

CFD–DEM-based optimization of an air-assisted fertilizer conveying system using surplus blower airflow from a precision seeder

Haiji Wang

Wuwei Vocational and Technical University

Zhaojun Wang

230141@wwvtu.edu.cn

Wuwei Vocational and Technical University

Yajie Zhan

Wuwei Vocational and Technical University

Zengli Wang

Wuwei Vocational and Technical University

Kaibo Tang

Shihezi University

Wancheng Dong

Shihezi University

Article

Keywords: Agricultural machinery, pneumatic fertilizer conveying, energy reuse, CFD–DEM coupling, parameter optimization

Posted Date: September 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10900627/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

CFD–DEM-based optimization of an air-assisted fertilizer conveying system using surplus blower airflow from a precision seeder

Haiji Wang¹, Zhaojun Wang^{1*}, Yajie Zhan¹, Zengli Wang¹, Kaibo Tang² and Wancheng Dong^{2*}

¹ College of Agriculture and Food Engineering, Wuwei Vocational and Technical University, Wuwei, 733000, China.

² College of Mechanical and Electrical Engineering, Shihezi University, Shihezi, 832000, China

*Correspondence: Zhaojun Wang, 230141@wwvtu.edu.cn

Wancheng Dong, Dong_shzu@163.com

Abstract: To address energy waste from surplus airflow discharge in air-suction seeders, a pneumatic fertilizer delivery system was developed using residual fan pressure as auxiliary power. Coupled computational fluid dynamics and discrete element simulations with bench tests investigated effects of pipe diameter, airflow velocity, and fertilizer delivery rate on performance, using velocity non-uniformity coefficient and discharge uniformity coefficient of variation as indices. Single-factor and orthogonal experiments determined optimal parameters. Results showed airflow velocity had the greatest influence, followed by pipe diameter and delivery rate. Interactions between pipe diameter and airflow velocity, and between airflow velocity and delivery rate, significantly affected airflow uniformity and discharge consistency. The optimal combination was pipe diameter 25 mm, airflow velocity 20 m·s⁻¹, and delivery rate 13.50 g·s⁻¹, yielding velocity non-uniformity coefficient 6.37% and discharge uniformity coefficient of variation 1.85%. Bench validation showed average relative errors below 9%, confirming model reliability. This study provides theoretical and technical support for developing pneumatic fertilizer delivery systems for air-suction seeders and establishing energy reuse mechanisms in agricultural machinery.

Keywords: Agricultural machinery; pneumatic fertilizer conveying; energy reuse; CFD–DEM coupling; parameter optimization

1. Introduction

Chemical fertilizer is a core input for ensuring grain yield improvement and food security, contributing 40%~60% to grain yield increase [1]. However, the application rate of chemical fertilizer per unit area of arable land in China has long remained above 300 kg·hm⁻², far exceeding the world average. Consequently, problems such as soil acidification, water eutrophication, and greenhouse gas emissions caused by excessive application are becoming increasingly severe [2-4]. Against the background of agricultural green development and the “dual carbon” goals, improving fertilizer use efficiency and developing precision fertilization equipment have become urgent tasks in the field of agricultural mechanization [5-6]. Combined seeding and fertilizing machines can complete multiple operations such as fertilizing, seeding, soil covering, and compaction in a single pass, and have become the mainstream development direction. In the seeding process, the fan outlets of air-suction seeders mostly adopt an open design, with large amounts of surplus airflow discharged directly to the atmosphere. The energy utilization rate of the fan is only 40%~50%, which not only causes energy waste, but the dust carried by the airflow also exacerbates local environmental pollution [7]. If the surplus airflow is secondarily utilized as auxiliary power for fertilizer delivery to achieve the dual function of “negative-pressure seeding and positive-pressure fertilization”, it would have important practical significance for reducing overall machine operating energy consumption, improving system integration, and promoting energy conservation and emission reduction in agricultural mechanization [8].

Pneumatic conveying technology has broad application prospects in the field of seeding and fertilizing machinery due to its advantages of being seed-friendly, high efficiency, and flexible

pipeline layout [9]. Pneumatic precision seeders were successfully developed in the 1940s, and by the 1980s, countries such as the United States and Canada had completed large-scale promotion of pneumatic conveying technology in the seeding field, with the produced seeding and fertilizing equipment capable of efficient “one-device-multiple-row” operation [10,11]. Research on pneumatic fertilizer delivery in China has developed rapidly in recent years, mainly focusing on the structural design of fertilizer discharge devices and the improvement of fertilizer delivery performance. Yang Qinglu et al. developed layered fertilization regulation devices and layered deep-application devices for a pneumatic centralized variable-rate fertilizer discharge system, achieving upper, middle, and lower three-layer fertilization [12,13]; Liao Yitao et al. designed a pneumatic fertilizer delivery system for a high-speed planter suitable for both rapeseed and wheat, achieving synchronous pneumatic conveying of seeds and fertilizer by optimizing airflow distribution and mixing structures [14]; Zhang et al. designed a spiral conveying pipe structure, significantly improving fertilizer delivery uniformity through high-speed rotating air-fertilizer mixed flow [15]. The above studies indicate that the significant differences in suspension velocity and conveying characteristics between fertilizer particles and seeds (due to the high density), wide particle size distribution, and easy moisture absorption and agglomeration of fertilizer particles constitute the core challenge of pneumatic fertilizer delivery. The uniformity of airflow distribution and the uniformity of air-fertilizer mixing directly determine the consistency of fertilizer application among rows, yet research on dedicated fertilizer delivery pipelines and matching parameters of supporting air sources based on the physical properties of fertilizer particles remains insufficient.

To reveal the gas-solid two-phase flow transmission mechanism in pneumatic fertilizer delivery pipelines and improve fertilizer delivery performance, Yang Qinglu et al. conducted numerical analysis of particle motion in a centralized fertilizer distributor based on the CFD-DEM coupling method, revealing the distribution law of gas-solid two-phase flow inside the

distributor [16]; Wang Lei et al. constructed a gas-solid coupling model for the seed delivery tube of a rapeseed combined seeding and fertilizing device, verifying the effectiveness of airflow-assisted conveying [17]; Li Liwei established a numerical model of the gas-fertilizer mixing chamber for a pneumatic rice fertilizer applicator, investigating the influence mechanisms of the throat area, throat length, gas inlet pressure, and fertilizer discharge rate on fertilization performance [18]; Wang et al. constructed a CFD-DEM coupled simulation model for a multi-channel pneumatic granular fertilizer spreader, investigating the influence mechanisms of the fluted roller fertilizing process and rotating airflow field on the discharge consistency of each channel and fertilization uniformity [19]. Existing studies have shown that structural parameters such as pipe diameter, airflow velocity, and bend curvature radius, as well as operating parameters, significantly affect particle motion trajectories, velocity distribution, and fertilizer discharge uniformity. However, overall, coupled numerical simulation studies have mainly focused on seed delivery pipelines or general-purpose fertilizer delivery pipelines, and coupled simulation research on the entire process of fertilizer particle start-up, acceleration, and stable conveying under the condition of low-velocity positive-pressure airflow from the fan remains insufficient. The interaction mechanisms between pipeline structural parameters and airflow parameters on fertilizer delivery uniformity need to be systematically revealed.

In summary, existing research still has three main deficiencies: First, the utilization rate of surplus airflow from the fan of air-suction seeders is low, and there is a lack of dedicated pneumatic-assisted fertilizer delivery pipeline designs matching the characteristics of fan exhaust airflow. Second, the coupled transmission mechanism of gas-solid two-phase flow in fertilizer delivery pipelines is still unclear, and the interaction laws among key parameters such as pipe diameter, airflow velocity, and fertilizer delivery rate need to be further revealed. Third, existing research has mainly focused on seed conveying and fertilizer discharge devices, while

systematic research on the gas-solid coupling dynamic matching mechanism under the condition of surplus airflow from the fan is still lacking.

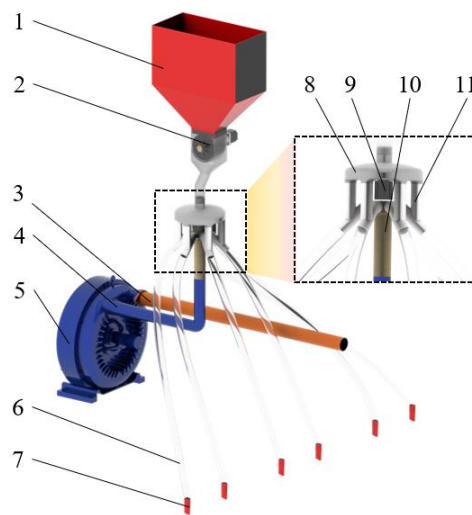
To address the above problems, this study takes the surplus airflow from the fan outlet of an air-suction cotton seeder as auxiliary power to design a pneumatic-assisted fertilizer delivery pipeline system. Using the CFD-DEM coupled simulation method, the influence laws of fertilizer conveying pipe diameter, airflow velocity, and fertilizer delivery rate on fertilizer delivery performance were systematically investigated. The optimal parameter ranges were determined through single-factor experiments, and the optimal parameter combination was obtained using Box–Behnken design and response surface optimization. Bench tests were conducted to verify the fertilization performance of the system, aiming to establish a quantitative matching relationship among “airflow velocity-pipeline geometric parameters-particle conveying uniformity”, providing a theoretical basis and technical reference for the development of pneumatic-assisted fertilization systems for air-suction seeders.

2. Materials and methods

2.1 Overall design of the pneumatic-assisted fertilization system

Based on the pneumatic seeding-fertilizing-mulching combined machine, a pneumatic-assisted fertilizer delivery device was designed. The device mainly comprises a fertilizer feeding unit, a fertilizer distribution unit, a pneumatic-assisted fertilizer delivery pipeline, and furrow openers, as shown in **Figure 1(a)**. The device adopts an operating mode of “negative-pressure pneumatic seeding—mechanical fertilizer feeding and distribution—positive-pressure pneumatic-assisted fertilizer delivery”, and its main working process is shown in **Figure 1(b)**. The air inlet of the fan provides negative pressure for the pneumatic seeding device to achieve precision seed metering. The fertilizer feeding unit quantitatively discharges fertilizer through an external fluted roller fertilizer meter. The fertilizer distribution unit uses a mechanical

centrifugal fertilizer distributor to evenly allocate fertilizer to six outlets. The pneumatic-assisted fertilizer delivery pipeline consists of an airflow distributor, air-fertilizer mixers, and fertilizer delivery tubes, which deliver fertilizer to each row under airflow assistance. The surplus airflow from the fan outlet is introduced into the fertilizing system through an air pipeline to provide a positive-pressure air source. During operation, fertilizer enters the distributor from the fertilizer meter. After being evenly distributed under the combined action of centrifugal force and the thrust of fertilizer-leveling blades, it falls into each air-fertilizer mixer, where it mixes with the airflow to form a gas-solid two-phase flow. The mixture then passes through the fertilizer delivery tubes into the furrow openers, and is finally deep-placed beside the seed rows.



- 1.Fertilizer hopper 2.Fertilizer feeding unit 3.Negative-pressure inlet pipe 4.Positive-pressure outlet pipe
5. Fan 6. Fertilizer delivery tube 7.Fertilizer outlet 8.Fertilizer distributor 9.Fertilizer discharge motor
10.Airflow distributor 11.Air-fertilizer mixer

Fig. 1 Schematic diagram of pneumatic-assisted fertilizer delivery system

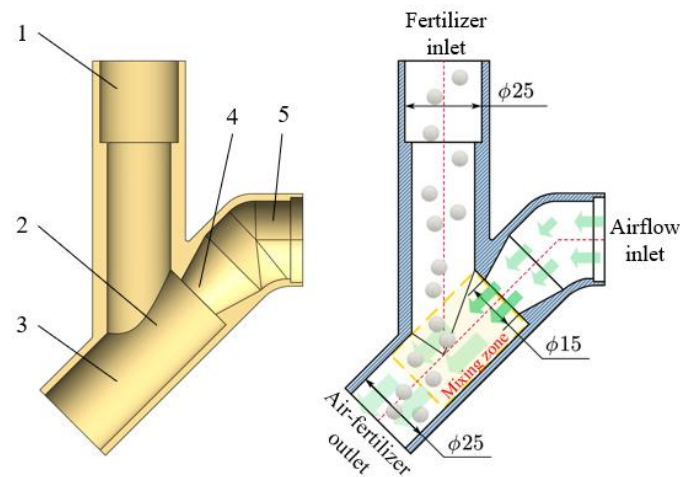
2.2 Structural Design of Key Components

2.2.1 Airflow distributor

The airflow distributor serves as a critical junction connecting the fan outlet to the pneumatic-assisted fertilizer delivery pipeline. Its function is to rationally distribute the airflow

from the fan outlet, ensuring that all six branches receive uniform and stable pneumatic power. To minimize flow deviation and local energy loss during distribution, a structure featuring central air intake with six circumferentially arranged air outlets was adopted. The airflow diffuses uniformly from the central inlet to each branch in the radial direction, and the axisymmetric layout suppresses vortex generation to ensure airflow consistency among all branches. The distributor employs an equal-resistance structural design, rendering the local resistance of each branch approximately identical. Regarding key dimensional parameters, the inlet pipe diameter is 72 mm, matching the fan outlet diameter, with the two connected by a steel wire reinforced hose. To reduce velocity non-uniformity caused by flow channel variations, all six branch outlet diameters are 25 mm and connected to the inlets of the air-fertilizer mixers. The branches are arranged at equal angular intervals along the circumference, maintaining geometric symmetry.

2.2.2 Air-fertilizer mixer



1. Fertilizer inlet tube 2. Air-fertilizer mixing chamber 3. Fertilizer outlet
4. Constricted tube 5. Air inlet tube

Fig. 2 Schematic Diagram of the Structure of Air-Fertilizer Mixer

The air-fertilizer mixer, designed based on the Venturi principle and shown in **Figure 2**, is the core component for achieving efficient mixing of airflow and fertilizer particles. It consists

of a fertilizer inlet, an air inlet, a mixing chamber, and a fertilizer outlet. The fertilizer inlet is connected to the outlet of the fertilizer distributor, the air inlet is connected to a branch of the airflow distributor, and the fertilizer outlet is connected to the fertilizer delivery tube. According to the Venturi effect, when the positive-pressure airflow passes through the constricted section and enters the mixing chamber, the flow cross-sectional area decreases, causing the airflow velocity to increase sharply [20]. Based on the continuity equation, the airflow velocity at the constricted section is given by **Equation (1)**:

$$v_2 = v_1 \left(\frac{d_1}{d_2} \right)^2 \quad (1)$$

Where v_1 is the airflow velocity at the air inlet, $\text{m}\cdot\text{s}^{-1}$; v_2 is the airflow velocity at the constricted section, $\text{m}\cdot\text{s}^{-1}$; d_1 is the diameter of the air inlet, mm; and d_2 is the diameter of the constricted section, mm.

The increased airflow velocity creates a negative pressure zone at the throat of the mixing chamber. Under the combined action of negative pressure and self-gravity, fertilizer particles rapidly enter the mixing chamber, fully mixing with the airflow to form a gas-solid two-phase flow before entering the fertilizer delivery tube. The feeding angle is set at 45° to effectively utilize the shear force of the high-velocity airflow to break up potential particle agglomerates and promote uniform fertilizer dispersion. Both the fertilizer inlet diameter d_3 and the air inlet diameter d_1 are set at 25 mm to match the upstream and downstream interfaces. The throat and fertilizer outlet diameters of the mixing chamber are 25 mm to maintain conveying channel continuity. The constricted section diameter is the core parameter of the Venturi effect, directly affecting the airflow velocity and negative pressure intensity at the throat. For pneumatic conveying of low-density materials, the contraction ratio is generally 0.3~0.6. An excessively small constricted section diameter d_2 will significantly increase local resistance and energy consumption, while an excessively large diameter will fail to generate sufficient negative

pressure, leading to insufficient fertilizer suction capacity. With the contraction ratio set at 0.6, the constricted section diameter d_2 is determined to be 15 mm.

2.2.3 Selection and Layout of Fertilizer Delivery Tubes

The fertilizer delivery tube serves as the terminal executive component of the pneumatic-assisted fertilizer delivery pipeline. It is required to possess high strength, good toughness, wear resistance, and transparency for observing the internal conveying status. Therefore, PVC steel wire reinforced hose is selected as the fertilizer delivery tube. Regarding pipe diameter selection, five specifications of 19, 22, 25, 28, and 32 mm are chosen to systematically investigate the matching relationship between airflow conveying capacity and fertilizer delivery rate. Due to varying installation distances between the fertilizer feeding unit and each fertilizing furrow opener, the lengths and inclination angles of the fertilizer delivery tubes differ. Based on the fertilizer hopper installation position, working width, and seeding row spacing, the minimum installation distance for each tube is calculated: the two central tubes are 1200 mm, the two outermost tubes are 1500 mm, and the remaining two tubes are 1350 mm. The varying tube lengths result in different frictional resistances along each branch, which must be compensated during subsequent airflow parameter matching. To prevent fertilizer accumulation and blockage even without airflow assistance, the inclination angle at any point along the tube must exceed the friction angle between fertilizer particles and the tube wall. According to actual installation constraints, the inclination angles of all fertilizer delivery tubes range from 45° to 80°.

2.3 Dynamics Analysis of Fertilizer Particles

The motion of fertilizer particles in the delivery tube can be divided into two cases: the first is non-contact motion, in which the fertilizer particles move through the pipe without contacting the inner wall; the second is contact motion, in which the fertilizer particles directly

contact the inner wall while moving along the pipe, possibly accompanied by collisions, friction, and other interactions.

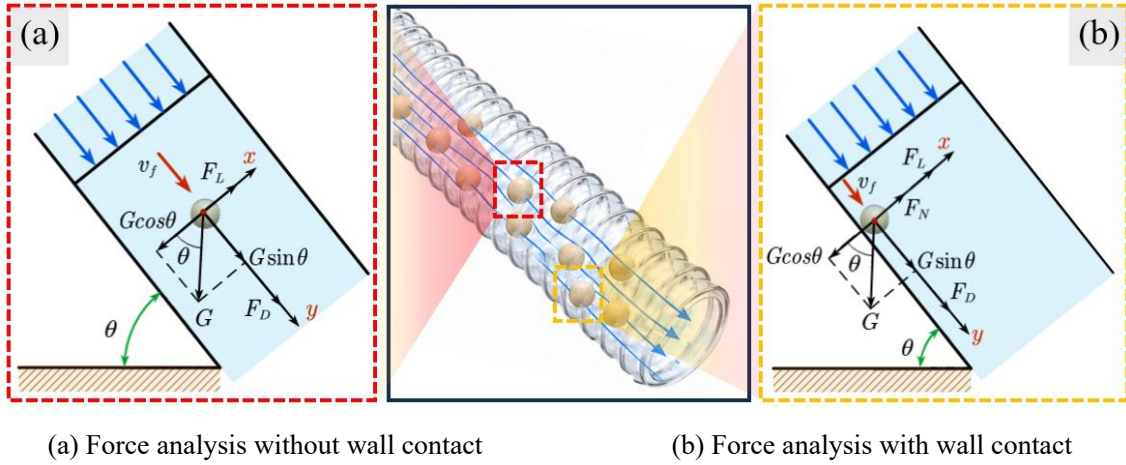


Fig.3 Force Diagram of Fertilizer Granules in a Pipeline

Force analysis was conducted for fertilizer particles in these two motion states. Assuming the fertilizer delivery tube is inclined at an angle θ to the horizontal, and both fertilizer particles and airflow move along the pipe. When the fertilizer particles are not in contact with the pipe wall, the particles are mainly subjected to airflow drag force F_D , lift force F_L perpendicular to the airflow direction, and the self-weight G of the fertilizer particles. When the particle velocity is less than the airflow velocity, F_D represents the drag force exerted by the airflow on the particles; otherwise, it acts as resistance. A coordinate system is established as shown in **Figure 3(a)**, and the force analysis yields:

$$\begin{cases} F_X = F_L - G \cos \theta \\ F_Y = F_D + G \sin \theta \end{cases} \quad (2)$$

When fertilizer particles come into contact with the pipe wall during motion, in addition to the airflow drag force F_D , the lift force F_L perpendicular to the airflow direction, and the self-weight G of the fertilizer particles, the particles are also subjected to the normal support force F_N from the fertilizer delivery tube wall and the friction force between the fertilizer particles and the tube wall. The force analysis is shown in **Figure 3(b)**, and we have:

$$\begin{cases} F_X = F_L + F_N - G \cos \theta \\ F_Y = F_D + G \sin \theta - f \\ f = \mu F_N \end{cases} \quad (3)$$

where F_X represents the force on the fertilizer particle along the X direction, N; F_Y represents the force on the fertilizer particle along the Y direction, N; and μ is the friction coefficient between the fertilizer particles and the pipe.

The calculation formula for the drag force F_D exerted by airflow on particles is shown in **Equation (4)**:

$$F_D = \frac{1}{8} C_d \pi d_f^2 \rho_0 (v_f - v_0)^2 \quad (4)$$

where d_f is the fertilizer particle diameter, m; ρ_0 is the air density, $\text{kg}\cdot\text{m}^{-3}$, taken as $1.205 \text{ kg}\cdot\text{m}^{-3}$; v_f is the fertilizer particle velocity, $\text{m}\cdot\text{s}^{-1}$; v_0 is the airflow velocity, $\text{m}\cdot\text{s}^{-1}$; and C_d is the drag coefficient related to the particle slip Reynolds number Re_p .

The lift force F_L is caused by the pressure difference generated by the airflow on the surface of the fertilizer particles. It includes the Saffman shear lift force F_S produced by the velocity gradient and the Magnus force F_M generated by particle rotation, where F_S is related to the position and motion state of the particles in the flow field, and F_M is related to the angular velocity ω of particle rotation. When the particles are in a suspended state in the pipe, the gravitational component $G \cos \theta$ of the fertilizer particles along the X-axis can be considered to be in equilibrium with the lift force F_L . When the gravitational component $G \cos \theta$ is greater than the lift force F_L , the fertilizer particles will have a downward acceleration along the X-axis until a new equilibrium is reached or contact with the pipe wall is made. When contacting the pipe wall, the gravitational component $G \cos \theta$ is balanced by the lift force F_L and the normal support force F_N from the pipe wall.

From **Equations (2), (3), and (4)**, the differential equation of motion in the Y-axis direction for fertilizer particles in a suspended state in the pipe is shown in **Equation (5)**:

$$\frac{dv_f}{dt} = \frac{C_d \pi d_f^2 \rho_0}{8m} (v_f - v_0)^2 + g \sin \theta \quad (5)$$

When fertilizer particles are in contact with the pipe wall during motion, the differential equation of motion in the Y -axis direction (i.e., along the pipe) is shown in **Equation (6)**:

$$\frac{dv_f}{dt} = \frac{C_d \pi d_f^2 \rho_0}{8m} (v_f - v_0)^2 + g \sin \theta - \frac{\mu F_N}{m} \quad (6)$$

where m is the mass of the fertilizer particle, kg.

According to **Equations (5) and (6)**, the motion state of fertilizer particles is affected by the particle mass, airflow velocity, particle velocity, and the inclination angle θ of the fertilizer delivery tube to the horizontal. When the fan operating parameters are fixed, the airflow velocity in the pipeline is significantly influenced by the structural dimensions of the fertilizer delivery pipes.

2.4 Simulation Model

2.4.1 Simulation Model Establishment and Solver Configuration

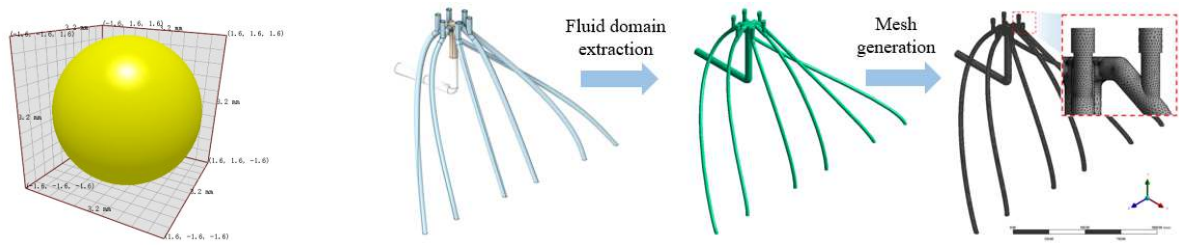
The fertilizer particles used in the experiments were mainly organic microbial fertilizer produced by Woda Agricultural Technology Co., Ltd. Coupled simulations of fertilizer particles and conveying airflow in the pneumatic-assisted fertilizer delivery system were conducted using ANSYS Fluent 2022 R1 and EDEM 2022.1 software based on the CFD-DEM coupled simulation method. The CFD-DEM simulation parameters were determined according to the fertilizer particle parameter calibration methods in references [21,22] and fertilization operation requirements, as shown in **Table 1**.

Table 1. Parameters of Simulation and Contact

Item	Item	Details	Index	Value
EDEM	Materials	Particle	Microbial fertilizer particle diameter/mm	3.2
			Weight/g	0.27
			Water content/%	0.054

CFD	Materials		Density/(kg·m ⁻³)	1.72×10 ³	
			Poisson's ratio	0.32	
			Shear modulus/Pa	1.33×10 ⁷	
		Wire reinforced PVC hose	Density/(kg·m ⁻³)	1.45×10 ³	
			Poisson's ratio	0.44	
			Shear modulus/Pa	4.30×10 ⁸	
		Interaction	Particle- Wire reinforced PVC hose	Coefficient of restitution	0.302
				Coefficient of static friciton	0.30
				Interaction contact model	0.10
		Particle	Particle generation	Factory type	Dynamic
	Generation rate/(g·s ⁻¹)			10~30	
			Fluid/air	Density/(kg·m ⁻³)	1.225
				Viscosity/Pa·s	1.7894e-05
			Velocity-inlet	Velocity magnitude/(m·s ⁻¹)	0~20
Turbulence			Turbulence intensity/%	5	
			Hydraulic diameter/mm	25	
Flow-outlet			Outlet type	Pressure outlet	
Wall		Wall motion	Stationary wall		
		Shear condition	No slip		

Based on material characteristic parameters, a single-sphere model of fertilizer particles was established using EDEM software, as shown in **Figure 4(a)**. Meanwhile, a three-dimensional geometric model of the pneumatic-assisted fertilizer delivery pipeline system was built using SolidWorks software and appropriately simplified. The fluid domain was extracted from the simplified model using ANSYS DesignModeler, and subsequently meshed in ANSYS Mesh, as shown in **Figure 4(b)**. To balance coupling calculation accuracy and computational efficiency, fine meshes were employed in regions with complex geometric structures, combined with edge and surface refinement methods. Through grid independence verification, the final meshing scheme was confirmed to satisfy the calculation accuracy requirements.



(a) DEM model of fertilizer particles

(b) Fluid domain establishment

Fig. 4 Establishment of the coupled model

2.4.2 Coupled Solution Method and Simulation Condition Settings

In ANSYS Fluent 2022 R1, the Transient solver was selected with the gas phase set as air. The Realizable $k-\varepsilon$ turbulence model was employed, the pressure-based solver was adopted, and the SIMPLEC algorithm was used for pressure -velocity coupling. The boundary conditions were configured as follows: the fan outlet was designated as the velocity inlet of the flow field, with airflow velocities ranging from 0 to $20 \text{ m}\cdot\text{s}^{-1}$ and direction perpendicular to the inlet plane; the fertilizer inlets of the air-fertilizer mixers and the outlets of the fertilizer delivery tubes were set as pressure outlets; all walls were assigned no-slip stationary wall boundary conditions. The Hertz-Mindlin no-slip contact model was applied for both particle-particle and particle-wall interactions, with the intrinsic and contact parameters of fertilizer particles and ABS material input into the simulation.

CFD-DEM coupled simulations were performed using EDEM 2022 and ANSYS Fluent 2022 R1. The Eulerian-Eulerian coupling algorithm was employed to achieve momentum and energy exchange between the airflow and fertilizer particles. In EDEM, the time step was set to $1.5 \times 10^{-5} \text{ s}$ to ensure stability of data transfer during coupled calculations; the Fluent time step was set to 100 times that of EDEM, namely $1.5 \times 10^{-3} \text{ s}$, with 1,200 iterations per time step. The data saving interval was 0.001 s, with 100 saving steps. The total coupled simulation duration was 6 s, and data were collected after 3 s when the fluid-solid coupling system had reached a stable state.

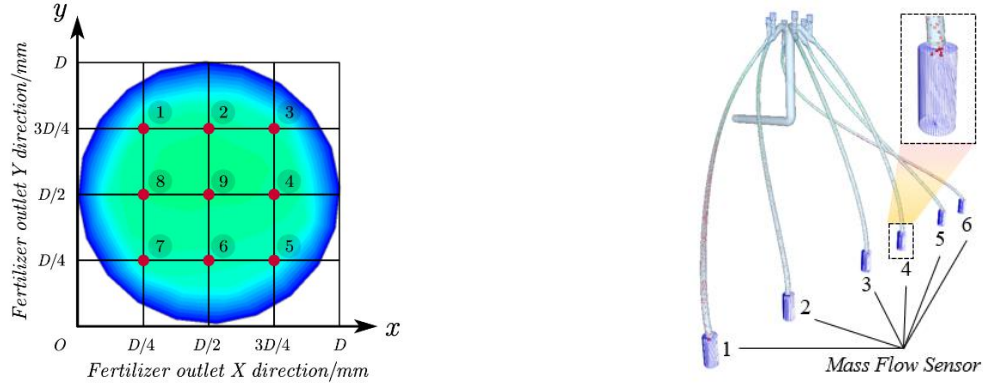
2.4.3 Experimental Factors and Evaluation Indices

Preliminary theoretical analysis and pre-test results indicated that the conveying performance of the pneumatic-assisted fertilizer delivery pipeline is jointly affected by pipeline structural parameters and operating parameters. Therefore, to investigate the effects of structural and operating parameters of the pneumatic-assisted fertilizer delivery device on the test indices, pipe diameter, airflow velocity in the pipeline, and fertilizer delivery rate were selected as experimental factors, while the velocity non-uniformity coefficient and the coefficient of variation of discharge uniformity were selected as test indices to design the simulation experiments. The experimental factors and level coding are shown in **Table 2**.

Table 2. Levels and coding of test factors

Code	Factor Levels		
	Conveying pipe diameter /mm	Airflow velocity /m·s ⁻¹	Fertilizer application rate /g·s ⁻¹
+1	28	20	20
0	25	15	15
-1	22	10	10

The testing methods for airflow velocity and fertilizer discharge at each outlet of the pneumatic-assisted fertilizer delivery pipeline are shown in **Figure 5**. Data were collected after 3 s from the start of the simulation, when the airflow field and particle phase motion in the fluid-solid coupling system had reached a steady state. Velocity contours were added at the cross-sections of each outlet using the Fluent post-processing software CFD-Post, and the 9-point sampling method was employed to obtain the airflow velocities at various points on each cross-section and calculate their average values. During EDEM post-processing, mass sensors were placed at each outlet to record the fertilizer mass passing through each outlet per unit time. Based on the statistical data, the velocity non-uniformity coefficient at the outlets and the coefficient of variation of discharge uniformity were calculated for each combination of factor levels.



(a) Measurement of airflow velocity at outlet (b) Measurement of coefficient of variation for consistency

Fig. 5 Schematic of measurement methods

The calculation formulas for the velocity non-uniformity coefficient M and the coefficient of variation of inter-row discharge uniformity N are as follows:

$$M = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (v_i - \bar{v}_a)^2}}{\bar{v}_a} \times 100\% \quad (7)$$

Where n is the number of measuring points; V_i is the airflow velocity at the i -th measuring point on the outlet cross-section, $\text{m} \cdot \text{s}^{-1}$; and $\bar{v}_a$ is the average airflow velocity at the outlet cross-section, $\text{m} \cdot \text{s}^{-1}$.

$$N = \frac{\sqrt{\frac{1}{a-1} \sum_{i=1}^a (X_i - \bar{X})^2}}{\bar{X}} \times 100\% \quad (8)$$

$$\bar{X} = \frac{1}{a} \sum_{i=1}^a X_i \quad (9)$$

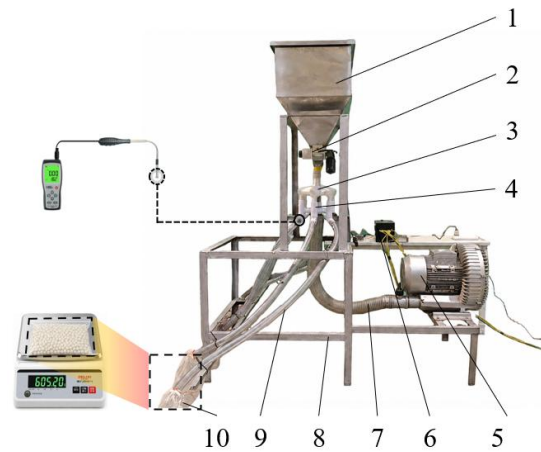
where a is the number of fertilizer outlets, and $a=6$ in this study; x_i is the mass of fertilizer discharged from the i -th outlet per unit time, g; and $\bar{x}$ is the arithmetic mean of x_i , g.

Regarding the experimental design, single-factor experiments were first conducted to investigate the influence of fertilizer conveying pipe diameter, airflow velocity, and fertilizer delivery rate on fertilizer delivery performance, so as to determine the optimal value ranges of each factor. Subsequently, Box–Behnken design was employed within these effective ranges to further analyze the effects of each factor and their interactions on the velocity non-uniformity

coefficient and the coefficient of variation of discharge uniformity. A response surface model was established for parameter optimization to obtain the optimal parameter combination for the pneumatic-assisted fertilizer delivery pipeline. Finally, bench tests were conducted to verify the numerical simulation results.

2.5 Verification of simulation results

2.5.1 Bench experiment



1.Fertilizer hopper 2.Fertilizer metering device 3.Fertilizer distributor 4.Air-fertilizer mixer 5.Fan
6.Frequency converter 7.Air supply pipeline 8.Frame 9.Fertilizer delivery tube 10.Fertilizer collection bag

Fig. 6 Bench test

To verify the reliability of the numerical simulation of the pneumatic-assisted fertilizer delivery device, a physical test prototype was constructed according to the optimal parameter combination, as shown in **Figure 6**. The test site was located at the Modern Agriculture Practical Training Base of Wuwei Vocational and Technical University. A self-made test bench was used, and a Delta MS300 frequency converter was employed to adjust the fan speed to control the airflow velocity. An SYT-2000V intelligent digital pressure anemometer and a high-precision electronic balance were used to measure the airflow velocity and fertilizer discharge at each outlet. The velocity non-uniformity coefficient and the coefficient of variation of inter-row discharge uniformity were calculated according to **Equations (7) and (8)**. The above process was repeated three times, and the average value was taken as the experimental result.

In the bench test, the operating parameters were kept consistent with those in the simulation experiment.

3. Results

3.1 Working Process and Particle Trajectory Analysis

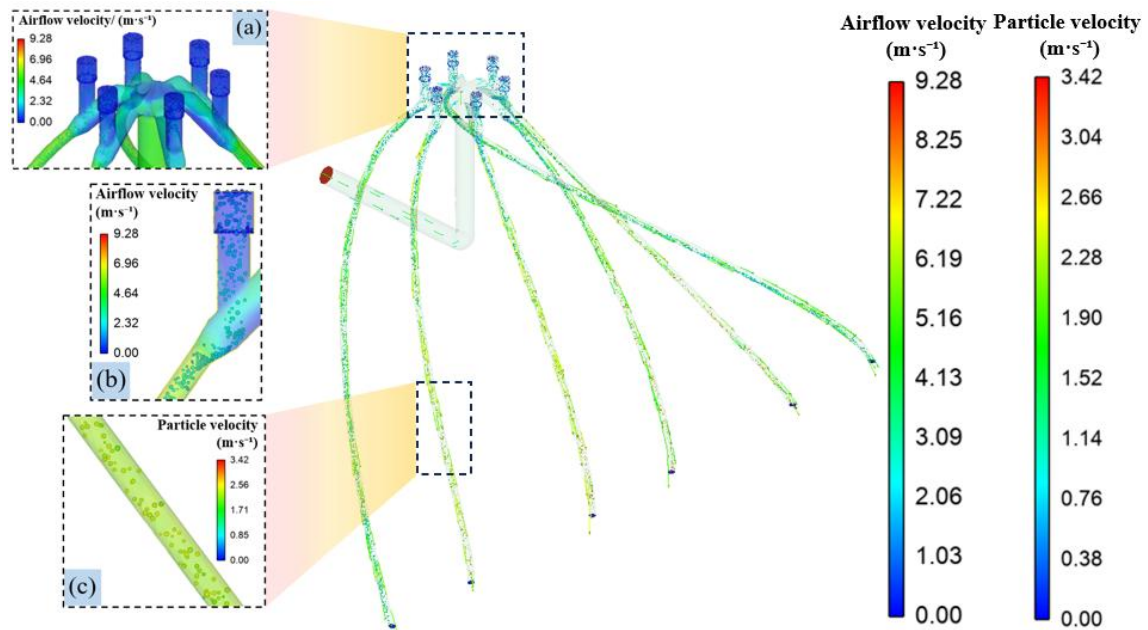


Fig. 7 Working process of pneumatic-assisted fertilizer delivery system

The fan provides positive-pressure airflow for the pneumatic-assisted fertilizer delivery device. The airflow first enters the main air supply pipeline and then flows into the airflow distributor, where it is uniformly distributed to six branches under the action of the air distribution chamber, as shown in **Figure 7(a)**. The airflow enters the air inlet of the air-fertilizer mixer and forms a low-pressure zone at the constricted section, drawing fertilizer particles into the delivery pipeline. Under the action of the airflow, the particles rapidly transition from a low-velocity state to motion aligned with the airflow direction, continuously adjusting their orientation and accelerating forward, as shown in **Figure 7(b)**. With continuous airflow action, the fertilizer particles enter the delivery pipeline and are fully acted upon by the airflow, forming a stable gas-solid two-phase flow. In the fertilizer delivery tubes, the particles

remain suspended under the combined action of gravity and airflow thrust and move along the airflow direction, achieving uniform and stable fertilizer delivery, as shown in **Figure 7(c)**.

The motion trajectories of fertilizer particles in the pneumatic conveying system are significantly affected by the airflow velocity distribution and pipeline geometric structure. Near the distributor outlet and the constricted section of the air-fertilizer mixer, the particles are in the initial acceleration stage due to high airflow velocity and large velocity gradients, resulting in a significant increase in collision frequency with the pipe wall and mixer structure. In this region, particle collisions exhibit high-frequency dense characteristics, mainly concentrated in the transition area between the constricted section and the pipe wall. In the constricted section, particles undergo an intense acceleration process from the static pressure zone to the dynamic pressure zone. The airflow velocity increases sharply at the constricted section, and the drag force on the particles increases abruptly; however, inertia causes their motion to lag behind the airflow, resulting in frequent inelastic collisions between particles and the wall as well as between adjacent particles. The motion state of the particle group at this stage can be summarized as a cyclic process of “high-speed collision–energy dissipation–attitude readjustment.” Part of the kinetic energy of the particles is converted into thermal and acoustic energy dissipated at the contact between the wall and particles, and part is converted into the rotational kinetic energy of the particles. As the gas-solid two-phase flow gradually develops and enters the main delivery pipeline, the particle motion direction becomes highly consistent with the dominant airflow direction, and the number of collisions decreases significantly; secondary collisions only occur to a limited extent in pipe bends or regions with large velocity gradients. The particle collision frequency transitions from high-frequency dense in the inlet section to low-frequency sparse in the conveying section. The constricted section and distributor structure are the key regions determining particle collision frequency, while long straight pipe sections mainly maintain stable particle delivery in a suspended state. Reasonable

optimization of the constricted section geometry and airflow uniformity of the distributor can effectively reduce the number of wall impacts of particles in the initial stage, thereby reducing the fertilizer breakage rate and energy loss, while also contributing to improving the stability of the gas-solid two-phase flow in the delivery pipeline and the uniformity of fertilizer discharge.

3.2 Single-factor Experiment Results

3.2.1 Effect of conveying pipe diameter

Under the conditions of an inlet airflow velocity of $20 \text{ m}\cdot\text{s}^{-1}$ and a fertilizer delivery rate of $20 \text{ g}\cdot\text{s}^{-1}$, as shown in **Figure 8**, the velocity non-uniformity coefficient exhibited an overall trend of first increasing and then leveling off with increasing pipe diameter. The reasons for this trend are as follows: under small pipe diameter conditions, the boundary layer had a weak disturbing effect on the mainstream region; as the pipe diameter increased, the airflow cross-sectional area expanded, the velocity gradient and boundary layer differences intensified, and local flow field instability increased the velocity non-uniformity. However, after exceeding a certain diameter, the flow field became fully developed, the turbulent redistribution effect was enhanced, and the change in velocity non-uniformity tended to slow down.

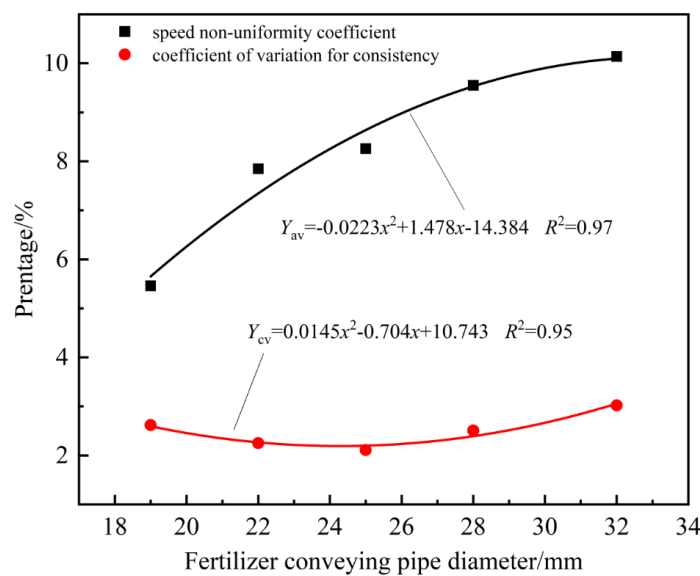


Fig. 8 Relationship curves of fertilizer conveying pipe diameter versus test indices

The coefficient of variation of discharge uniformity at each outlet exhibited a U-shaped trend of first decreasing and then increasing with pipe diameter. Therefore, a pipe diameter of 22~25 mm facilitated the formation of a stable gas-solid two-phase flow structure, with good matching between particle distribution and the velocity field, yielding optimal discharge uniformity. Excessively small pipe diameters easily caused repeated collisions among particles, resulting in significant kinetic energy loss, while excessively large pipe diameters reduced airflow conveying capacity and aggravated particle settling, thereby increasing discharge fluctuations. Considering both evaluation indices, the effective value range for the fertilizer conveying pipe diameter was determined to be 22~28 mm.

3.2.2 Effect of airflow velocity

Under the conditions of a fertilizer conveying pipe diameter of 22 mm and a fertilizer delivery rate of $20 \text{ g}\cdot\text{s}^{-1}$, as shown in **Figure 9**, the velocity non-uniformity coefficient exhibited a trend of rapid increase followed by leveling off with increasing airflow velocity. As the inlet airflow velocity increased, the Reynolds number rose, turbulent kinetic energy and shear stress were enhanced, and velocity gradients intensified. Meanwhile, the secondary flows and recirculation zones induced by the airflow distributor and the diameter-reduction regions of the fertilizer conveying pipe became more difficult to dissipate, causing the cross-sectional velocity field to deviate from a uniform distribution.

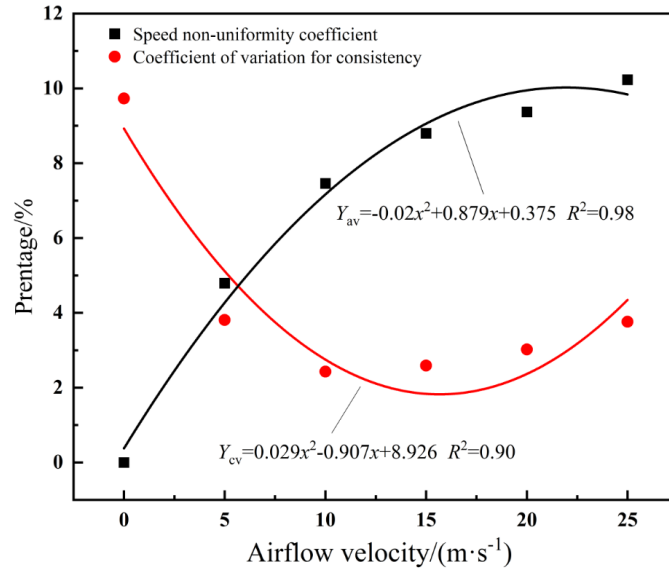


Fig. 9 Relationship curves of airflow velocity versus test indices

The coefficient of variation of discharge uniformity exhibited a U-shaped trend of first decreasing and then increasing with increasing velocity. At an airflow velocity of 0 m·s⁻¹ (without pneumatic assistance), fertilizer particles flowed under gravity alone, readily forming agglomerates and blockages within the pipe, resulting in the highest coefficient of variation; it decreased to 3.81% at 5 m·s⁻¹ and reached a minimum of 2.11% at 10 m·s⁻¹, then gradually increased over the 15~25 m·s⁻¹ range. At low velocities, particle-carrying capacity was insufficient, with intermittent deposition and re-entrainment of particles in the near-wall layer coexisting, leading to poor pneumatic conveying stability. When the inlet airflow velocity exceeded 10 m·s⁻¹, particle suspension and slip velocity achieved a relatively matched state, yielding the lowest dispersion. Excessively high velocities increased turbulence intensity and particle-wall collision frequency, aggravating slip velocity and segregation effects and thereby increasing discharge fluctuations. Therefore, the effective value range for inlet airflow velocity was determined to be 10~20 m·s⁻¹, ensuring conveying reliability while achieving more stable discharge uniformity.

3.2.3 Effect of fertilizer delivery rate

Under the conditions of a fertilizer conveying pipe diameter of 25 mm and an inlet airflow velocity of 20 m·s⁻¹, as shown in **Figure 10**, the velocity non-uniformity coefficient exhibited

an overall increasing trend within the fertilizer delivery rate range of 10~30 $\text{g}\cdot\text{s}^{-1}$. At low to medium fertilizer delivery rates, the volume fraction of fertilizer particles was relatively low, with weak near-wall collisions and shielding effects, resulting in a velocity field that was relatively close to a uniform distribution. When the fertilizer delivery rate exceeded 20 $\text{g}\cdot\text{s}^{-1}$, uneven airflow distribution occurred, significant differences existed in the airflow forces acting on particles, and cross-sectional velocity gradients increased sharply, leading to a rapid increase in velocity non-uniformity.

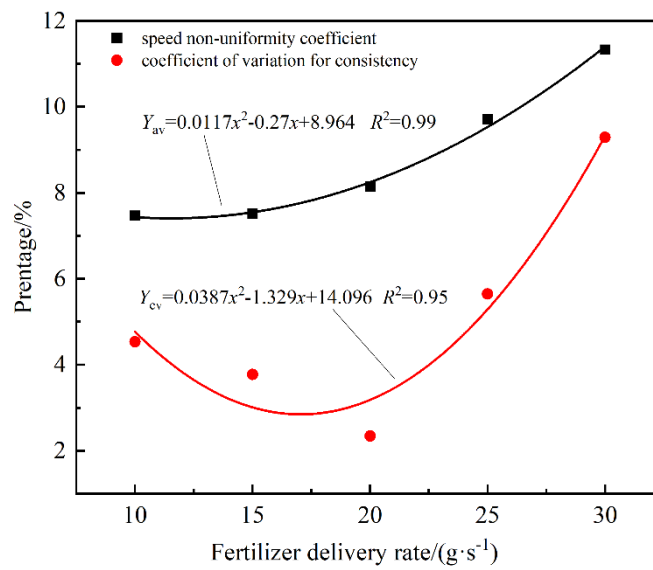


Fig. 10 Relationship curves of fertilizer delivery rate versus test indices

The coefficient of variation of discharge uniformity exhibited a trend of first decreasing and then increasing. In the low fertilizer delivery rate stage, it was affected by the conveying capacity threshold; intermittent particle deposition and subsequent re-entrainment caused pulsating supply. At 20 $\text{g}\cdot\text{s}^{-1}$, the matching degree between particle suspension and slip velocity in each fertilizer conveying pipe was optimal, with stable interphase coupling and the most uniform discharge. Under high load conditions of 20~30 $\text{g}\cdot\text{s}^{-1}$, the segregation effect in each pipe was enhanced, pressure drop fluctuations expanded, and discharge fluctuations increased rapidly. The U-shaped variation pattern of the coefficient of variation of discharge uniformity was not completely synchronized with that of the velocity non-uniformity coefficient: the

former reached its optimum at $20 \text{ g}\cdot\text{s}^{-1}$, while the latter was already at a relatively low level in the $10\sim 15 \text{ g}\cdot\text{s}^{-1}$ range. Therefore, the effective value range for fertilizer delivery rate was determined to be $10\sim 20 \text{ g}\cdot\text{s}^{-1}$.

3.3 Results of orthogonal experiments

3.3.1 Experimental results and variance analysis

Based on the effective value ranges of each factor determined by single-factor experiments, a three-factor, three-level Box–Behnken design was developed using Design-Expert 13.0 software. The experimental scheme and results are shown in **Table 3**, and the variance analysis results of the test indices are shown in **Table 4**.

Table 3. Test Plan and Experimental Data

Run number	Factor level			Response value	
	Fertilizer conveying pipe diameter	Airflow velocity	Fertilizer delivery rate	Velocity non- uniformity coefficient	Coefficient of variation of discharge uniformity
	x_1/mm	$x_2/\text{m}\cdot\text{s}^{-1}$	$x_3/\text{g}\cdot\text{s}^{-1}$	$M/\%$	$N/\%$
1	25	15	15	9.33	3.94
2	25	15	15	9.21	3.97
3	28	10	15	12.71	6.59
4	25	20	15	6.88	2.43
5	25	10	20	15.74	8.72
6	22	15	10	9.89	4.60
7	25	10	10	13.26	6.92
8	22	20	15	6.81	2.67
9	28	15	10	8.67	3.44
10	28	20	15	6.66	1.80
11	25	15	15	9.19	4.03
12	22	15	20	11.21	5.78
13	28	15	20	10.04	4.68
14	22	10	15	14.84	7.78
15	25	20	10	7.42	2.93

Table 4. ANOVA results for the evaluation indices

Variance source	M			N		
	Sum of squares	Value of F	Value of P	Sum of squares	Value of F	Value of P
Model	116.79	2832.49	<0.0001**	59.23	652.33	<0.0001**
x_1	2.73	595.05	<0.0001**	2.33	231.22	<0.0001**
x_2	81.62	17816.36	<0.0001**	38.92	3857.72	<0.0001**
x_3	2.55	556.31	<0.0001**	1.81	178.95	<0.0001**
x_1x_2	0.9801	213.93	<0.0001**	0.0256	2.54	0.1721
x_1x_3	0.0006	0.1364	0.7270	0.0009	0.0892	0.7772
x_2x_3	0.6919	151.02	<0.0001**	0.2982	29.55	0.0029**
x_1^2	0.0045	0.9756	0.3686	0.0120	1.19	0.3247
x_2^2	3.62	790.08	<0.0001**	2.05	203.26	<0.0001**
x_3^2	1.57	343.21	<0.0001**	1.41	139.59	<0.0001**
Residual	0.0229	-	-	0.0504	-	-
Lack of fit	0.0114	0.6651	0.6471	0.0462	7.34	0.1222
Pure error	0.0115	-	-	0.0042	-	-
Sum	116.81	-	-	59.28	-	-

Note: Degrees of freedom for the model and error were both 14, ** means highly significant ($P < 0.01$), * means significant ($0.01 \leq P < 0.05$).

The P-values of the regression models for both the velocity non-uniformity coefficient and the coefficient of variation of inter-row discharge uniformity in the regression variance analysis were less than 0.001, indicating that the regression models were highly significant. The coefficients of determination R^2 were 0.9998 and 0.9991, respectively, and the P-values of the lack of fit terms were all greater than 0.1, further confirming the high goodness of fit of the regression equations. The order of significance of the effects of each factor on the response indices was: airflow velocity > fertilizer conveying pipe diameter > fertilizer delivery rate. After eliminating insignificant terms, the quadratic regression equations for the velocity non-uniformity coefficient M and the coefficient of variation of inter-row discharge uniformity N are shown in **Equations (10)** and **(11)**, respectively:

$$M = 43.5981 - 0.502x_1 - 2.438x_2 - 0.415x_3 + 0.033x_1x_2 - 0.023x_2x_3 + 0.042x_2^2 + 0.029x_3^2 \quad (10)$$

$$N = 22.2088 + 0.052x_1 - 1.337x_2 - 0.511x_3 - 0.015x_2x_3 + 0.031x_2^2 + 0.027x_3^2 \quad (11)$$

3.3.2 Interaction effects of significant factors on conveying performance

To intuitively reveal the influence of various factors and their interactions on the response indices, the significant interaction terms from **Equations (10)** and **(11)** were plotted as response surface plots. The analysis is as follows.

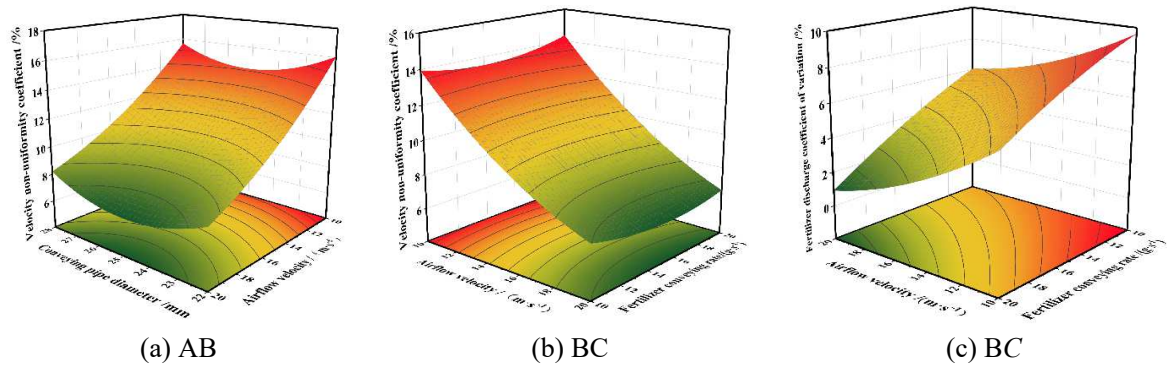


Fig. 11 Effect of significant interaction factors on fertilizer delivery performance

The effect of the interaction between fertilizer conveying pipe diameter and airflow velocity on the velocity non-uniformity coefficient is shown in **Figure 11(a)**. At low airflow velocities, the velocity non-uniformity coefficient exhibited a significant decreasing trend with increasing fertilizer conveying pipe diameter. This was mainly because smaller pipe diameters increased the airflow conveying resistance, while the interaction between particles and the pipe wall was enhanced, disturbing the gas-solid two-phase flow and resulting in uneven airflow velocity distribution among different fertilizer delivery branches. As the pipe diameter increased, the influence of local resistance on the flow field distribution weakened, and the uniformity of airflow distribution was improved. However, under high airflow velocity conditions, the effect of fertilizer conveying pipe diameter on the velocity non-uniformity coefficient gradually decreased. This was because higher airflow velocities enhanced the airflow momentum, improved the stability of gas-solid flow, and reduced the sensitivity of airflow distribution to variations in pipe diameter. When the fertilizer conveying pipe diameter was in the range of

22~25 mm and the airflow velocity was maintained at a high level, the velocity non-uniformity coefficient reached lower values. This indicates that the rational matching of fertilizer conveying pipe diameter and airflow velocity is the key to improving the uniformity of airflow distribution in the pneumatic-assisted fertilizer delivery system.

The effect of the interaction between airflow velocity and fertilizer delivery rate on the velocity non-uniformity coefficient is shown in **Figure 11(b)**. With increasing airflow velocity, the velocity non-uniformity coefficient decreased significantly, while increasing fertilizer delivery rate weakened the uniformity of airflow distribution. This was mainly because higher fertilizer delivery loads increased the solid-phase concentration, causing particle motion to produce stronger disturbances on the airflow field. At high airflow velocities, the enhanced aerodynamic force improved particle suspension capability, mitigating the adverse effects caused by increased fertilizer delivery rate. Therefore, when fertilizer delivery load increases, maintaining sufficient airflow velocity is a necessary condition to ensure the stability of gas-solid conveying.

The effect of the interaction between airflow velocity and fertilizer delivery rate on the coefficient of variation of discharge uniformity is shown in **Figure 11(c)**. Under low airflow velocity conditions, increasing the fertilizer delivery rate led to an increase in the coefficient of variation of discharge uniformity. This was because insufficient aerodynamic force resulted in reduced particle suspension capability and decreased continuity of particle conveying, causing discharge fluctuations among different fertilizer delivery outlets. As airflow velocity increased, the adverse effects brought about by increasing fertilizer delivery rate gradually weakened. The enhanced airflow carrying capacity improved particle conveying stability and reduced discharge fluctuations. However, under high airflow velocity conditions, excessively high fertilizer delivery rates still caused an increase in the coefficient of variation of discharge

uniformity. This was because excessively high solid-phase loads reduced gas-solid coupling efficiency and promoted particle agglomeration, affecting uniform fertilizer conveying.

3.4 Parameter Optimization

To further improve the operating performance of the pneumatic-assisted fertilizer delivery device, the Numerical optimization module in Design-Expert 13.0 software was employed, with the minimization of both the velocity non-uniformity coefficient and the coefficient of variation of inter-row discharge uniformity as optimization objectives, and constraints were imposed on each factor according to actual working conditions. Therefore, the desirability function approach was adopted to convert the multi-objective problem into a single-objective problem, with the optimization criterion that both indices simultaneously reach their minimum values. The objective function and constraints are as follows:

$$\text{Objective Function: } P = \begin{cases} \min M(A, B, C) \\ \min N(A, B, C) \end{cases} \quad (12)$$

$$\text{Constraint Conditions: } s. t. \begin{cases} 22 \leq A \leq 28 \\ 10 \leq B \leq 20 \\ 10 \leq C \leq 20 \end{cases} \quad (13)$$

The optimal parameter combination obtained is: fertilizer conveying pipe diameter of 24.931 mm, airflow velocity of $20 \text{ m} \cdot \text{s}^{-1}$, and fertilizer delivery rate of $13.449 \text{ g} \cdot \text{s}^{-1}$, yielding a velocity non-uniformity coefficient of 6.37% and a coefficient of variation of inter-row discharge uniformity of 1.85%. Considering the limitations of commercially available fertilizer conveying pipe specifications, the pipe diameter was rounded to 25 mm according to engineering approximation principles, and the fertilizer delivery rate was rounded to $13.50 \text{ g} \cdot \text{s}^{-1}$. This provides data support and a theoretical basis for the subsequent bench test verification of the fertilization performance of the pneumatic-assisted fertilization system.

3.5 Bench Test Validation

Analysis of the test data showed that the velocity distribution at measuring points and the discharge from each outlet were similar to the simulation results, as shown in **Table 5**. The

velocity non-uniformity coefficients from the three repeated tests were 6.10%, 7.03%, and 6.86%, respectively, with a maximum deviation of 0.66% from the optimized simulation value and an average relative error of 7.43%. The coefficients of variation of inter-row discharge uniformity from the three repeated tests were 2.11%, 1.93%, and 1.99%, respectively, with a maximum deviation of 0.26% from the optimized simulation value and an average relative error of 8.65%. The test results were basically consistent with the simulation results, indicating that the optimized model design was reasonable and capable of effectively simulating the airflow velocity variation and particle distribution in the fertilizer delivery system under actual conditions.

Table 5. Result of verification experiment

Evaluation index	Optimal value /%	Experimental value /%	Relative error /%
Velocity non-uniformity coefficient	6.37	6.10	4.24
		7.03	10.36
		6.86	7.69
Fertilizer discharge coefficient of variation	1.85%	2.11	14.05
		1.93	4.32
		1.99	7.57

4. Discussion

The motion state of fertilizer particles in the pneumatic conveying pipeline is jointly determined by drag force, lift force, gravity, and inter-particle collisions. Single-factor experimental results showed that under the condition of a fertilizer conveying pipe diameter of 25 mm, both evaluation indices approached optimal values: an excessively small pipe diameter caused cross-sectional contraction and significantly increased particle collision frequency, while high-shear zones near the wall induced energy dissipation and flow field instability; an excessively large pipe diameter reduced the average cross-sectional velocity, resulting in insufficient lift and drag forces required for particle suspension and easily forming intermittent

deposition layers. The effective range of airflow velocity of $10\sim 20\text{ m}\cdot\text{s}^{-1}$ can be explained from the perspective of gas-solid coupling dynamics: when the flow velocity was below $10\text{ m}\cdot\text{s}^{-1}$, the gas-phase momentum flux was insufficient to overcome the radial component of particle gravity, and particles exhibited pulsating conveying characteristics of intermittent deposition–re-entrainment; when the velocity exceeded $20\text{ m}\cdot\text{s}^{-1}$, turbulence intensity increased with the square of flow velocity, particle-wall collision frequency rose substantially, and spatial uniformity of the velocity field degraded. A fertilizer delivery rate of approximately $20\text{ g}\cdot\text{s}^{-1}$ exhibited optimal discharge uniformity, reflecting the matching relationship between solid-phase mass concentration and gas-phase conveying capacity: at excessively high rates, the solid-phase load increased and local high-concentration zones formed transient sand dunes that disturbed the mainstream flow field; at excessively low rates, intermittent particle supply caused pulsating flow patterns. The Venturi mixer reduced the initial velocity dispersion of particles through the negative pressure effect generated by airflow acceleration in the constricted section, effectively buffering the adverse effects of high fertilizer delivery rates on uniformity.

Analysis of variance of orthogonal experiments showed that airflow velocity, as the primary significant factor, exerts its influence through the coupling relationship between dynamic pressure in the main pipeline and static pressure distribution in the distributor. According to Bernoulli's equation, dynamic pressure is proportional to the square of flow velocity; when airflow velocity increased from $10\text{ m}\cdot\text{s}^{-1}$ to $20\text{ m}\cdot\text{s}^{-1}$, dynamic pressure increased by nearly three times. High dynamic pressure caused the static pressure at each branch pipe inlet to converge, effectively suppressing flow deviation caused by minor geometric differences; under low dynamic pressure conditions, static pressure was highly sensitive to local disturbances, and minor resistance differences could be amplified into significant velocity gradients. The main effects of fertilizer conveying pipe diameter and fertilizer delivery rate both exhibited variation

amplitudes below 2%, functioning more as “modulation” rather than “driving” of the mainstream flow field. The interaction term between airflow velocity and fertilizer delivery rate had extremely significant effects on both response indices: high airflow velocity could compensate for the non-uniformity caused by high fertilizer delivery rate through enhanced momentum flux, maintaining stable suspension of the particle group; under low airflow velocity conditions, even at low fertilizer delivery rates, the pulsating effect caused by intermittent particle supply still induced discharge fluctuations. This pattern provides engineering implications for field parameter regulation: system design should prioritize ensuring sufficient airflow velocity, then match pipe diameter and fertilizer delivery rate; when operating conditions fluctuate, appropriately reducing the fertilizer delivery rate can maintain uniformity, reflecting the synergistic compensation mechanism among parameters.

This study further expands the theoretical foundation and design methodology based on existing achievements in pneumatic conveying technology. Compared with the CFD-DEM study by Yang Qinglu et al. [13] on the local distribution structure of centralized fertilizer metering devices, this study focuses on utilizing the surplus positive-pressure airflow from the planter fan to achieve secondary utilization of pneumatic power, and conducts supplementary investigations on structural and operating parameters including airflow rate, pipe diameter, and fertilizer delivery rate, thereby extending the theoretical foundation of pneumatic-assisted fertilizer delivery. In contrast to the study by Li Liwei et al. [18] on the gas-fertilizer mixing chamber of rice fertilizer applicators, this study incorporates a specially designed enhanced section of the Venturi mixer and an airflow distribution structure, refining the design methodology for pneumatic conveying of fertilizer particles. Furthermore, this study focuses on the key factors affecting fertilizer delivery performance, employs response surface analysis to optimize the interaction effects among these factors, and establishes a quantitative matching relationship for multi-factor coupling.

The innovation points are as follows: First, the surplus airflow from the fan outlet of the air-suction seeder is utilized as the sole auxiliary power source for the fertilizer delivery system, achieving “dual-purpose” operation of the seeding fan. Second, an air-fertilizer mixer based on the Venturi principle was designed, which enhances the suction and dispersion capabilities of fertilizer particles through the negative pressure effect at the constricted section. Third, response surface optimization was employed to obtain the optimal parameter combination for fertilizer delivery performance (fertilizer conveying pipe diameter of 25 mm, airflow velocity of $20 \text{ m}\cdot\text{s}^{-1}$, and fertilizer delivery rate of $13.50 \text{ g}\cdot\text{s}^{-1}$), providing a parameter basis for the engineering application of pneumatic-assisted fertilization systems.

5. Conclusion

This study addressed the problem of low utilization efficiency of surplus airflow from the fan outlet of air-suction seeders. A pneumatic-assisted fertilizer delivery system was designed using positive-pressure airflow from the fan as auxiliary power. A CFD-DEM gas-solid coupling model was established to investigate the gas-solid two-phase conveying characteristics and particle motion behavior during the fertilizer delivery process, and the influence of key operating parameters on conveying performance was systematically analyzed. The main conclusions are as follows:

(1) The established CFD-DEM pneumatic-assisted fertilizer delivery system model revealed the conveying mechanism of fertilizer particles. Under airflow action, fertilizer particles rapidly accelerated in the inlet region and gradually formed a stable suspended motion state in the fertilizer delivery pipes. Particle motion was jointly affected by aerodynamic force, gravity, and particle–wall interactions, indicating that gas-solid coupling stability is an important factor determining conveying performance.

(2) Single-factor experiments were conducted to determine the optimal value ranges of fertilizer conveying pipe diameter, airflow velocity, and fertilizer delivery rate. Orthogonal experiments and response surface optimization results showed that the optimal operating parameter combination for the system was: fertilizer conveying pipe diameter of 25 mm, airflow velocity of $20 \text{ m}\cdot\text{s}^{-1}$, and fertilizer delivery rate of $13.50 \text{ g}\cdot\text{s}^{-1}$. Under these conditions, the model predicted a velocity non-uniformity coefficient of 6.37% and a coefficient of variation of discharge uniformity of 1.85%, indicating that the optimized parameter combination can effectively improve airflow distribution uniformity and fertilizer delivery consistency.

(3) Bench test validation showed that the average relative errors between simulated and experimental values for the velocity non-uniformity coefficient and the coefficient of variation of discharge uniformity were 7.43% and 8.65%, respectively. The experimental results were basically consistent with the simulation results, proving that the established CFD-DEM pneumatic-assisted fertilizer delivery system model is reasonable and reliable, and can effectively simulate airflow velocity variation and particle distribution in the fertilizer delivery system under actual conditions. The proposed pneumatic-assisted fertilizer delivery system can utilize the existing surplus airflow of air-suction seeding equipment as fertilizer delivery power without requiring additional power sources, providing a feasible technical solution for improving airflow utilization efficiency of agricultural equipment and developing energy-saving integrated seeding and fertilizing equipment.

References

1. Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences. *China Chemical Fertilizer Use Report 2023* (Science Press, 2023) (in Chinese).

- 658 2. Xu, D. *Research on the Adoption of Green Production Technology by Chinese Farmers*
659 (Social Sciences Academic Press, 2023) (in Chinese).
- 660 3. Yang, Y. R., He, Y. C. & Li, Z. L. Social capital and the use of organic fertilizer: an empirical
661 analysis of Hubei Province in China. *Environ. Sci. Pollut. Res.* **27**, 15211–15222 (2020).
- 662 4. Qian, W. et al. Synergistic regulation of chemical fertilizer reduction and organic substitution
663 on aggregate stability in calcareous cinnamon soil and winter wheat yield. *J. Nucl. Agric.*
664 *Sci.* **40(9)**, 1852–1863 (2026) (in Chinese).
- 665 5. Zang, L., Wang, X. & Liu, X. Strategic research on a diversified food supply system under
666 the greater food concept. *Strateg. Study CAE* (in the press) (in Chinese).
- 667 6. Guo, Y., Geng, Z., Liao, Y. et al. Research on the impact of agricultural new quality
668 productive forces on the carbon rebound effect in agriculture. *Resour. Dev. Mark.* (in the
669 press) (in Chinese).
- 670 7. Luo, B. & Hu, X. Strategic deployment for building China into a leading agricultural country:
671 an interpretation of the No. 1 Central Document of 2026. *Reform* **(4)**, 1–17 (2026) (in
672 Chinese).
- 673 8. Li, R. Research on key technologies and strategies for energy conservation and emission
674 reduction in automated agricultural machinery operation. *Digit. Agric. Intell. Agric. Mach.*
675 **(6)**, 39–41 (2024) (in Chinese).
- 676 9. Bühler Group. *Global Trends in Agricultural Pneumatic Technology: Seeding and Fertilizing*
677 56–58 (Bühler Group, 2018).
- 678 10. Liao, Y. et al. Research progress and development trends in precision seeding technologies
679 for major grain and oil crops. *Trans. Chin. Soc. Agric. Mach.* **56(9)**, 1–19 (2025) (in
680 Chinese).
- 681 11. Canadian Agricultural Engineering Society. The adoption of pneumatic seeding technology
682 in Canadian agriculture. *Can. Biosyst. Eng.* **43**, 4.15–4.22 (2001).

12. Yang, Q. et al. Development of layered fertilizer amount adjustment device of pneumatic centralized variable fertilizer system. *Trans. Chin. Soc. Agric. Eng.* **36(1)**, 1–10 (2020) (in Chinese).
13. Yang, Q. et al. Design and experiment of layered deep fertilization device of different fertilizers based on pneumatic distribution. *Trans. Chin. Soc. Agric. Mach.* **52(10)**, 61–73 (2021) (in Chinese).
14. Liao, Y. et al. Design and experiment of pneumatic fertilizer discharging system for high speed seeder for rapeseed and wheat. *Trans. Chin. Soc. Agric. Mach.* **56(7)**, 60–71 (2025) (in Chinese).
15. Zhang, L. et al. Design and experiment of spiral conveying pipe in pneumatic centralized fertilizer discharge system. *PLoS One* **20**, e0320126 (2025).
16. Yang, Q. et al. Structural optimization and experiment of pneumatic centralized fertilizer system. *Trans. Chin. Soc. Agric. Eng.* **36(13)**, 1–10 (2020) (in Chinese).
17. Wang, L. et al. Design and experiment of lightweight and simple centralized seeding-fertilizing device for rapeseed in hilly and mountainous areas. *Trans. Chin. Soc. Agric. Mach.* **55(9)**, 89–101 (2024) (in Chinese).
18. Li, L. et al. Simulation analysis of gas-solid two-phase flow in the pneumatic conveying fertilizer feeder of a rice fertilizer applicator. *Trans. Chin. Soc. Agric. Mach.* **49(Suppl. 1)**, 171–180 (2018) (in Chinese).
19. Wang, X. et al. Discharge rate consistency of each channel for UAV-based pneumatic granular fertilizer spreader. *Int. J. Agric. Biol. Eng.* **16(4)**, 20–28 (2023).
20. Munson, B. R., Young, D. F., Okiishi, T. H. & Huebsch, W. W. *Fundamentals of Fluid Mechanics* 7th edn (John Wiley & Sons, 2013).

21. Wen, X., Yuan, H., Wang, G. & Jia, H. Calibration method of friction coefficient of granular fertilizer by discrete element simulation. *Trans. Chin. Soc. Agric. Mach.* **51(2)**, 115–122, 142 (2020) (in Chinese).
22. Yu, S. et al. Calibration of physical characteristic parameters of granular fungal fertilizer based on discrete element method. *Processes* **10**, 1564 (2022).

Acknowledgements

This work was supported by the Key Talent Project of Gansu Province (Grant number 2026RCXM083) and the Key University-level Team of Wuwei Vocational College (Grant number WWOCT-A2024001).

Author contributions

H.J.W. (Haiji Wang) performed the numerical simulations and data curation, analyzed and visualized the data, and drafted the original manuscript. Z.J.W. (Zhaojun Wang) contributed to methodology and resources, provided supervision, acquired funding, and performed writing – review & editing. Y.J.Z. (Yajie Zhan) assisted in building the experimental test bench and contributed to validation. Z.L.W. (Zengli Wang) performed the bench tests and data collection. K.B.T. (Kaibo Tang) contributed to manuscript revision and data verification. W.C.D. (Wancheng Dong) conceived the study (conceptualization), provided supervision, and performed writing – review & editing. All authors reviewed and approved the final manuscript.

Data availability

The authors confirm that all data generated or analysed during this study are included in this article.

728 **Declarations**

729 **Ethics approval and consent to participate:** This study did not involve human participants,
730 human data, or animal experiments. Ethical approval was not required.

731 **Consent for publication:** Not applicable.

732 **Competing interests:** The authors declare no competing interests.