

Article

Design and Experiment of Air–Fertilizer Separator for Pneumatic Deep Fertilization in Paddy Fields

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Abstract

Supplemental fertilizer application is critical for improving rice yield. Pneumatic deep fertilization effectively improves fertilizer utilization, but high-speed airflow may disturb the soil and affect the location of the fertilizer particles. An air–fertilizer separator was developed in this study to separate the fertilizer from the airflow before the two-phase flow rushes into the soil, and the airflow is directed away from the surface of the paddy soil. The structural and operating parameters of the air–fertilizer separator are determined in this paper. A quadratic orthogonal rotation combination experiment was conducted, taking structural parameters of the device as variables, and fertilizer injection speed, separation loss rate, and outlet airflow speed as performance indicators, to optimize the design parameters of the air–fertilizer separator. The variance analysis and surface response analysis of the experimental data are conducted, and the mathematical models between the indicators and the influencing factors are established. The optimal parameters were determined using multi-objective optimization, and the experimental verification was carried out. The optimal parameters for the air–fertilizer separator were obtained as an arc radius of the AFAST of 380 mm, central angle of arc trough of 45°, and depth of primary separation arc-trough of 12.5 mm. The validation experimental results show that the fertilizer injection speed is 21.45 m/s, the fertilizer separation loss rate is 10.22%, and the outlet airflow speed is 42.54 m/s. The experimental values are close to the predicted values, with errors of 1.2%, 1.7%, and 1.3%. The results of the study may provide a reference for the development of an air–fertilizer separator for pneumatic deep fertilization in paddy fields.

Keywords: deep fertilization in paddy fields; air–fertilizer separator; structural parameter; fertilizer injecting speed; outlet airflow speed; fertilizer separation loss rate



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1. Introduction

Rice is an important food crop, and its yield stability is directly related to global food security [1]. Supplementary application of fertilizer can ensure a continuous supply of nutrients during the growth of rice, and it is one of the important measures to increase rice yield [2]. Broadcasting is the most common method for rice fertilizer application [3,4], but there are problems such as a low fertilizer utilization rate and uneven distribution of fertilizer particles in the field [5]. Compared with broadcast fertilization, deep fertilization

of rice can save about 10% of fertilizer and increase the fertilizer utilization rate by over 50% [6]. Deep fertilization can greatly improve the nutrient environment of the paddy field and reduce water pollution.

Research on deep fertilization devices mainly focuses on synchronous side-deep fertilization during rice transplantation [7,8] and direct seeding [9,10]. In terms of deep fertilization research, some manually operated deep fertilization devices for rice seedlings were developed [11,12]. Wang Jinfeng and his team developed an electric two-row deep fertilization and weeding machine for paddy fields [13]; Southeast Asian countries employ the practice of super-granular urea (USG) deep placement in rice production and have developed some related machines [14,15]. In 2009, Wohab developed a deep placement machine (BARI) for large-particle urea [16]. Since then, some scholars have improved the BARI and developed other machines with similar working principles [17–21]. Most of the above devices used a mechanical furrow opener, and there are problems such as sludge sticking in the opener and blockage of fertilizer at the outlet [22].

As for pneumatic fertilizer application, Zuo Xingjian designed an air-blast rice side-deep precision fertilization device [23]. Li Liwei conducted two-phase flow simulations of the pneumatic-conveying fertilizer feeder of a rice fertilizer applicator [24]. These deep fertilizer application devices are to inject fertilizer and fluid into the paddy field together, and the high-speed airflow may disturb the soil and it may escape from the muddy soil, resulting in the shift of fertilizer with the fluid, decreasing the quality of fertilization.

Therefore, an air–fertilizer separator for the pneumatic deep fertilization in paddy fields was designed in this study, which diverts the air out before the two-phase air–fertilizer flow into the paddy soil, to reduce the impact of the airflow on the slurry soil. Kinetic analysis and experimental study of fertilizer particles in the air–fertilizer separator were carried out to determine and optimize the structural parameters.

2. Materials and Methods

2.1. Structure and Working Process of Pneumatic Deep Fertilization Device for Rice

A pneumatic deep fertilization device for paddy fields was developed, as shown in Figure 1, which mainly consists of an air supply system, a profiling mechanism, a fertilizer metering system, a fertilizer feeding port, a fertilizer speeding tube, a water divider, and an air–fertilizer separator.

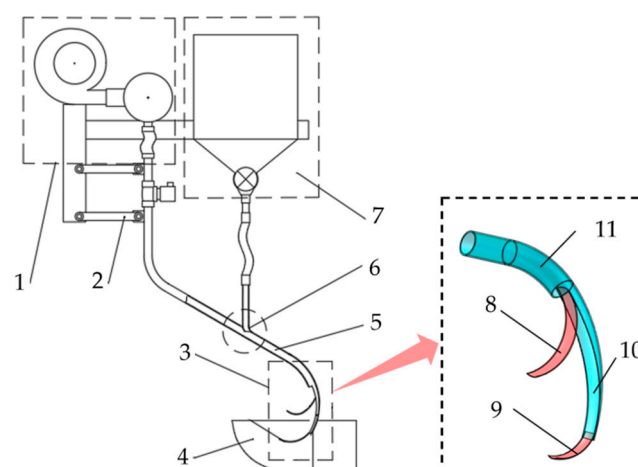


Figure 1. Overall structure of the pneumatic deep fertilization device for paddy fields. 1. Air supply system; 2. profiling mechanism; 3. air–fertilizer separator; 4. water divider; 5. fertilizer acceleration tube; 6. air–fertilizer mixing interface; 7. fertilizer metering system; 8. primary air-diverting arc plate; 9. secondary air-diverting arc plate; 10. arc-shaped trough; 11. air–fertilizer separation arc-shaped tube (AFAST).

During operation, the fertilizer particles are metered from the fertilizer metering system, mixed with the high-pressure airflow from the air supply system at the air–fertilizer mixing interface, and then accelerated in the acceleration tube. Before the two-phase flow of air–fertilizer enters the soil, the air–fertilizer separator separates and diverts the airflow to the atmosphere, and the high-speed fertilizer particles penetrate into the slurry soil, where surface water has been swept away by the water divider. The soil then falls back to cover the fertilizer.

The air–fertilizer separator consists of an air–fertilizer separation arc-shaped tube (AFAST) connected with the fertilizer acceleration tube, an arc-shaped trough that is the extension and half of the separation tube, and two air-diverting arc plates that are set at both ends and the top of the trough.

When the accelerated fertilizer particles with airflow rush into the separation arc-tube and arc-shaped trough, they will run closer to the back wall of the separation tube and trough under the action of centrifugal force, so the fertilizer and airflow separate since the fertilizer is denser than air; the airflow is directed away by the two arc-shaped air diverting plates mounted at the beginning and end of the trough. The fertilizer moves along the arc-shaped trough, until it leaves the trough and penetrates into the soil.

2.2. Parameter Design of Air–Fertilizer Separator

2.2.1. Structural Design and Parameter Determination of the Air–Fertilizer Separator

The air–fertilizer separator was designed and the main structural parameters are shown in Figure 2.

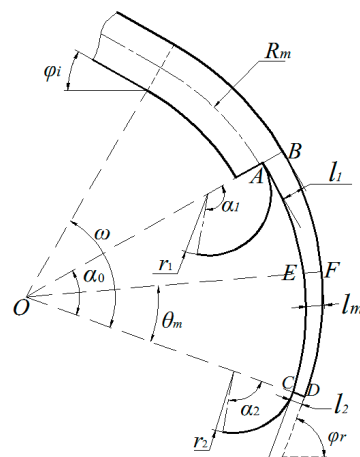


Figure 2. Structural parameter of air–fertilizer separator. φ_i is the setting angle of the separator; ω is the center angle of the separator; α_0 is the central angle of the arc-shaped trough; φ_r is the angle between the trajectory of the fertilizer entering the soil and the soil surface; OF is the bisector of the trough; AB is the primary air–fertilizer outlet; CD is the secondary air–fertilizer outlet; α_1 is central angle of the primary air-diverting arc plate; α_2 is the center angle of the secondary air-diverting arc plate; l_m is the depth of EF ; l_2 is the depth of CD ; r_1 is the radius of the primary air-diverting arc plate; r_2 is the radius of the secondary air-diverting arc plate.

The separator is tilted at $\varphi_i = 30^\circ$ to ensure the vertical free-fall of fertilizer from the fertilizer discharge system into the air–fertilizer mixing interface.

The included angle (φ_r) between the fertilizer trajectory into the soil and the soil surface should not be less than 60° [25], to ensure the depth of the fertilizer into the soil. The φ_r is set as 70° in this study. The central angle ω of the separator is 80° according to the geometric relationship.

OF is the bisector of the central angle of the arc-shaped trough. Point E is located on the line segment OF . The length of EF is half of the sum of the depths of arc-shaped troughs

l_1 and l_2 . In cutting off the inner part along the circular path through points A, E, and C, the resultant arc-shaped trough is made to match the requirements of the outlet dimensions and central angle.

Air-diverting arc plates are installed at the beginning and end of the arc-shaped trough. The primary air–fertilizer outlet AB and the secondary air–fertilizer outlet CD are formed by the arc plate and the arc-shaped trough. The depths of the arc-shaped troughs at the two air–fertilizer outlets are defined as the primary arc-trough depth (l_1) and the secondary arc-trough depth (l_2).

The air-diverting plate is designed with a curved arc structure to guide the airflow away from the soil surface, to avoid disturbance of the paddy soil. The radius of the primary air-diverting arc plate r_1 is designed as 70 mm, the radius of the secondary air-diverting arc plate r_2 is designed as 50 mm, and the tangent at the end of the two air-diverting arc plates forms an angle of 10° with the horizontal line. According to geometric relations, the center angle α_1 of the primary air-diverting arc plate and the center angle α_2 of the secondary air-diverting arc plate are as follows:

$$\alpha_1 = \alpha_0 + \varphi_r + 10^\circ \quad (1)$$

$$\alpha_2 = \varphi_r + 10^\circ \quad (2)$$

where α_0 is the central angle of the arc-shaped trough, rad.

According to Formula (1), the central angle of the primary air-diverting arc plate should be adjusted with the central angle of the arc-shaped trough; the angle of the secondary air-diverting arc plate is 80° when φ_r is 70° .

2.2.2. Determination of the AFAST Diameter

The diameter of air–fertilizer arc-shaped tube (AFAST) is as follows [23]:

$$D = \sqrt{\frac{4Q}{\pi v_a}} \quad (3)$$

where Q is the airflow rate, m^3/s ; v_a is the air speed, m/s .

Assuming the air leakage rate of the system is 10%, the airflow rate Q can be calculated as follows:

$$Q = \frac{1.1bv_mq}{10000\mu\gamma} \quad (4)$$

where b is the rice row spacing, m; v_m is the forward speed of the fertilization machine, m/s ; q is the application rate of the fertilizer, kg/hm^2 ; μ is the mixing concentration ratio; and γ is the air volume weight, kg/m^3 .

The conveying air speed of a pneumatic fertilization system is calculated as follows:

$$v_a = Kv_f \quad (5)$$

where v_a is the air speed, m/s ; K is the speed coefficient, set to 6 in this study; and v_f is the terminal speed of fertilizer, m/s .

According to the pre-test, the terminal speed of large urea particles is 6.98–9.09 m/s [26]. The row spacing of rice is 300 mm, the set working speed of the pneumatic deep fertilization machine is 1.5 m/s , the fertilization rate is 150 kg/hm^2 [13], and the material-to-air concentration ratio μ in the pneumatic fertilization system is generally taken as 0.5 [27]. Then, the inner diameter (D) of the AFAST can be worked out as according to Equation (3), and it is determined as 25 mm in this study.

2.2.3. Arc Radius of the AFAST

The arc radius of the AFAST (R_m) affects the centrifugal force of the fertilizer particles, so as to affect the air–fertilizer separation. The kinematic analysis of fertilizer particles in the AFAST is shown in Figure 3.

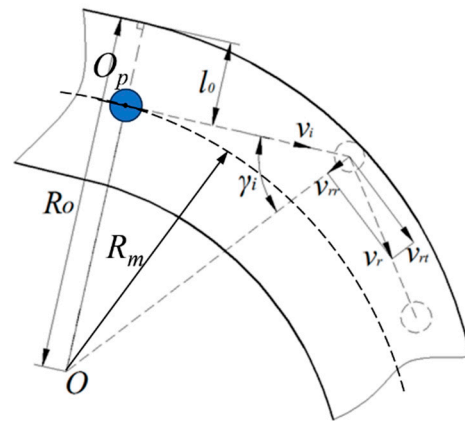


Figure 3. The motion of the fertilizer particle entering into the arc-shaped air–fertilizer separation tube. R_0 is the radius of the back wall of AFAST; R_m is the arc radius of AFAST center line; l_0 is the distance between the initial incident position of the fertilizer particles and the back wall of AFAST; m ; O_p is the center of the fertilizer particle; O is the center of the separator; γ_i is the angle between the direction of the incident speed of the fertilizer particles and OO_p ; v_i is the incident speed of the fertilizer particles; v_r is the rebound velocity of the fertilizer particles; v_{rr} is the radial rebound velocity of the fertilizer particles; v_{rt} is the tangential rebound velocity of the fertilizer particles.

The higher the incident speed, the better the air–fertilizer separation performance. However, the incident speed v_i should be less than the critical impact speed v_l of the fertilizer particles for a better separation, and v_l is the incident speed for vertical injection of fertilizer particles. The granular fertilizers in common use are classified as brittle materials and can be regarded as elastic materials before breakage [28]. The peak impact stress $\sigma_{\max}$ of brittle particle–wall collisions, according to Hertz contact mechanics, can be expressed as follows [29,30]:

$$\sigma_{\max} = \frac{3}{2\pi} \left(\frac{4E^*}{3R_e^{\frac{3}{4}}} \right)^{\frac{2}{3}} \left(\frac{5m_e v_e^2}{4} \right)^{\frac{1}{15}} \quad (6)$$

where m_e is the equivalent mass of the collision object, kg; E^* is the equivalent elastic modulus of the collision object, Pa; R_e is the equivalent diameter of the collision object, m; and v_e is the impact speed, m/s.

The critical impact speed (v_l) at which the fertilizer particles break upon normal collision with the wall of the AFAST can be expressed as follows:

$$v_l = 1.56 \sqrt{\left(\frac{\sigma_l^5}{\rho E_p^4} \right)} \quad (7)$$

where σ_l is the critical impact stress for fertilizer particle breakage, Pa; E_p is the equivalent elastic modulus of fertilizer and materials of the air–fertilizer separator, Pa; and ρ is the density of the fertilizer, kg/m³.

The equivalent elastic modulus E_p [31] is as follows:

$$\frac{1}{E_p} = \frac{1 - \mu_f^2}{E_f} + \frac{1 - \mu_t^2}{E_t} \quad (8)$$

where E_f is the elastic modulus of the fertilizer particles, Pa; E_t is the elastic modulus of the material of the air–fertilizer separator, Pa; μ_f is the Poisson’s ratio of the fertilizer particles; and μ_t is the Poisson’s ratio of the material of the air–fertilizer separator.

In order to avoid breakage of the fertilizer when entering the air–fertilizer separator, the incident speed of the fertilizer should meet the following condition:

$$v_i \leq \frac{v_l}{\cos \arcsin \frac{R_o - l_0}{R_o}} \quad (9)$$

According to Equation (9), it can be determined that when l_0 is equivalent to the inner diameter of the acceleration tube (D), and the angle γ_i is minimal, the fertilizer is most susceptible to breaking. To prevent breakage of the fertilizer, the arc radius of the AFAST (R_m) should meet the following relationship:

$$R_m \geq \frac{v_i D}{v_l^2} \left(v_i + \sqrt{v_i^2 - v_l^2} \right) \quad (10)$$

where D is the inner diameter of the AFAST, m.

The property parameters [26,32] of the fertilizer granules (urea) used in this study and the air–fertilizer separator material (PMMA) are shown in Table 1.

Table 1. Property parameters of materials.

Material	Density (kg/m ^{−3})	Poisson’s Ratio	Elastic Modulus (MPa)
Urea	1332	0.25	140
PMMA	1200	0.41	1.95×10^5

In the case of brittle materials, the critical impact stress for particle breakage (σ_l) can be regarded as being equivalent to the ultimate compressive stress [33]. According to previous experiments, the ultimate compressive stress of fertilizer used in this study is 36.66 MPa [26].

The final injection speed of fertilizer at the outlet should be 18–25 m/s to ensure the depth of fertilization [34]. Considering the speed loss during the movement, the incident speed v_i of the fertilizer is set to 30 m/s to ensure sufficient injection speed. According to Equation (10) and known parameters, the arc radius of the AFAST (R_m) should be greater than 162 mm.

It can be observed from Figure 2 that the small arc radius of the AFAST (R_m) will result in an increase in centrifugal force, which may cause the fertilizer to collide with the wall of the tube. Considering the overall structure and motion stability, R_m is set as 330 mm.

According to pneumatic conveying theory, the maximum speed of fertilizer particles after being accelerated in a straight tube is as follows [35]:

$$v_{p\max} = v_i \approx 0.6v_a \quad (11)$$

where $v_{p\max}$ is the maximum speed of fertilizer particles after pneumatic acceleration, m/s.

According to Formula (11), the airflow speed is set as 50 m/s preliminarily.

The other key structural parameters of the air–fertilizer separator are initially determined as follows: primary arc-trough depth $l_1 = 12$ mm and secondary arc-trough depth $l_2 = 6$ mm. The central angle of the arc-shaped trough is $\alpha_0 = 40^\circ$, and the arc radius of the AFAST (R_m) is 330 mm. Under these conditions, the central angle of the primary air-diverting arc plate is 120° .

2.3. Experimental Details and Result Analysis of Air–Fertilizer Separator

2.3.1. Experimental Equipment and Materials

A test bench was developed, as shown in Figure 4, which consists of a high-pressure blower (XG-1500, flow rate of 250 m³/h, air pressure of 32 kPa, rated power of 1.5 kW, Chengyu Electromechanical Equipment Co., Ltd., Chendu, China), a silicon-controlled-rectifier electronic voltage regulator (DTY-4000, Wenfu Electric Co., Ltd., Wenzhou, China), an anemometer (YIOU ZC1000-1F-9, wind speed measuring range of 1–90 m/s, accuracy of 0.01 m/s, Yiou Instrument Equipment Co., Ltd., Shanghai, China), a regulated air chamber, an electric fertilizer metering mechanism, a PLEXLOGGER high-speed dynamic image analyzer (Shinano Kenshi Co., Ltd., Nagano, Japan), a fertilizer acceleration tube, and an air–fertilizer separation mechanism (material of PMMA for easy observation).

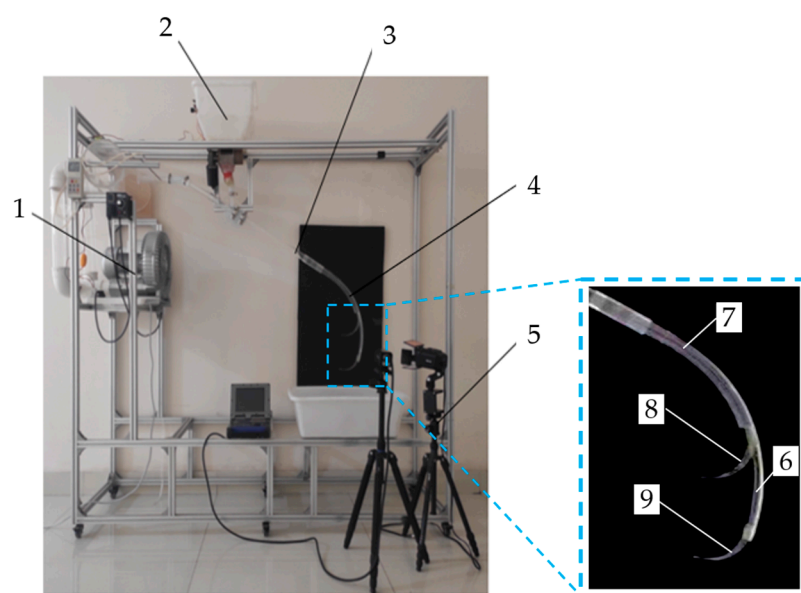


Figure 4. Air–fertilizer separator performance test bench. 1. Fan; 2. fertilizer feeder; 3. acceleration tube; 4. separation tube; 5. high-speed dynamic image analyzer; 6. arc-shaped trough; 7. AFAS; 8. primary air-diverting arc plate; 9. secondary air-diverting arc plate.

The fertilizer used in the experiment was urea (China National Coal Group Corp., Beijing, China). Fertilizer particles with a similar mass and particle sizes were selected for the experiment and analysis. Fertilizer particles were sieved using sieves with an aperture of 4 mm and 3.2 mm, respectively (Linshuo-brand sieve, with mesh apertures of 4 mm and 3.2 mm), and fertilizer particles on the 3.35 mm sieve were taken for the experiment.

2.3.2. Experimental Indicators and Test Method

(1) Fertilizer injection speed

Fertilizer injection speed affects the depth of penetration into the paddy soil. A high-speed dynamic image analyzer was used to capture the movement of fertilizer particles ejected from the secondary air–fertilizer outlet and import the image into post-processing software. The speeds of 30 random fertilizer particles were captured and the average value was calculated.

(2) Fertilizer separation loss rate

The fertilizer separation loss rate reflects the air–fertilizer separator’s performance. In this study, a high-speed dynamic image analyzer was used to record the number of fertilizer particles ejected from the secondary air–fertilizer outlet within 3 s (n_1) and the

number ejected from other locations (n_2), and the separation loss rate η_p was calculated using Equation (12).

$$\eta_p = \frac{n_2}{n_1 + n_2} \quad (12)$$

where n_1 is the number of fertilizer particles ejected from the secondary air–fertilizer outlet, pcs; n_2 is the number of fertilizer particles ejected at other locations, pcs.

(3) Outlet airflow speed

The outlet airflow speed reflects the air–fertilizer separation ability of the air–fertilizer separator. The airflow speed at the secondary air–fertilizer outlet was measured using a YIOU anemometer.

2.3.3. Experimental Design

The primary objective of the experiment was to optimize the parameters of the air–fertilizer separator according to their influence on the indicators. The arc radius of the AFAST and the central angle of the arc-shaped trough affect the centrifugal force of the fertilizer particles, so as to affect the air–fertilizer separation performance; the depth of the primary arc-trough influences both the air–fertilizer separation performance and fertilizer separation loss rate.

Therefore, quadratic orthogonal rotation combination experiments were conducted, taking the arc radius of the AFAST (X_1), the central angle of the arc-shaped trough (X_2), and the primary arc-trough depth (X_3) as experimental factors, and the fertilizer injection speed, fertilizer separation loss rate, and outlet airflow speed were taken as evaluation indicators. The range of values for the three experimental factors was determined by preliminary single-factor experiments and theoretical analysis. The levels of the experimental factors were coded as shown in Table 2.

Table 2. Factor-level code table.

Level	Arc Radius of AFAST X_1 (mm)	Central Angle of Arc-Shaped Trough X_2 (°)	Primary Arc-Trough Depth X_3 (mm)
+1.68	390	54	16
1	378	51	15
0	360	46	13.5
−1	342	41	12
−1.68	330	38	11

3. Results and Discussion

3.1. Experimental Results

The experiment arrangement and results are shown in Table 3. The data processing and analysis were performed using Design-Expert 13.

Table 3. Experimental design and results.

No.	Arc Radius of AFAST X_1 (mm)	Central Angle of Arc-Shaped Trough X_2 (°)	Primary Arc-Trough Depth X_3 (mm)	Fertilizer Injection Speed Y_1 (m/s)	Fertilizer Separation Loss Rate Y_2 (%)	Outlet Airflow Speed Y_3 (m/s)
1	−1	−1	−1	21.57	11.84	46.55
2	1	−1	−1	21.88	10.36	44.31
3	−1	1	−1	20.58	12.85	41.29
4	1	1	−1	21.21	11.12	40.06

Table 3. Cont.

No.	Arc Radius of AFAST X_1 (mm)	Central Angle of Arc-Shaped Trough X_2 (°)	Primary Arc-Trough Depth X_3 (mm)	Fertilizer Injection Speed Y_1 (m/s)	Fertilizer Separation Loss Rate Y_2 (%)	Outlet Airflow Speed Y_3 (m/s)
5	−1	−1	1	21.89	8.47	57.83
6	1	−1	1	21.86	7.65	50.98
7	−1	1	1	21.23	10.78	48.02
8	1	1	1	21.99	11.02	44.73
9	−1.68	0	0	21.41	11.6	49.1
10	1.68	0	0	21.87	9.93	43.59
11	0	−1.68	0	21.93	8.63	52.94
12	0	1.68	0	21.23	12.17	41.39
13	0	0	−1.68	21.13	12.45	40.32
14	0	0	1.68	22.00	8.88	52.15
15	0	0	0	21.83	10.37	45.98
16	0	0	0	21.67	10.3	46.65
17	0	0	0	21.55	10.43	46.23
18	0	0	0	21.56	10.21	45.97
19	0	0	0	21.66	10.78	45.93
20	0	0	0	21.73	9.8	45.93
21	0	0	0	21.61	10.78	46.13
22	0	0	0	21.67	10.3	46.27
23	0	0	0	21.64	10.45	46.88

3.2. Analysis of Experimental Results

The regression models for the fertilizer injection speed (Y_1), fertilizer separation loss rate (Y_2), and outlet airflow speed (Y_3) were all established and analyzed at the significance level of $\alpha = 0.05$ (Table 4).

It can be obtained from the analysis of variance in Table 4 that all three models are highly significant ($p < 0.0001$), with F -values well above the critical threshold. Their multiple correlation coefficients were 0.94, 0.97, and 0.99, indicating strong agreement between the predicted and measured values. The lack-of-fit tests were not significant ($p > 0.05$), confirming the validity of the models for prediction.

For the fertilizer injection speed, the order of factor influence is $X_2 > X_3 > X_1$; for the separation loss rate, it is $X_3 > X_2 > X_1$; and for the outlet airflow speed, it is $X_3 > X_2 > X_1$. After removing insignificant terms, the final regression equations for the three responses were obtained, as shown in Equation (13).

$$\begin{cases} Y_1 = 37.29 - 7.13 \times 10^{-3} X_1 - 0.74 X_2 + 0.16 X_3 + 1.64 \times 10^{-3} X_1 X_2 + 0.02 X_2 X_3 \\ Y_2 = 193.84 - 0.5 X_1 - 1.09 X_2 - 9.29 X_3 + 0.01 X_1 X_3 + 0.07 X_2 X_3 \\ Y_3 = 30.03 - 0.14 X_1 - 3.01 X_2 + 18.70 X_3 + 6.73 \times 10^{-3} X_1 X_2 - 0.03 X_1 X_3 - 0.12 X_2 X_3 + 0.02 X_2^2 \end{cases} \quad (13)$$

Table 4. Analysis of variance of regression equation of fertilizer injection speed.

Source	Fertilizer Injection Speed, Y_1 /(m/s)				
	Sum of Squares	df	Mean Square	F-Value	p-Value
Model	2.40	9	0.27	25.21	<0.0001 **
X_1	0.44	1	0.44	41.34	<0.0001 **
X_2	0.83	1	0.83	78.5	<0.0001 **
X_3	0.75	1	0.75	70.60	<0.0001 **

Table 4. Cont.

Source	Fertilizer Injection Speed, Y_1 /(m/s)				
	Sum of Squares	df	Mean Square	F-Value	p-Value
X_1X_2	0.15	1	0.15	14.56	0.0021 **
X_1X_3	0.01	1	0.01	0.52	0.4831
X_2X_3	0.16	1	0.16	15.09	0.0019 **
X_1^2	0.01	1	0.01	0.59	0.4576
X_2^2	0.027	1	0.03	2.52	0.1363
X_3^2	0.034	1	0.03	3.22	0.0962
Residual	0.14	13	0.01	-	-
Lack of fit	0.079	5	0.02	2.13	0.1632
Pure error	0.0596	8	0.01	-	-
Cor total	2.547	22	-	-	-

Source	Fertilizer Separation Loss Rate, Y_2 /(%)				
	Sum of Squares	df	Mean Square	F-Value	p-Value
Model	34.38	9	3.82	48.98	<0.0001 **
X_1	3.19	1	3.19	40.88	<0.0001 **
X_2	13.16	1	13.16	168.66	<0.0001 **
X_3	14.88	1	14.88	190.75	<0.0001 **
X_1X_2	0.08	1	0.08	1.05	0.3239
X_1X_3	0.86	1	0.86	11.09	0.0054 **
X_2X_3	1.91	1	1.91	24.5	0.0003 **
X_1^2	0.20	1	0.2	2.59	0.1315
X_2^2	0.002	1	0.0042	0.05	0.8198
X_3^2	0.01	1	0.0952	1.22	0.2893
Residual	1.01	13	0.078	-	-
Lack of fit	0.31	5	0.062	0.7	0.64
Pure error	0.71	8	0.09	-	-
Cor total	35.39	22	-	-	-

Source	Outlet Airflow Speed, Y_3 /(m/s)				
	Sum of Squares	df	Mean Square	F-Value	p-Value
Model	379.8	9	42.2	267.23	<0.0001 **
X_1	38.32	1	38.32	242.67	<0.0001 **
X_2	148.24	1	148.24	938.73	<0.0001 **
X_3	177.58	1	177.58	1124.48	<0.0001 **
X_1X_2	2.61	1	2.61	16.53	0.0013 **
X_1X_3	5.56	1	5.56	35.22	<0.0001 **
X_2X_3	5.36	1	5.36	33.96	<0.0001 **
X_1^2	0.08	1	0.08	0.48	0.5011
X_2^2	2.05	1	2.05	12.96	0.0032 **
X_3^2	0.01	1	0.014	0.09	0.7675
Residual	2.05	13	0.16	-	-
Lack of fit	1.13	5	0.23	1.97	0.1875
Pure error	0.92	8	0.11	-	-
Cor total	381.86	22	-	-	-

Note: ** is extremely significant.

3.3. Response Surface Analysis

3.3.1. Effect of Factors on Fertilizer Injection Speed and Parameter Optimization

The effect of the factors on fertilizer injection speed is shown in Figure 5. It can be observed that the fertilizer injection speed is jointly affected by the arc radius of the AFAST, the central angle of the arc-shaped trough, and the primary arc-trough depth. When the trough depth is 13.5 mm and the central angle is fixed, injection speed increases with the

arc radius. Conversely, when the arc radius is fixed, injection speed decreases with the increasing central angle because the enlarged outlet space weakens the airflow acceleration.

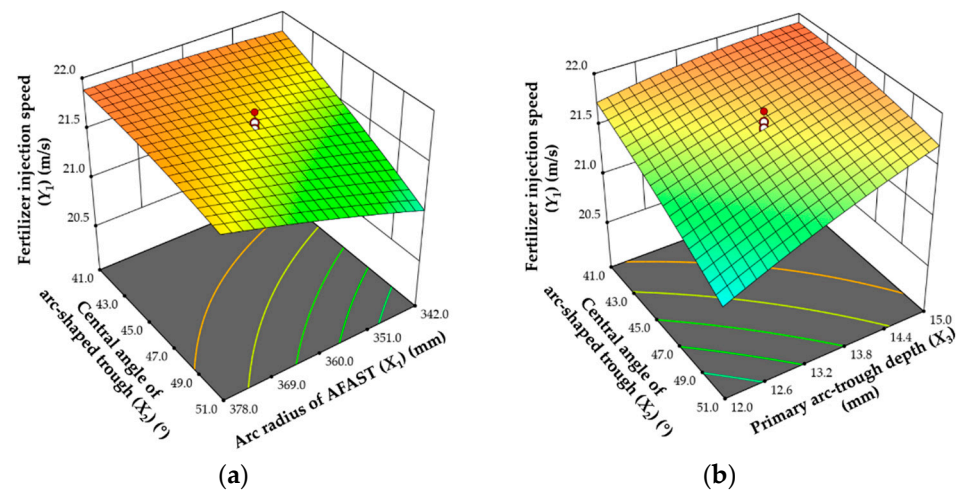


Figure 5. Effects of factors on fertilizer injection speed. (a) The interaction between the arc of AFAST and the central angle of the arc-shaped trough; (b) the interaction between the primary arc-trough depth and central angle of arc-shaped trough.

At an arc radius of 360 mm, the injection speed rises with the increase in trough depth but it will decrease with the increase in central angles. Based on the regression model, the optimal parameter combination is an arc radius of 377.84 mm, a central angle of 47.87° , and a trough depth of 14.88 mm. Under these conditions, the predicted injection speed is 21.98 m/s.

3.3.2. Effect of Factors on Fertilizer Separation Loss Rate and Parameter Optimization

The influence of structural parameters on the fertilizer separation loss rate is presented in Figure 6. When the central angle is 46° and the trough depth is constant, the fertilizer separation loss rate will decrease with the increase in arc radius of the AFAST. Similarly, at a fixed arc radius of the AFAST, increasing the trough depth will reduce the loss rate, whereas at a fixed depth, the loss rate rises with the increase in central angle of the arc-shaped trough.

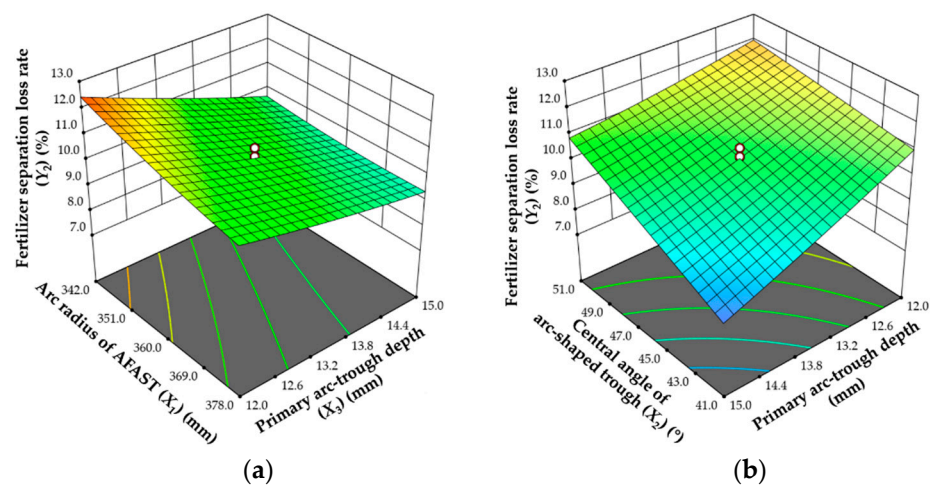


Figure 6. Effects of various factors on fertilizer separation loss rate. (a) The interaction between the primary arc-trough depth and arc radius of arc-shaped tube; (b) the interaction between the primary arc-trough depth and central angle of arc-shaped trough.

In summary, both larger arc radii and deeper troughs are favorable for reducing fertilizer separation loss, while greater central angles have the opposite effect. Regression model optimization identified the best combination as an arc radius of 377.84 mm, a central angle of 41.24° , and a trough depth of 15 mm, under which the predicted loss rate is 7.79%.

3.3.3. Effect of Factors on Outlet Airflow Speed and Parameter Optimization

The effects of different parameters on the outlet airflow speed are shown in Figure 7. At arc radius of 360 mm, the airflow speed increases with the increase in trough depth but decreases with the increase in the central angle of the arc-shaped trough. When the arc-shaped trough depth is 13.5 mm, the airflow speed decreases with the increase in the arc radius of the AFAST and the central angle of arc-shaped trough.

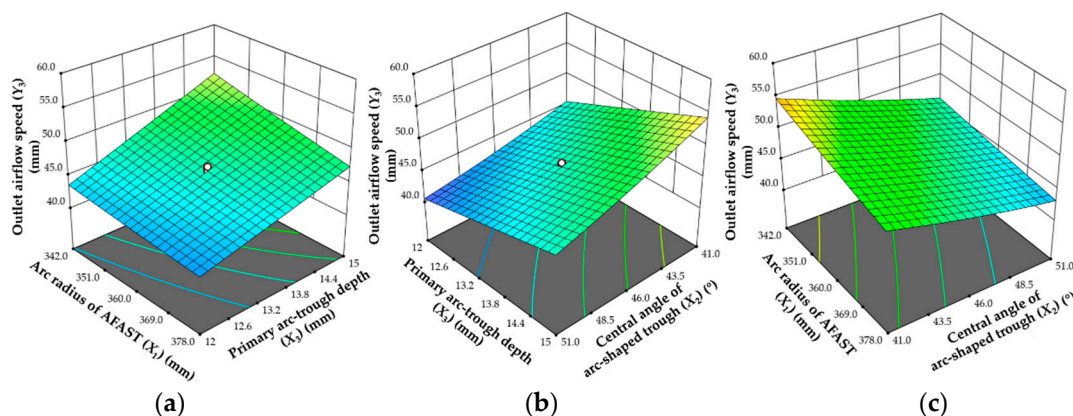


Figure 7. Influence of various factors on outlet airflow speed. (a) The interaction between the primary arc-trough depth and arc radius of arc-shaped tube; (b) the interaction between the primary arc-trough depth and central angle of arc-shaped trough; (c) the interaction between the arc radius of AFAST and the central angle of the arc-shaped trough.

These results indicate that the outlet airflow speed is particularly sensitive to the depth and the central angle of the arc-shaped trough. According to the regression model, the optimal configuration is an arc radius of 377.84 mm, a central angle of 50.76° , and a trough depth of 11.97 mm; then, the predicted airflow speed is 40.32 m/s.

3.4. Comprehensive Parameter Optimization and Experimental Verification

Design-Expert 13 was used for parameter optimization. According to the importance of the indicators, the target for the fertilizer injection speed is set as maximal, with a weight of 0.2; the target for fertilizer separation loss rate is set as minimal, with a weight of 0.3; and the target of outlet airflow speed is set as minimal and the weight is set as 0.5.

The optimal structural parameters for the air–fertilizer separator are obtained as follows: the arc radius of the AFAST is 377.84 mm, the central angle of arc-shaped trough is 44.77° , and the primary arc-trough depth is 12.47 mm. Then, the model predicts a fertilizer injection speed of 21.70 m/s, a fertilizer separation loss rate of 10.35%, and an outlet airflow speed of 43.28 m/s.

To verify the optimal parameter combination, verification tests were repeated three times using the constructed test system. The optimized parameters are rounded with the arc radius of the AFAST of 380 mm, the central angle of the arc-shaped trough of 45° , and a primary arc-trough depth of 12.5 mm.

The images of the fertilizer particles in the separator are captured using a high-speed camera, as shown in Figure 8. It can be observed that the fertilizer moves along the back wall of the arc-shaped separator and finally shoots into the soil.

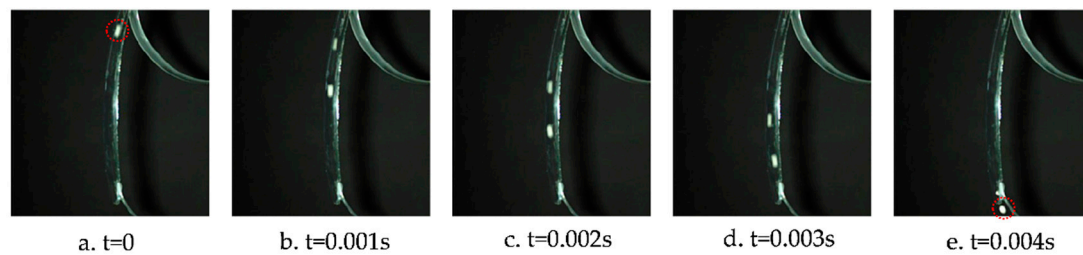


Figure 8. Movement state of fertilizer inside the separator.

The verification results showed that the mean values were 21.45 m/s for the fertilizer injection speed, 42.54 m/s for the outlet airflow speed, and 10.22% for the fertilizer separation loss rate; the test values of each factor are close to the predicted values, with errors of 1.2%, 1.7%, and 1.3%, respectively, indicating that the binomial optimization based on orthogonal rotation combination experiments and the predictions of the regression model have high accuracy and reproducibility.

4. Conclusions and Discussion

- (1) An air–fertilizer separator for a pneumatic deep fertilization machine was designed to separate the air and fertilizer before they enter the paddy soil and to direct the airflow away from the fertilizer. The structural parameters of the air–fertilizer separator were determined.
- (2) The testing system was developed, and the bench tests were carried out, and a regression model was established between the fertilizer injection speed, fertilizer separation loss rate, and outlet airflow speed, and the arc radius of the AFAST, central angle of arc-shaped trough, and primary arc-trough depth. Each factor and their interactions had a significant impact on the evaluation index. The regression models have a good fit and can be used for evaluation index prediction.
- (3) The optimal parameters of the air–fertilizer separator are determined using multi-objective optimization as follows: arc radius of the AFAST of 380 mm, central angle of the arc-shaped trough of 45° , and depth of the primary arc-shaped trough of 12.5 mm. Three verification tests were repeated using the built test system, and the results are a fertilizer injection speed of 21.45 m/s, a fertilizer separation loss rate of 10.22%, and an outlet airflow speed of 42.54 m/s. The air–fertilizer separator can meet the design requirements for deep pneumatic fertilization.
- (4) It should be noted that the present study was carried out mainly under controlled laboratory conditions. Field environments may affect the separation performance. In addition, only one type of fertilizer granule was tested. Therefore, a simulation study and field test should be carried out to verify the results of the study and optimize the parameters of the air–fertilizer separator.

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