qn}{60vw} = 166.67 \frac{qn}{vw} \quad (2)$$

where q is the discharge mass per screw revolution (kg rev^{-1}); D and d are the outer and inner diameters of the conveying screw (m), respectively; s is the screw pitch (m); b is the flight thickness (m); h_s is the screw-flight depth (m); L_p is the average flight length (m); ρ is the bulk density (kg m^{-3}); φ is the filling coefficient; η is the sliding coefficient; n is the screw rotational speed (rev min^{-1}); v is the forward speed (m s^{-1}); w is the route spacing or working width (m); and Q_A is the areal application rate (kg ha^{-1}).

All quantities in Equations (1) and (2) are expressed in SI units, so the equations are dimensionally homogeneous and do not depend on a particular local area unit. As a complete numerical example, the experimentally determined discharge slope for conventional rice was $q = 0.0697 \text{ kg rev}^{-1}$. For $Q_A = 52.5 \text{ kg ha}^{-1}$, $v = 2.35 \text{ m s}^{-1}$, and $w = 8.03 \text{ m}$, Equation (2) gives $n = 60 Q_A vw / (10^4 q) = 85.3 \text{ rev min}^{-1}$, which lies within the tested 10–110 (rev min^{-1}) calibration range. The final controller setting was then checked by a stationary collection test.

The flight thickness b was set to 3 mm. For preliminary screw sizing, the filling coefficient φ and sliding coefficient η were both assigned an initial engineering value of 0.9, based on the design assumptions of near-full groove filling and limited axial slip in the short screw trough. These values were not regarded as universal material constants. The bulk densities ρ of rice, rapeseed, and fertilizer were 600, 680, and 860 kg m^{-3} , respectively [28]. Because φ and η may vary with particle geometry, surface moisture, feeding conditions, and operating parameters, the theoretical equations were used only to determine the initial structural parameters and rotational speed of the conveying screws.

Equation (1) shows that the predicted discharge per revolution is proportional to the product $\varphi\eta$. When the other coefficient is held constant, the normalized sensitivities are $S_\varphi = S_\eta = 1$. Changing either coefficient from 0.90 to 0.85 or 0.95 changes the predicted discharge per revolution by -5.56% or $+5.56\%$, respectively. Changing both coefficients simultaneously results in a variation of -10.80% to $+11.42\%$. To reduce the influence of this parameter uncertainty on the selection of operating conditions, the screw speed–discharge relationships were experimentally determined over 10–110 rpm, and the operating screw speed calculated using Equation (2) was subsequently calibrated against the measured relationship before the field experiments.

Based on these considerations, the parameters of the conveying screws were configured as follows: for fertilizer, $D_1 = 66 \text{ mm}$, $d_1 = 16 \text{ mm}$, and $s_1 = 50 \text{ mm}$; for rice, $D_2 = 57 \text{ mm}$, $d_2 = 22 \text{ mm}$, and $s_2 = 33 \text{ mm}$; and for rapeseed, $D_3 = 58 \text{ mm}$, $d_3 = 41 \text{ mm}$, and $s_3 = 23 \text{ mm}$.

2.2.2. Force Analysis of Particles in the Oscillating Tube

Particle motion in the oscillating tube was considered in two stages. The first stage was the accelerated motion of particles inside the tube, and the second stage was the broadcasting motion after the particles struck the particle-evening strip [29].

(1) First stage: Analysis of accelerated motion in the oscillating tube

To establish the kinematic model, the following assumptions were made: (1) the initial velocity of the particles entering the tube was zero; (2) no kinetic energy was transferred

among particles; and (3) the friction coefficient of the inner wall of the oscillating tube was uniform.

As shown in Figure 3, the force balance is written along the oscillating-tube axis. Let l denote the instantaneous particle displacement from the tube inlet ($0 \leq l \leq L$). The governing equation is:

$$m \frac{d^2 l}{dt^2} = mg \sin \alpha - \mu mg \cos \alpha + ml\omega^2 \cos \alpha \sin \theta \quad (3)$$

where m is the particle mass (kg); l is the instantaneous displacement along the oscillating tube (m); g is gravitational acceleration (m s^{-2}); α is the inclination angle of the oscillating tube ($^\circ$); μ is the sliding friction coefficient; ω is the instantaneous oscillation angular velocity (rad s^{-1}); and θ is the instantaneous oscillation phase angle (rad).

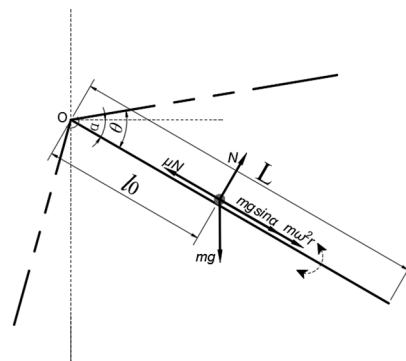


Figure 3. Schematic diagram of the force analysis of a broadcasting particle during accelerated motion. The dashed lines indicate the limiting positions of the oscillating tube during oscillation, and the included angle represents the oscillation angle.

Equations (3)–(5) use a phase-frozen quasi-static approximation in which ω and θ are treated as constant while a particle passes through the tube. Thus, the solution represents the instantaneous exit state at a specified phase rather than an average over a complete oscillation cycle. A cycle-resolved solution would require $\theta = \theta(t)$ and numerical integration of Equation (3).

Dividing Equation (3) by m , using $d^2 l / dt^2 = v(dv/dL)$, and integrating from $l = 0$ and $v = 0$ to an arbitrary position l gives:

$$\frac{1}{2} v^2 = g(\sin \alpha - \mu \cos \alpha) l + \frac{1}{2} \omega^2 l^2 \cos \alpha \sin \theta \quad (4)$$

At the tube outlet ($l = L$), the exit velocity is therefore:

$$v_0 = \sqrt{2gL(\sin \alpha - \mu \cos \alpha) + \omega^2 L^2 \cos \alpha \sin \theta} \quad (5)$$

where L is the length of the oscillating tube (m), and v_0 is the particle exit velocity (m s^{-1}).

Accordingly, this analytical model was used to identify the effects of L , ω , α , and θ on the mechanical discharge process, whereas the final structural and operational parameters were determined experimentally.

(2) Second stage: Analysis of broadcasting motion after striking the particle-evening strip

After acceleration, the particle strikes the particle-evening strip at a velocity of v_0 with a coefficient of restitution e ($0 \leq e \leq 1$), as illustrated in Figure 4. The following assumptions were used: (1) the impact was treated as a two-dimensional elastic collision; (2) aerodynamic drag was neglected; and (3) the particle followed a parabolic trajectory after the collision.

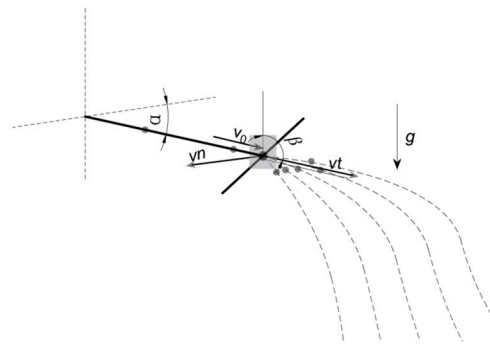


Figure 4. Schematic diagram of the collision and broadcasting analysis. The dashed curves indicate the trajectories of the broadcast material after impact with the conveying strip.

The post-collision velocity is resolved into the following components:

$$\begin{cases} v_x = v_0 \sin(\alpha - \beta) \cos \beta + e v_0 \cos(\alpha - \beta) \sin \beta \\ v_y = v_0 \sin(\alpha - \beta) \sin \beta - e v_0 \cos(\alpha - \beta) \cos \beta - g t \end{cases} \quad (6)$$

where e is the coefficient of restitution, and β is the collision contact angle ($^\circ$), and t is the time after impact (s).

The broadcast distribution depends on the initial collision velocity v_0 and the geometric parameters of the particle-evening strip. Therefore, the oscillating-tube parameters, including the tube length L , oscillation angular velocity ω , and inclination angle α , directly affect broadcasting uniformity.

After the particle leaves the tube, a simplified aerodynamic correction can be expressed as [30]:

$$m \frac{d\mathbf{v}_p}{dt} = m\mathbf{g} + \frac{1}{2} \rho_a C_D A_p |\mathbf{u}_a - \mathbf{v}_p| (\mathbf{u}_a - \mathbf{v}_p) \quad (7)$$

where ρ_a is air density (kg m^{-3}), C_D is the drag coefficient, A_p is the particle projected area (m^2), $\mathbf{v}_p$ is particle velocity, and $\mathbf{u}_a$ is the local air velocity.

Setting $\mathbf{u}_a = 0$ represents still-air drag, whereas a spatially varying $\mathbf{u}_a$ can represent UAV rotor-induced airflow. In the present study, the three-dimensional rotor airflow was not measured or coupled with the particle model; therefore, Equations (3)–(6) describe only the mechanical discharge and the initial post-impact state. Actual downwash effects were included only through the UAV performance and field verification experiments. A coupled CFD–particle model is required for airflow-resolved trajectory prediction.

2.3. Experimental Design

2.3.1. Stability of Screw Conveying Test

To evaluate the discharge stability of the screw conveyor, conventional Huanghuazhan rice (Rice Research Institute, Guangdong Academy of Agricultural Sciences, Guangzhou, China), hybrid Yongyou 12 rice (Ningbo Seed Co., Ltd., Ningbo, China), Yangguang 131 rapeseed (Oil Crops Research Institute, Chinese Academy of Agricultural Sciences, Wuhan, China), and Stanley compound fertilizer (Stanley Agriculture Group Co., Ltd., Linyi, China) were selected as the experimental materials. The physical properties of the four materials, determined experimentally in this study or obtained from relevant literature, are summarized in Table A1 in Appendix A. The source of each parameter is clearly identified in the table. Values measured in this study are labeled accordingly, whereas literature-derived values are accompanied by the corresponding references. Both rice materials were pre-germinated until embryo protrusion, with measured moisture contents of approximately 30%. Screw rotational speed was varied from 10 to 110 rev min^{-1} .

at intervals of 10 rev min^{-1} , and the discharged mass within 1 min was measured at each speed level. The experimental test bench is shown in Figure 5.

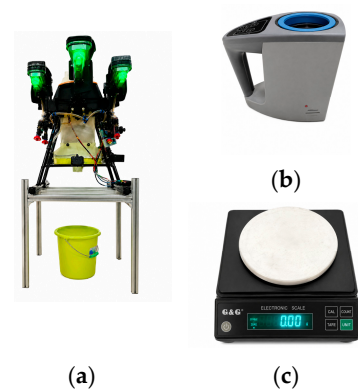


Figure 5. Screw conveyor stability test: (a) experimental test bed; (b) grain moisture meter; (c) electronic balance.

The metering-rate coefficient of variation, CV_m , was used to evaluate the repeatability and stability of screw discharge and was calculated as follows:

$$CV_m = \frac{\sqrt{\frac{\sum_{i=1}^{n_m} (M_i - \bar{M})^2}{n_m - 1}}}{\bar{M}} \times 100\% \quad (8)$$

where CV_m is the metering-rate coefficient of variation; M_i is the discharge mass measured in the i -th repetition, g; $\bar{M}$ is the mean discharge mass, g; and n_m is the number of repeated discharge measurements.

2.3.2. Single-Factor Experiment of the Oscillating Tube

Conventional Huanghuazhan rice that had been pre-germinated until embryo protrusion was selected to test the performance of the oscillating tube on the test bed. Collection boxes measuring $50 \text{ cm} \times 50 \text{ cm}$ (length $\times$ width), were arranged as 6 rows $\times$ 15 columns, providing a fixed lateral sampling width of 7.5 m (Figure 6). The tube outlet was 2.0 m above the ground, the screw rotational speed was $40 \text{ (rev min}^{-1}\text{)}$, and the broadcasting duration was 1 min. During each single-factor series, only the factor under investigation was varied; the other three factors were held at the third levels in Table 1: inclination angle $\alpha = 20^\circ$, tube length $L = 200 \text{ mm}$, oscillation angle $\beta = 70^\circ$, and oscillation frequency $\gamma = 3.0 \text{ Hz}$.

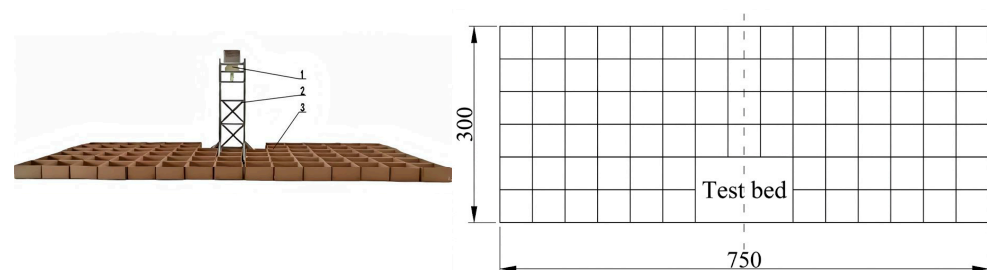


Figure 6. Layout of collection boxes: 1. broadcasting device; 2. Fixed-height frame; 3. collection box. All dimensions in the layout are in centimeters. The dashed line indicates the centerline of the test bed.

Table 1. Factor levels of the bench test.

Factor	Level					
Inclination angle of the oscillating tube α (°)	0	10	20	30	40	50
Length of the oscillating tube L (mm)	100	150	200	250	300	350
Oscillation angle of the oscillating tube B (°)	50	60	70	80	90	100
Oscillation frequency γ (Hz)	2	2.5	3	3.5	4	4.5

The inclination angle, length, oscillation angle, and oscillation frequency of the oscillating tube were selected as the four factors listed in Table 1. According to NY/T 3881-2021, the single-pass broadcasting-uniformity coefficient of variation, CV_b , was retained as the primary evaluation index, and $CV_b \leq 45\%$ was regarded as acceptable for rice, rapeseed, and granular fertilizer [31]. For each lateral column, the deposited amount was calculated as the arithmetic mean of the six collection boxes aligned in the flight direction. The single-pass broadcasting-uniformity coefficient of variation was calculated across the lateral columns as follows:

$$CV_b = \frac{\sqrt{\frac{\sum_{j=1}^{n_b} (X_j - \bar{X})^2}{n_b - 1}}}{\bar{X}} \times 100\% \quad (9)$$

where CV_b is the single-pass broadcasting-uniformity coefficient of variation; X_j is the mean deposited amount in the j -th lateral column; $\bar{X}$ is the mean deposited amount across all evaluated lateral columns; and n_b is the number of lateral columns included in the calculation. In the single-factor experiment, $n_b = 15$.

For each lateral column, the deposited amount was calculated as the arithmetic mean of the six boxes aligned in the flight direction; no lateral interpolation or extrapolation was applied. The mean deposited amount used for the width threshold was calculated over the fixed 15-column sampling domain rather than over a variable tail length. Effective spreading width, We , was defined as the full left-to-right width between the outer edges of the contiguous collection-box interval containing the deposition centroid and meeting the 50% mean-deposition criterion; We is therefore a full width, not a centerline-to-edge half-width. When the qualifying deposition reached an outermost column, $We = 7.5$ m was reported as a right-censored minimum estimate rather than an exact width.

To estimate the effect of consecutive parallel passes using the measured single-pass data, the route spacing, S , was set equal to the corresponding effective spreading width, We . For a measured single-pass lateral deposition profile $m(x)$, the accumulated deposition at the j -th lateral sampling position was calculated by periodically superimposing the profiles of the current and adjacent passes:

$$M(x_j) = \sum_k m(x_j - kS) \quad (10)$$

where $M(x_j)$ is the accumulated deposition at lateral position X_j , $m(x)$ is the measured single-pass deposition profile, S is the route spacing, and k is an integer identifying the current and adjacent passes. In practice, only passes whose measured deposition profiles overlapped the evaluated interval were included in the summation.

The multiple-pass broadcasting-uniformity coefficient of variation, CV_{mp} , was then calculated over one representative route-spacing interval as follows:

$$CV_{mp} = \frac{\sqrt{\frac{\sum_{j=1}^{n_{mp}} (X_j - \bar{X})^2}{n_{mp} - 1}}}{\bar{X}} \times 100\% \quad (11)$$

where X_j is the accumulated deposited amount at the j -th lateral position, $\bar{X}$ is the mean accumulated deposited amount, and n_{mp} is the number of lateral positions included in the representative route-spacing interval.

Values of $m(x)$ outside the measured lateral domain were assigned a value of zero because no experimental observations were available beyond the sampling boundaries. Consequently, results obtained for cases in which $We = 7.5$ m should be regarded as sampling-domain-limited estimates rather than exact multiple-pass performance values. The original single-pass CV_b values were retained to allow direct comparison with the calculated multiple-pass CV_m values.

2.3.3. Orthogonal and Material-Specific CCD Performance Experiments

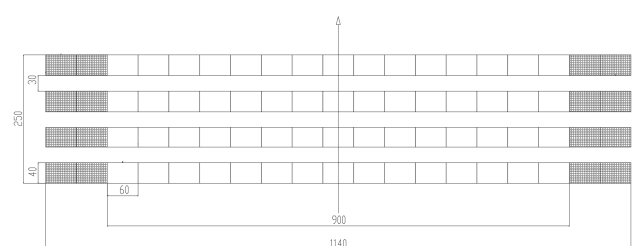
A performance test was conducted to assess whether the oscillating-tube device could broadcast rice, rapeseed, and fertilizer and to identify suitable parameter combinations. Flight height, forward speed, and broadcasting material were selected as the main influencing factors.

Conventional Huanghuazhan rice, hybrid Yongyou 12 rice, Yangguang 131 rapeseed, and Stanley compound fertilizer were selected as the experimental materials. The rice seeds were pre-germinated until embryo protrusion, and their surface moisture content was controlled at $30 \pm 2\%$.

The experiments were conducted at Jiangxi Agricultural University on 25 December 2024. The available field note classified the wind as a northeast Beaufort force 1 breeze (approximately $0.3\text{--}1.5\text{ m s}^{-1}$); instrumented mean wind speed, gust speed, temperature, relative humidity, rotor speed, payload, and flight-state fluctuations were not recorded. Collection boxes ($60\text{ cm} \times 40\text{ cm}$) were arranged in a $4\text{-row} \times 15\text{-column}$ grid. The 0.60 m dimension was lateral to the flight direction, giving a fixed sampled width of 9.0 m . To minimize bouncing, each box contained a 2 cm layer of moist soil and was placed on a rigid plastic stool 25 cm high. Boxes in the same row were adjacent, row spacing was 30 cm , and a 10-m take-off and landing buffer zone was reserved at each end of the collection area (Figure 7).



(a)



(b)

Figure 7. Experimental setup of the UAV broadcasting performance test: (a) experimental site; (b) standard and extended collection-box layouts. The central 9.0 m domain was used for CV_b calculation, while the shaded boxes represent the additional collection boxes used to determine the complete effective spreading width, We . All dimensions are in centimeters. The arrow indicates the forward direction of the machine.

For operating conditions in which the deposition profile reached the outermost boxes of the 9.0 m central grid, additional collection-box columns were arranged laterally beyond the original boundaries to capture the complete deposition profile. Depending on the observed profile extent, two additional columns were added on the left side and two additional columns were added on the right side. The resulting total lateral measurement width was 1.14 m. The number of additional columns and the total measurement width used for each affected run are provided in Table S25 of the Supplementary Materials.

The performance test was conducted as a single-pass experiment so that the effects of flight height, forward speed, and broadcasting material could be evaluated without the confounding effect of overlap between adjacent flight paths. For each lateral sampling position, the deposited amounts collected by the four boxes aligned in the flight direction were averaged to obtain the corresponding lateral deposition value.

To ensure consistency and comparability among all experimental runs, the single-pass broadcasting-uniformity coefficient of variation, CV_b , was calculated using Equation (9) and only the original 15 central columns, corresponding to the fixed 9.0 m central sampling domain. For each lateral column, the deposited amount was calculated as the arithmetic mean of the four collection boxes aligned in the flight direction. Therefore, $n_b = 15$ for all $L16(4^3)$ and material-specific CCD runs. The additional lateral collection boxes were used exclusively to determine the complete effective spreading width, We , and were not included in the CV_b calculation.

The effective spreading width was determined from the complete measured lateral deposition profile according to the effective-width criterion defined above. For runs in which the profile extended beyond the original central domain, the measurements from the additional lateral boxes were included when determining We . No lateral interpolation or extrapolation was used. Therefore, the reported effective spreading widths of 9.2 and 9.4 m were directly measured continuous responses rather than estimated or right-censored values.

Flight height, h , forward speed, v , and broadcasting material, B , were arranged in a 16-run $L16(4^3)$ orthogonal design using the four levels presented in Table 2. The orthogonal experiment was used for exploratory screening of the main effects of the three factors and was not used to fit the subsequent material-specific quadratic models.

Table 2. Coding of experimental factors.

Code	Factor		
	Flight Height, h (m)	Forward Speed, v ($m \cdot s^{-1}$)	Broadcasting Material, B
1	2.00	1.00	Conventional Huanghuazhan rice
2	2.50	2.00	Hybrid Yongyou 12 rice
3	3.00	3.00	Yangguang 131 rapeseed
4	3.50	4.00	Stanley compound fertilizer

The single-pass coefficient of variation, CV_b , and effective spreading width, We , were used as the evaluation indices. A lower CV_b and a larger We indicated better broadcasting performance. An effective spreading width of at least 6 m was retained as an engineering reference, and $CV_b \leq 45\%$ was adopted as the applicable uniformity criterion. Because all We values exceeding 9.0 m were directly obtained from the extended lateral collection arrangement, they were treated as exact continuous observations in the range analysis and ANOVA of the $L16(4^3)$ experiment.

The L16(4³) data were analyzed using a main-effects-only fixed-effects model. Flight height, h , and forward speed, v , were treated as quantitative linear factors, whereas broadcasting material, B , was treated as a four-level categorical factor. The statistical model was expressed as:

$$Y_{ijk} = \beta_0 + \beta_1 h_i + \beta_2 v_j + \tau_k + \varepsilon_{ijk} \quad (12)$$

where Y_{ijk} represents the observed single-pass broadcasting-uniformity coefficient of variation, CV_b , or effective spreading width, We ; β_0 is the intercept; β_1 and β_2 represent the linear effects of flight height and forward speed, respectively; τ_k represents the categorical effect of the k -th broadcasting material; and ε_{ijk} is the residual error. The $h \times v$, $h \times B$, and $v \times B$ interaction terms were not included because the unreplicated L16(43) design did not provide sufficient independent information to estimate the complete two-factor interaction structure without aliasing. Therefore, the orthogonal experiment was used only for exploratory main-effect screening.

Based on the exploratory results of the L16(4³) orthogonal experiment, flight height, h , and forward speed, v , were selected as the quantitative factors for the subsequent response-surface experiments. Broadcasting material was treated as a categorical factor and was investigated separately through independent material-specific CCD experiments.

Separate two-factor central composite design experiments were conducted independently for conventional Huanghuazhan rice, hybrid Yongyou 12 rice, Yangguang 131 rape-seed, and Stanley compound fertilizer, using CV_b and We as the responses. Each CCD comprised four factorial points, four axial points, and six independently replicated center points, resulting in 14 runs for each material. The center-point replicates were used to estimate pure error and assess model lack of fit.

All We values used in the material-specific CCD models were obtained from directly measured lateral deposition profiles. When the deposition profile reached the boundary of the original 9.0 m central domain, the extended lateral collection arrangement was used to determine the complete effective spreading width. These values were therefore included as exact continuous responses in the quadratic regression analyses. For all CCD runs, CV_b was calculated consistently using the original 9.0 m central sampling domain.

The coded and actual factor levels used for Stanley compound fertilizer are presented in Table 3. The complete CCD matrices, run orders, point types, coded and actual factor levels, run-level CV_b and We responses, replicate information, and details of the extended collection arrangements are provided in the Supplementary Materials. Separate quadratic models were fitted for each material and response using Design-Expert 13.0. Model adequacy was evaluated using analysis of variance, model significance, lack-of-fit tests, coefficients of determination, and residual diagnostics.

Table 3. Coded and actual levels of the factors used in the CCD experiment for Stanley compound fertilizer.

Factor	−1.414	−1	0	1	1.414
Flight height, h (m)	1.793	2.000	2.500	3.000	3.207
Forward speed, v (m·s ^{−1})	0.379	1.000	2.500	4.000	4.621

Note: The complete CCD ranges were 1.793–3.207 m for flight height and 0.379–4.621 m s^{−1} for forward speed. For numerical optimization, conservative operational constraints of 2.0–3.2 m and 1.0–4.0 m s^{−1}, respectively, were imposed. All axial and factorial CCD points were retained for quadratic-model fitting.

For subsequent numerical optimization, the factor constraints were defined separately for each broadcasting material according to its corresponding CCD domain. For Stanley compound fertilizer, conservative operational constraints of $2.0 \leq h \leq 3.2$ m and $1.0 \leq v \leq 4.0$ m s⁻¹ were used. These operational constraints lie entirely within the full fertilizer-specific CCD ranges of 1.793–3.207 m for flight height and 0.379–4.621 m s⁻¹ for forward speed. The axial CCD points outside these conservative operational constraints were retained for model fitting but were not included in the numerical-optimization search region.

2.3.4. Field Verification Experiment

A limited field demonstration was conducted on 28 October 2025 after rotary tillage and land preparation, as shown in Figure 8. The available field note classified the wind as Beaufort force 2 (approximately 1.6–3.3 m s⁻¹). Instrumented wind statistics, temperature, humidity, rotor speed, payload, and actual flight-height and speed fluctuations were not recorded. The test therefore demonstrates operation only under the documented site and weather category and is not an independent validation of a response-surface model.



Figure 8. Field experiment: (a) operation site; (b) data collection.

The field boundaries were planned using the UAV remote controller, and the field was covered using consecutive parallel passes. Route spacing and forward speed were set according to the model-recommended operating conditions obtained from the material-specific CCD analysis, and screw rotational speed was calculated using Equation (2) and calibrated by stationary collection. Five 0.16-m² sampling areas were distributed within the treated field. Because the complete lateral distribution and effective width were not remeasured and independent flights were not replicated, the resulting CV_f values represent a limited practical multiple-pass demonstration rather than statistical model validation.

3. Results

3.1. Results and Analysis of the Screw Conveying Stability Test

The results are presented in Figure 9. Within the screw rotational speed range of 10–110 rpm, the CV of the metering rate for conventional Huanghuazhan rice, hybrid Yongyou 12 rice, Yangguang 131 rapeseed, and Stanley compound fertilizer ranged from 0.25% to 1.11%, 0.28% to 1.60%, 0.20% to 1.55%, and 0.51% to 2.10%, respectively. The CV of the metering rate did not exceed 1.60% for rice and rapeseed and was no greater than 2.10% for fertilizer. These values met the requirements for discharge stability specified in NY/T 3881-2021 (Technical Specification for Quality Evaluation of Remote-Control Flying Seeders): rice $\leq 2.6\%$, rapeseed $\leq 2.6\%$, and granular fertilizer $\leq 7.8\%$. In addition, the linear regression results in Figure 9a indicate that the discharge amounts of rice, rapeseed,

and fertilizer all had highly significant linear relationships with screw rotational speed ($p < 0.001$). Together, these results show that the device can provide a stable material supply for UAV broadcasting operations.

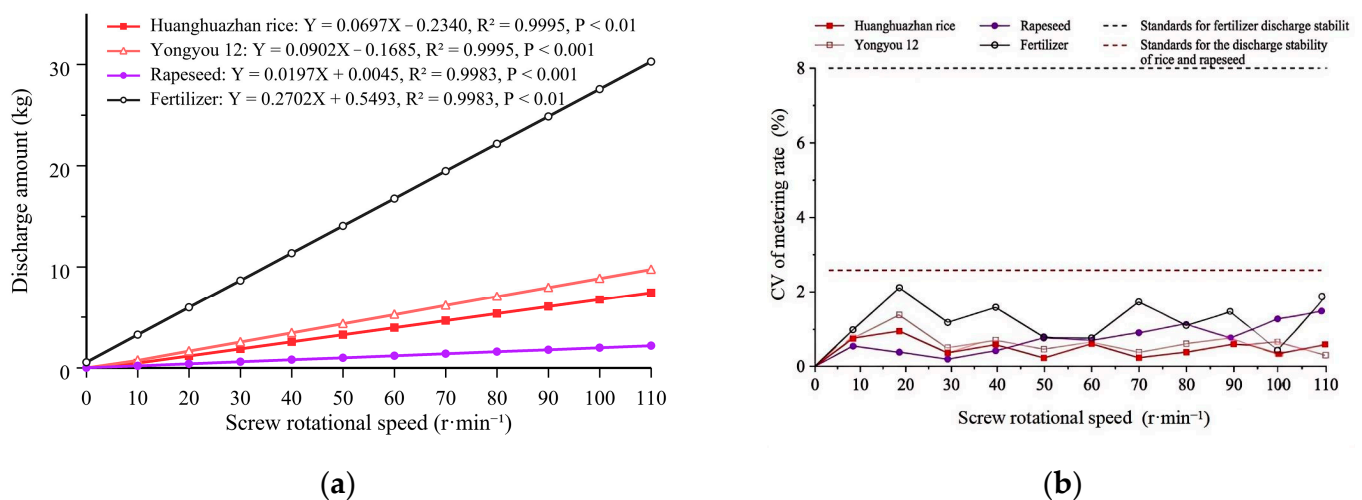


Figure 9. Experimental results and statistics: (a) linear response relationship between screw rotational speed and discharge amount; (b) stability of discharge amount at different screw rotational speeds.

3.2. Results and Analysis of the Single-Factor Experiment on the Oscillating Tube

The measured lateral deposition profiles, profile-based single-pass broadcasting-uniformity coefficients of variation (CV_b), calculated multiple-pass broadcasting-uniformity coefficients of variation (CV_{mp}), and effective spreading widths (We) are shown in Figure 10. Route overlap reduced broadcasting nonuniformity under most settings. For example, at $\alpha = 10^\circ$, the single-pass CV_b of 21.92% was reduced to a calculated CV_{mp} of 16.67%; at $\gamma = 4.5$ Hz, the CV_b of 35.19% was reduced to a CV_{mp} of 30.96%. However, route overlap could worsen uniformity when edge peaks from adjacent swaths were aligned. The CV_b and corresponding CV_{mp} were 13.53% and 20.41%, respectively, at $\alpha = 40^\circ$; 50.83% and 61.31%, respectively, at $L = 350$ mm; and 33.32% and 34.54%, respectively, at $\gamma = 4.0$ Hz. Therefore, route spacing should be selected based on the complete lateral deposition profile rather than on We alone.

At the finally selected levels, the one-factor overlap calculations gave CV_{mp} values of 16.67% for $\alpha = 10^\circ$, 36.69% for $L = 250$ mm, 41.73% for $\beta = 100^\circ$, and 34.54% for $\gamma = 4.0$ Hz. These values were obtained from separate one-factor series in which the other variables were fixed at their reference levels. Therefore, they cannot be combined to predict the multiple-pass CV_{mp} of the selected four-factor configuration. No separate four-factor bench confirmation was conducted. The selected structural configuration was subsequently used in the UAV performance and field experiments; however, the field results should be interpreted only as a limited practical demonstration rather than as an independent validation of the calculated overlap CV_{mp} .

Considering both single-pass and overlap behavior, the engineering starting settings were selected as $\alpha = 10^\circ$, $L = 250$ mm, $\beta = 100^\circ$, and $\gamma = 4.0$ Hz. The selected combination should be interpreted as a screened engineering configuration rather than as a statistically optimized four-factor solution.

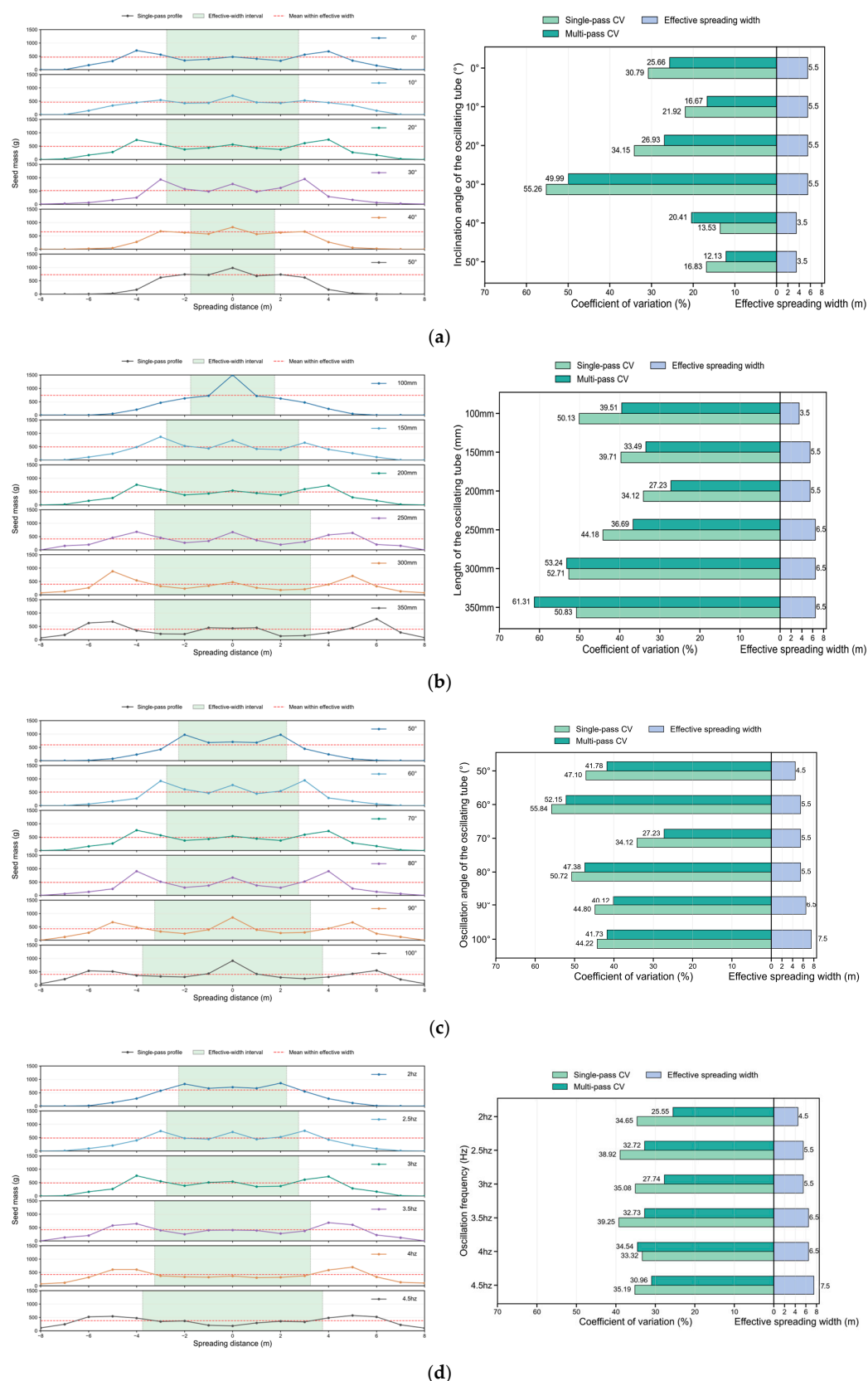


Figure 10. Results of the single-factor experiment on the oscillating tube: (a) inclination angle of the oscillating tube; (b) length of the oscillating tube; (c) oscillation angle of the oscillating tube; (d) oscillation frequency. In each lateral deposition-profile panel, the shaded band indicates the reported full effective-width interval, and the red dashed line indicates the mean deposition calculated from the sampling positions within that interval. The summary panels present the profile-based single-pass CV, the calculated multiple-pass CV at $S = We$, and the effective spreading width We .

3.3. Results of the Orthogonal and Material-Specific CCD Experiments

3.3.1. Orthogonal Experiment Results and Analysis

An L16(4³) orthogonal experiment was first conducted to evaluate the main effects of flight height, h , forward speed, v , and broadcasting material, B , on the single-pass broadcasting-uniformity coefficient of variation, CV_b , and effective spreading width, We . A lower CV_b and a larger We indicated better broadcasting performance. The experimental results are presented in Table 4, and the corresponding material distributions in the collection boxes are shown in Figure 11.

Table 4. Experimental results, range analysis, and analysis of variance.

Test Group	Factor			Broadcasting-Uniformity Coefficient of Variation CV_b (%)	Effective Spreading Width, We (m)
	Flight Height, h	Forward Speed, v	Broadcasting Material, B		
1	1	1	1	20.86	7.6
2	1	2	2	24.31	7.6
3	1	3	3	36.68	8.2
4	1	4	4	36.04	8.6
5	2	1	2	24.30	8.2
6	2	2	1	24.76	8.2
7	2	3	4	35.64	9.4 α
8	2	4	3	44.77	8.4
9	3	1	3	24.70	8.6
10	3	2	4	28.24	9.4 α
11	3	3	1	24.75	8.6
12	3	4	2	27.89	8.8
13	4	1	4	20.72	9.2 α
14	4	2	3	29.93	9
15	4	3	2	37.45	9
16	4	4	1	31.23	9.4 α
Coefficient of variation CV (%)	k_1	117.886	90.582	101.6	
	k_2	129.472	107.236	113.948	
	k_3	105.58	134.52	136.08	
	k_4	119.33	139.93	120.64	
	R	5.973	12.337	8.62	
Effective spreading width We (m)	k_1	32	33.6	33.8	
	k_2	34.2	34.2	33.6	
	k_3	35.4	35.2	34.2	
	k_4	36.6	35.2	36.6	
	R	1.15	0.4	0.75	

Note: α For these runs, the deposition profile reached the boundary of the original 9.0 m central sampling domain. Additional lateral collection boxes were therefore used to measure the complete deposition profile. The reported We values were directly measured from the extended arrangement and were not obtained through interpolation or extrapolation. CV_b was calculated consistently using only the original 9.0 m central domain.

Range analysis based on the mean response at each factor level indicated that the factors affecting CV_b followed the descending order of forward speed > broadcasting material > flight height, whereas those affecting We followed the order of flight height > broadcasting material > forward speed. Forward speed produced the largest range in CV_b , whereas flight height produced the largest range in We . Because range analysis is descriptive, these rankings were used only as an exploratory assessment of relative factor importance, and statistical significance was evaluated using the main-effects ANOVA.

To further evaluate the main effects of the three factors, a main-effects-only fixed-effects ANOVA was conducted using Design-Expert 13.0. Flight height and forward speed were treated as quantitative linear factors, whereas broadcasting material was treated as a four-level categorical factor. The two-factor interaction terms were excluded because the

original 2FI model was partially aliased and did not permit the complete interaction effects to be estimated independently. The revised ANOVA results are presented in Table 5.

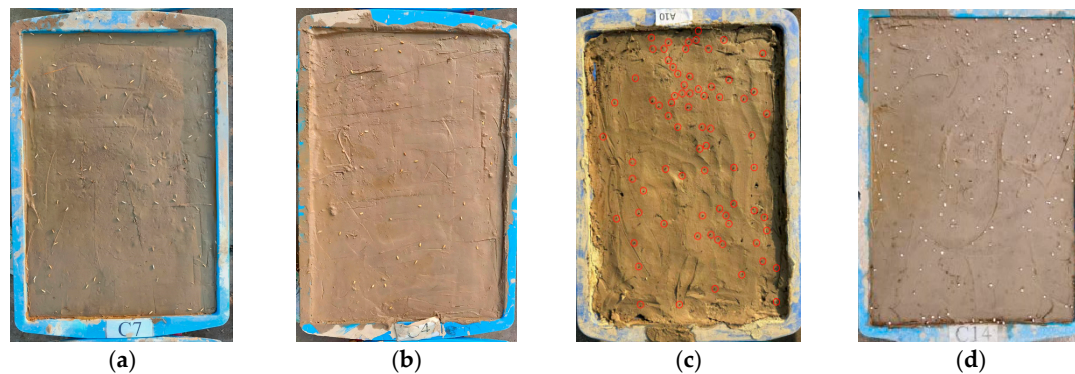


Figure 11. Experimental results in the collection boxes: (a) conventional Huanghuazhan rice; (b) hybrid Yongyou 12 rice; (c) Yangguang 131 rapeseed; (d) Stanley compound fertilizer. The red circles indicate the rapeseed seeds.

Table 5. Main-effects ANOVA of the L16(4³) exploratory screening experiment.

Source	Broadcasting-Uniformity Coefficient of Variation, CV _b (%)					Effective Spreading Width, We (m)				
	SS	df	MS	F	P	SS	df	MS	F	P
Model	543.83	5	108.77	6.56	0.0059	4.68	5	0.9361	20.48	<0.0001
Flight height, <i>h</i>	4.78	1	4.78	0.2885	0.6029	2.81	1	2.81	61.54	<0.0001
Forward speed, <i>v</i>	384.25	1	384.25	23.19	0.0007	0.4205	1	0.4205	9.20	0.0126
Broadcasting material, <i>B</i>	154.80	3	51.60	3.11	0.0753	1.45	3	0.4825	10.56	0.0019
Residual	165.72	10	16.57			0.4570	10	0.0457		
Cor Total	709.56	15				5.14	15			

Note: Flight height and forward speed were treated as quantitative linear factors, whereas broadcasting material was treated as a four-level categorical factor. Only the main effects were included in the model. Two-factor interactions were excluded because the unreplicated L16(4³) design did not permit their complete independent estimation without aliasing.

The revised main-effects ANOVA showed that forward speed significantly affected CV_b ($F = 23.19$, $p = 0.0007$), whereas flight height and broadcasting material were not significant ($p > 0.05$). Flight height, forward speed, and broadcasting material all significantly affected We ($p < 0.05$), with flight height showing the strongest effect. Because the L16(4³) experiment was unreplicated and intended only for exploratory main-effect screening, interaction effects were not interpreted.

For runs in which the deposition profile extended beyond the original 9.0 m central sampling domain, additional lateral collection boxes were used to capture the complete profile. Thus, We values exceeding 9.0 m were directly measured rather than interpolated, extrapolated, or treated as right-censored observations. The additional boxes were used only to determine We, whereas CV_b was calculated consistently from the original fixed 9.0 m central domain.

Based on the screening results, flight height and forward speed were retained as the controllable quantitative factors for the subsequent CCD experiments, while broadcasting material was treated as a categorical factor and evaluated through separate material-specific CCD experiments.

The L16(4³) experiment was used only for exploratory main-effect screening. The orthogonal-design data were not used to fit the material-specific quadratic models. Based on the screening results, flight height and forward speed were selected as the quantitative factors for the subsequent independent CCD experiments conducted separately for

each broadcasting material. The CCD modeling and optimization results are presented in Section 3.3.2.

3.3.2. Material-Specific CCD Experiment Results and Analysis

Following the orthogonal screening experiment, separate two-factor central composite design (CCD) experiments were conducted independently for conventional Huanghuazhan rice, hybrid Yongyou 12 rice, Yangguang 131 rapeseed, and Stanley compound fertilizer. Flight height, h , and forward speed, v , were used as the quantitative factors, whereas the coefficient of variation, CV_b , and effective spreading width, We , were used as the response variables.

For all CCD runs, CV_b was calculated consistently using the deposited amounts collected within the original fixed 9.0 m central sampling domain. When the deposition profile reached or extended beyond the outermost boxes of this central domain, additional collection boxes were arranged laterally beyond the original boundaries to capture the complete deposition profile. These additional lateral boxes were used exclusively to determine the complete effective spreading width and were not included in the CV_b calculation. Therefore, extension of the lateral collection arrangement did not alter the reported CV_b values.

All We values used in the material-specific CCD models were obtained from directly measured lateral deposition profiles. Effective-width values exceeding 9.0 m were determined from the extended collection arrangement rather than through interpolation or extrapolation. These values were therefore treated as directly measured continuous responses, rather than right-censored observations, in the subsequent ANOVA and quadratic regression analyses.

The coded and actual factor levels used for the Stanley compound-fertilizer CCD experiment are presented in Table 3. The complete CCD matrices, run orders, point types, coded and actual factor levels, run-level CV_b and We responses, replicate information, and details of the extended collection arrangements for the affected runs are provided in the Supplementary Materials. These CCD datasets were independent of the previous L16(4³) orthogonal experiment and were used for material-specific response-surface modeling and constrained parameter optimization.

Separate quadratic models were fitted for CV_b and We for each broadcasting material using Design-Expert 13.0. Model adequacy was evaluated using ANOVA, lack-of-fit tests, coefficients of determination, and residual diagnostics. Because the same modeling procedure was applied to all four materials, Stanley compound fertilizer is presented below as a representative example, while the complete statistical results for the other materials are provided in the Supplementary Materials.

For the Stanley compound-fertilizer CCD experiment, the deposition profiles extending beyond the original central sampling domain were measured using the extended collection arrangement, including the run with a reported We of 9.2 m.

For Stanley compound fertilizer, the quadratic model for CV_b was statistically significant ($F = 9.31$, $p = 0.0035$), whereas the lack of fit was not significant ($F = 3.82$, $p = 0.0914$). The model yielded an R^2 of 0.8534 and an adjusted R^2 of 0.7618. However, the predicted R^2 was 0.2098, indicating limited predictive capability. Therefore, the model was interpreted primarily as a description of the response within the investigated design domain, and independent confirmation is required before predictive application.

The quadratic model for We was statistically significant ($F = 8.89$, $p = 0.0040$), whereas its lack of fit was not significant ($F = 0.8017$, $p = 0.5441$). The model yielded an R^2 of 0.8475, an adjusted R^2 of 0.7522, and a predicted R^2 of 0.4995.

The fitted quadratic regression equations relating CV_b and We to the actual flight height, h , and forward speed, v , for Stanley compound fertilizer were as follows:

$$CV_b = -42.74154 + 44.91059 h + 8.45701 v - 3.68667 hv - 7.24583 h^2 + 0.831574 v^2 \quad (13)$$

$$W_e = 2.04438 + 4.22831 h + 0.164311 v + 0.133333 hv - 0.733333 h^2 - 0.081481 v^2 \quad (14)$$

To visualize the combined effects of flight height and forward speed on CV_b and W_e , response surface plots were generated for the four broadcasting materials, as shown in Figure 12.

As shown in Figure 12, the effective spreading width generally increased initially and then decreased with increasing flight height within the investigated ranges. The influence of forward speed on the coefficient of variation (CV_b) of material distribution followed a generally consistent trend, with CV_b increasing as forward speed increased. However, the response surfaces for conventional Huanghuazhan rice and hybrid Yongyou 12 rice changed relatively gradually, whereas those for Yangguang 131 rapeseed and Stanley compound fertilizer exhibited comparatively steeper gradients. This pattern suggests that the predicted responses of rapeseed and compound fertilizer were more sensitive to changes in flight height and forward speed within the investigated design domains; therefore, their operating parameters require more careful adjustment.

Based on the fitted material-specific quadratic models, numerical optimization was conducted separately for each broadcasting material using the optimization module of Design-Expert 13.0. The objectives were to maximize the effective spreading width and minimize CV_b , while flight height and forward speed were constrained to their respective experimentally investigated ranges. The objective functions and constraint conditions were established as follows:

$$\begin{cases} \max W_e(h, v) \\ \min CV(h, v) \\ 2 \text{ m} \leq h \leq 3.2 \text{ m} \\ 1 \text{ m/s} \leq v \leq 4 \text{ m/s} \end{cases} \quad (15)$$

The solution with the highest overall desirability was selected as the model-recommended operating condition for each broadcasting material. For Stanley compound fertilizer, the constrained numerical optimization yielded a model-recommended flight height of $h = 3.20 \text{ m}$ and a forward speed of $v = 2.25 \text{ m s}^{-1}$, with a predicted effective spreading width of 8.98 m and a predicted CV_b of 23.47% . The model-recommended operating conditions for all four broadcasting materials are summarized in Table 6. Because the predicted R^2 of the CV_b model was relatively low, this parameter combination should be interpreted as a constrained model-based recommendation within the investigated design domain rather than a global or independently verified optimum.

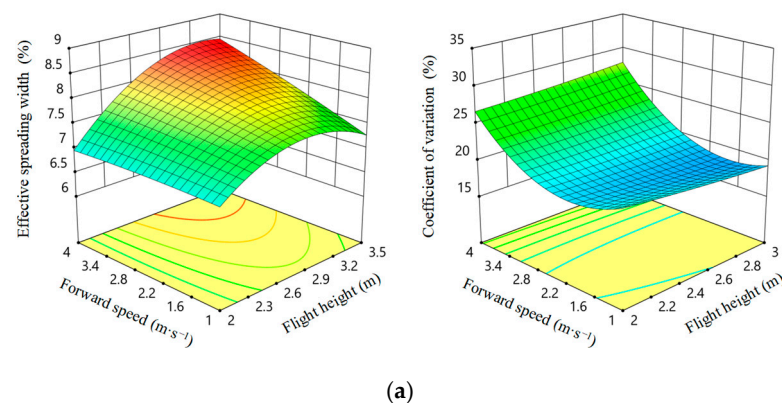


Figure 12. Cont.

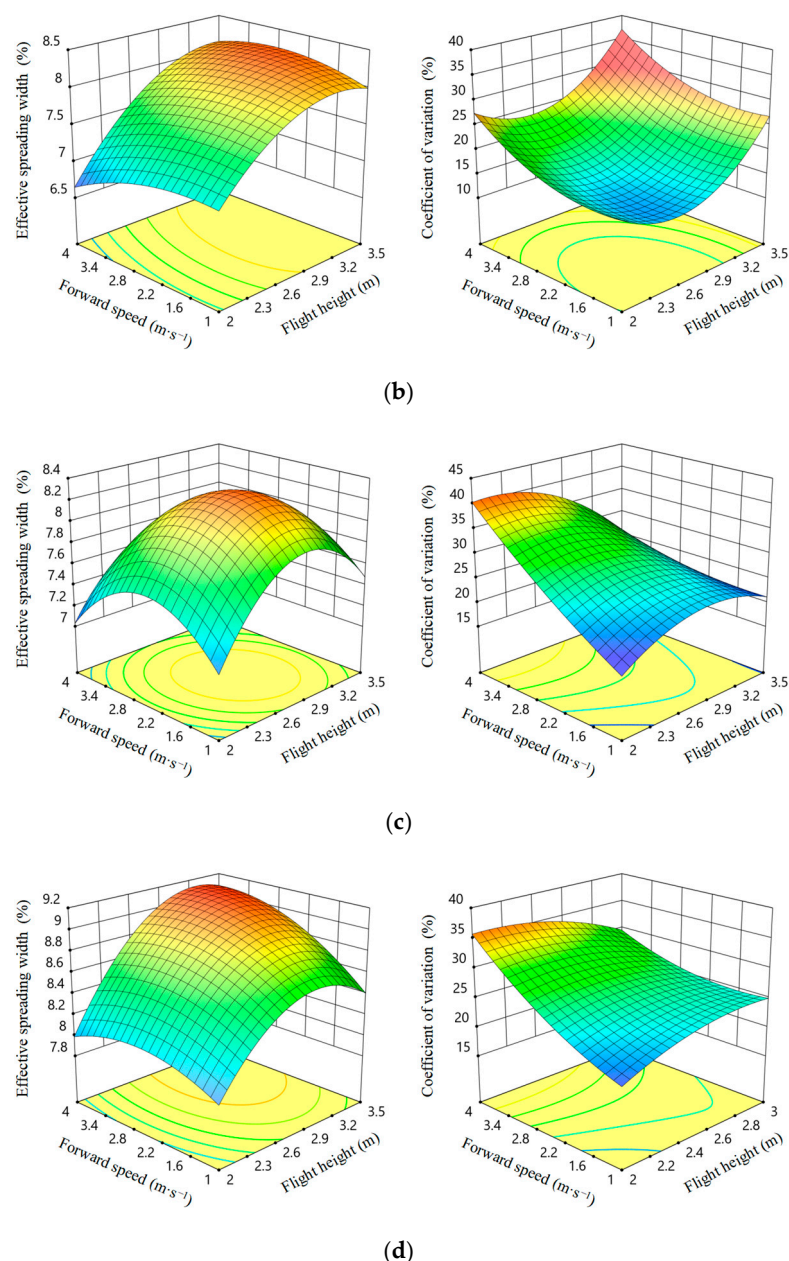


Figure 12. Response surfaces of the single-pass broadcasting-uniformity coefficient of variation, CV_b , and effective spreading width, We : (a) conventional Huanghuazhan rice; (b) hybrid Yongyou 12 rice; (c) Yangguang 131 rapeseed; (d) Stanley compound fertilizer.

Table 6. Model-recommended operating conditions and corresponding predicted responses for the four broadcasting materials.

Material	Flight Height (m)	Forward Speed ($m \cdot s^{-1}$)	Effective Spreading Width (m)	Predicted CV_b (%)
Conventional Huanghuazhan rice	3.04	2.35	8.03	19.12
Hybrid Yongyou 12 rice	2.79	1.70	8.06	14.57
Yangguang 131 rapeseed	3.00	1.80	8.19	25.93
Stanley compound fertilizer	3.20	2.25	8.98	23.47

3.4. Results and Analysis of the Field Verification Test

According to NY/T 3881-2021 and MH/T 1002.2-1995, the CV of the deposited amount per sampling area should not exceed 45%, and the pointwise-deviation criterion was set at

20% [31]. For the five field samples, the mean absolute pointwise deviation from the target count was calculated as:

$$E_{MAPD} = \frac{100}{N} \sum_{i=1}^N \frac{|x_i - x_0|}{x_0} \quad (16)$$

where X_i is the observed particle count in the i -th sampling area, X_0 is the target particle count per sampling area, and N is the number of sampling areas.

This metric represents the mean absolute deviation of the individual sampling values from the target, rather than the relative error between the overall sample mean and the target. Because the five field sampling locations constituted a spatial dataset different from both the repeated screw-discharge measurements and the lateral deposition profiles, the field-sample coefficient of variation, CV_f , was calculated independently as follows:

$$CV_f = \frac{\sqrt{\frac{\sum_{i=1}^{n_f} (y_i - \bar{y})^2}{n_f - 1}}}{\bar{y}} \times 100\% \quad (17)$$

where CV_f is the field-sample coefficient of variation; y_i is the observed particle count in the i -th field sampling area; $\bar{y}$ is the mean particle count across all field sampling areas; and n_f is the number of field sampling areas. In the present limited field demonstration, $n_f = 5$.

Table 7 shows sample CV_f values of 19.44%, 15.90%, 20.34%, and 13.76% for conventional rice, hybrid rice, rapeseed, and compound fertilizer, respectively. The mean absolute pointwise deviations were 15.56%, 19.05%, 19.02%, and 15.11%. These values satisfy the selected criteria for the five sampled locations, but the experiment did not cover the complete lateral distribution, did not estimate effective width, and did not include three independent replicate flights. The results are therefore reported as a limited field demonstration, not as independent validation of a response-surface model.

Table 7. Field test results.

Broadcasting Material	Observed Count per 0.16 m ² (Particles)					Target Count	E_{MAPD} (%)	CV_f (%)
	1	2	3	4	5			
Conventional Huanghuazhan rice	31	47	29	39	38	36	15.56	19.44
Hybrid Yongyou 12 rice	27	23	23	30	20	21	19.05	15.90
Yangguang 131 rapeseed	84	75	87	123	86	102	19.02	20.34
Stanley compound fertilizer	104	97	115	127	90	94	15.11	13.76

4. Discussion

4.1. Practical Operating Recommendations

For a new rice variety or untested granular material, repeating the full experimental procedure may not be necessary. The material should first be classified by particle size and shape, bulk density, surface moisture, and target application rate. The closest replaceable screw can then be selected as an initial option: the rapeseed screw for small seeds applied at relatively low rates, the rice screw for elongated or pre-germinated rice seeds, and the fertilizer screw for dense granular fertilizers.

Before field operation, a short stationary calibration should be conducted over a known period or number of screw revolutions to determine the actual discharge per revolution, q . Equation (2) can then be used to calculate the required screw rotational speed from the target application rate, UAV forward speed, and planned route spacing. Because q may

vary with material type, moisture condition, and batch, the calibration should be verified whenever the material changes.

The constrained model-recommended operating conditions listed in Table 6 were obtained within the material-specific CCD domains and should be regarded as initial engineering references for the corresponding tested materials rather than universally applicable or independently verified optima. For a new rice variety or an untested granular material, these settings should not be adopted directly without additional stationary calibration and a short single-swath confirmation test. Before full-field operation, the lateral deposition profile should be measured and candidate route spacings should be evaluated using the multiple-pass superposition method.

For a narrow, center-concentrated deposition profile, route spacing should generally be reduced to prevent gaps between adjacent swaths. When pronounced edge peaks occur, spacing should be selected according to the calculated multiple-pass CV rather than effective spreading width alone, because excessive overlap may cause local accumulation. Route spacing may be increased only when the profile is sufficiently broad and smooth, no gaps are predicted, and the multiple-pass CV remains acceptable. Any operation outside the material-specific CCD domain, including extrapolation beyond the investigated flight-height or forward-speed ranges, requires additional experiments and independent validation.

4.2. Comparison with Commercial Spreading Systems

The present prototype is not claimed to outperform mature commercial spreading systems in overall payload capacity, operational throughput, automation, or product support. For context, the DJI AGRAS T50 is specified for 0.5–5 mm dry granules, a 50 kg spreading payload, a nominal 8 m spreading width, and a small-gate option for low-rate spreading. The XAG V40 RevoCast is specified for 1–10 mm dry granules, a 25 L capacity, and an approximate spreading width of 4–10 m [32,33]. Because the UAV platforms, materials, target application rates, environmental conditions, and evaluation methods differ, these specifications provide context only and do not constitute a direct comparison with the present prototype.

The engineering distinction of the prototype is the combination of replaceable, material-specific screw metering and reciprocating oscillating-tube spreading. This architecture provides a potential route for directly metering low-rate small seeds without using fertilizer as a carrier. For the four tested materials, separate material-specific central composite design (CCD) experiments quantified the effects of flight height and forward speed on the coefficient of variation (CV) and effective spreading width (We) within the investigated design domains. These results establish prototype-specific operating relationships, but not superiority or commercial competitiveness relative to spinner-disc systems.

No representative commercial broadcaster was tested under matched conditions. Therefore, the study cannot provide quantitative comparative conclusions regarding minimum stable application rate, metering fluctuation, application-rate accuracy, effective spreading width, single- or multiple-pass CV, operational capacity, power or energy consumption, device mass, seed damage, blockage rate, or durability. The potential suitability of the replaceable-screw architecture for low-rate small seeds should thus be regarded as an engineering hypothesis requiring direct validation.

Future development should include closed-loop mass-flow or hopper-weight sensing, automatic calibration, variable-rate control, route-spacing optimization based on measured lateral deposition profiles, and compensation for ambient wind and rotor-induced airflow. Anti-clogging performance, wear resistance, seed damage, and long-term durability should

also be evaluated through matched side-by-side tests with representative commercial spinner-disc systems.

4.3. Limitations

A principal limitation of this study is that all experiments were conducted at a single site and under a narrow range of environmental conditions. The UAV performance test and limited field demonstration were performed at a prepared site at Jiangxi Agricultural University under wind-speed ranges of approximately 0.3–1.5 and 1.6–3.3 m s^{−1} (Beaufort forces 1 and 2), respectively. Time-series measurements of wind, gusts, temperature, relative humidity, payload, rotor speed, outlet position, and fluctuations in flight height and forward speed were not recorded. The material-specific CCD models and recommended settings are therefore limited to the investigated factor domains, material batches, and site conditions. Crosswinds, temperature, humidity, ground conditions, crop canopy, and rotor downwash may alter material flow, swath overlap, and particle deposition.

The analytical trajectory model covers only mechanical discharge and the initial post-impact motion. Equation (7) allows aerodynamic drag and a prescribed local air velocity to be included, but spatially and temporally varying three-dimensional rotor airflow was not coupled with the particle model, and outlet velocity and particle trajectories were not independently measured. The model should therefore be interpreted qualitatively rather than as a fully validated predictor.

The four oscillating-tube factors were screened through one-factor experiments using pre-germinated Huanghuazhan rice. No four-factor confirmation experiment was conducted, and interactions among tube inclination, tube length, oscillation angle, and oscillation frequency were not quantified. The selected settings should therefore be regarded as engineering starting values rather than a statistically optimized or universally applicable solution. Although separate two-factor CCD experiments were conducted for the four materials, the quadratic models describe only the effects of flight height and forward speed within the tested domains. Boundary solutions represent constrained optima within these domains rather than global optima. Seed breakage, embryo damage, and post-operation germination were not evaluated.

The field test used five-point samples per material and should be regarded as a limited field demonstration rather than an independent validation of the CCD models or effective spreading width. Rigorous confirmation requires repeated independent flights, complete lateral deposition profiles, and uncertainty estimates. No commercial spinner-disc broadcaster was tested under matched conditions; thus, quantitative comparisons of minimum stable application rate, metering fluctuation, effective spreading width, uniformity, throughput, power consumption, and device mass cannot be made.

Future work should integrate measured or CFD-predicted rotor airflow with particle tracking, conduct four-factor structural and independent CCD confirmation tests, and perform replicated full-width trials across sites, seasons, materials, and environmental conditions. Seed damage, germination, anti-clogging performance, wear resistance, durability, and matched comparisons with commercial systems should also be evaluated.

5. Conclusions

- (1) A multi-rotor UAV-based broadcasting prototype combining replaceable screw metering with reciprocating oscillating-tube spreading was developed and operated using conventional Huanghuazhan rice, hybrid Yongyou 12 rice, Yangguang 131 rapeseed, and Stanley compound fertilizer.
- (2) Three material-specific screw configurations were designed. The outer diameter, inner diameter, and pitch were 66, 16, and 50 mm for the fertilizer screw; 57, 22, and 33 mm

for the rice screw; and 58, 41, and 23 mm for the rapeseed screw, respectively. Within the tested rotational-speed range of 10–110 rev min^{−1}, the measured metering-rate coefficients of variation (CV_m) of the three screw configurations satisfied the adopted requirements under the present test conditions.

- (3) Single-factor experiments using pre-germinated Huanghuazhan rice identified $\alpha = 10^\circ$, $L = 250$ mm, $\beta = 100^\circ$, and $\gamma = 4.0$ Hz as the selected engineering settings for the subsequent prototype experiments. The L16(4³) screening experiment showed that forward speed significantly affected CV_b , whereas flight height, forward speed, and broadcasting material all significantly affected We , with flight height exerting the strongest influence.
- (4) Separate two-factor CCD experiments were conducted for the four broadcasting materials, and material-specific quadratic models were established for CV_b and We . The constrained model-recommended flight height and forward speed were 3.04 m and 2.35 m s^{−1} for conventional Huanghuazhan rice, 2.79 m and 1.70 m s^{−1} for hybrid Yongyou 12 rice, 3.00 m and 1.80 m s^{−1} for Yangguang 131 rapeseed, and 3.20 m and 2.25 m s^{−1} for Stanley compound fertilizer. In the limited consecutive-pass field demonstration, the field-sample coefficient of variation (CV_f) ranged from 13.76% to 20.34%, and the mean absolute pointwise deviation ranged from 15.11% to 19.05%.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16161749/s1>, Table S1: Coded and actual factor levels used in the CCD experiment for conventional Huanghuazhan rice; Table S2: Experimental design and response results of the CCD experiment for conventional Huanghuazhan rice; Table S3: ANOVA for the quadratic CV_b model for conventional Huanghuazhan rice; Table S4: Fit statistics for the quadratic CV_b model for conventional Huanghuazhan rice; Table S5: ANOVA for the quadratic We model for conventional Huanghuazhan rice; Table S6: Fit statistics for the quadratic We model for conventional Huanghuazhan rice; Table S7: Coded and actual factor levels used in the CCD experiment for hybrid Yongyou 12 rice; Table S8: Experimental design and response results of the CCD experiment for hybrid Yongyou 12 rice; Table S9: ANOVA for the quadratic CV_b model for hybrid Yongyou 12 rice; Table S10: Fit statistics for the quadratic CV_b model for hybrid Yongyou 12 rice; Table S11: ANOVA for the quadratic We model for hybrid Yongyou 12 rice; Table S12: Fit statistics for the quadratic We model for hybrid Yongyou 12 rice; Table S13: Coded and actual factor levels used in the CCD experiment for Yangguang 131 rapeseed; Table S14: Experimental design and response results of the CCD experiment for Yangguang 131 rapeseed; Table S15: ANOVA for the quadratic CV_b model for Yangguang 131 rapeseed; Table S16: Fit statistics for the quadratic CV_b model for Yangguang 131 rapeseed; Table S17: ANOVA for the quadratic We model for Yangguang 131 rapeseed; Table S18: Fit statistics for the quadratic We model for Yangguang 131 rapeseed; Table S19: Coded and actual factor levels used in the CCD experiment for Stanley compound fertilizer; Table S20: Experimental design and response results of the CCD experiment for Stanley compound fertilizer; Table S21: ANOVA for the quadratic CV_b model for Stanley compound fertilizer; Table S22: Fit statistics for the quadratic CV_b model for Stanley compound fertilizer; Table S23: ANOVA for the quadratic We model for Stanley compound fertilizer; Table S24: Fit statistics for the quadratic We model for Stanley compound fertilizer; Table S25: Details of the extended lateral collection measurements.

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Appendix A

The physical properties of the four broadcasting materials used in the experiments, determined experimentally in this study or obtained from relevant literature, are summarized in Table A1 [34–36].

Table A1. Physical properties of the four broadcasting materials obtained from experimental measurements and relevant literature.

Material	Material Condition	Particle Dimensions (mm)	Thousand-Particle Mass (g)	Angle of Repose (°)	Friction Coefficient	Restitution Coefficient
Conventional Huanghuazhan rice	Pre-germinated	$7.90 \times 3.12 \times 2.12$	25.6	37.09	0.45	0.4
Hybrid Yongyou 12 rice	Pre-germinated	$6.85 \times 3.28 \times 2.22$	22.5	33.91	0.525	0.4
Yangguang 131 rapeseed	Dry seed	$2.18 \times 2.00 \times 1.69$	3.51	19.7	0.38	0.39
Stanley compound fertilizer	Granular fertilizer	$3.89 \times 3.56 \times 3.34$	25.9	28.57	0.3	0.11

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