

Simulation and Experiment of Bottom Aeration Piping and Internal Flow Field in Trough Composting

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Trough composting is a highly efficient technology for treating livestock manure and converting it into valuable resources. The flow field in the aeration pipes and the flow field within the compost pile are critical factors affecting trough composting. Due to the large size of compost piles and the harsh internal environment, it is difficult to quantify the flow field distribution within the pipes and the compost piles. This study established a three-dimensional fluid model of the bottom pipeline and the compost pile within a 90 m³ trough composting system. The perforation spacing of the bottom pipe was optimized by gradually reducing the spaces between openings. Effect of optimized perforation spacing on flow velocity within the pipe and the compost pile were optimized. The results indicated that a gradually changed perforation structure can enhance both the magnitude and uniformity of flow velocity distribution within the pipeline and the compost pile. Field trials of trough composting at an engineering scale revealed that the average relative error between actual measured wind speeds over the compost pile and simulated values remained within 10%. This study provides a theoretical basis and data support for the engineering construction of aeration systems in trough composting.

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Keywords: Trough Composting; Flow field simulation; Aeration duct; Perforation spacing

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INTRODUCTION

With the rapid development of China's livestock farming industry, the production of poultry and livestock manure has been increasing dramatically in recent years (Ajmal *et al.* 2021). Improperly managed livestock manure has become a direct driver of ecological degradation (Zheng *et al.* 2019), hindering the development of the livestock industry. Aerobic composting is a highly efficient method for treating livestock manure. It offers low investment and operational costs, and it generates substantial economic returns through its final product (Aydın Temel *et al.* 2023). Compared to anaerobic fermentation, aerobic composting offers advantages such as lower energy consumption and shorter fermentation cycles, but it produces higher levels of gas emissions and odors during the process (Zhang *et al.* 2023). The principle of aerobic composting involves the decomposition of organic matter and the conversion and synthesis of humus through microbial-driven processes (Ma *et al.* 2018). Currently, China primarily utilizes aerobic composting to recycle solid manure resources (Peng *et al.* 2025). Enhancing compost production efficiency is a crucial approach to tackling manure pollution issues.

Having an adequate oxygen supply is a key to ensuring an effective composting process (Xiong *et al.* 2022). Traditional trough composting typically relies on mechanical turning as a means to achieve a suitable oxygen supply, but it suffers from high energy consumption and odor emissions. To address this issue, a static composting method has been proposed that involves covering the top of the compost pile with a selective permeable membrane and installing aeration pipes at the bottom. The membrane covering ensures the internal environment of the compost pile remains unaffected by external conditions while shortening the composting cycle and reducing greenhouse gas emissions (Sun *et al.* 2018; Zhang *et al.* 2024). This static composting method requires no mechanical turning, thereby reducing composting costs (Cao *et al.* 2024). Since there is no mechanical turning, bottom aeration becomes the sole method for oxygen supply during static composting. Aeration supplies oxygen to the fermentation process and removes excess moisture (Xu *et al.* 2025). However, the compacting effect of the composting materials causes oxygen to be transported from the bottom pipes through complex pathways to the top of the compost pile (Sun *et al.* 2022). This can result in an insufficient oxygen concentration at the top, leading to anaerobic conditions (Zeng *et al.* 2016). Gases such as methane and nitrous oxide produced by anaerobic fermentation can cause harm to the ecological environment (Mora *et al.* 2013). Therefore, the rational design of the bottom aeration system is a prerequisite for clean production in composting.

The bottom pipe aeration orifices in trough composting are typically perforated uniformly. The airflow velocity at different perforation locations in uniformly perforated pipes frequently exhibits inconsistencies (Cheng *et al.* 2025). If the flow velocity difference between orifices is too large, it will cause uneven air distribution within the compost pile, affecting composting efficiency. Adjusting the orifice spacing is a method that enables uniform outflow from the aeration orifices. Cao *et al.* (2023) found that gradually reducing the perforation spacing along the direction of air flow within the duct enhances convective heat transfer efficiency at the inlet. Raphe *et al.* (2021) adjusted the uniform perforation spacing of the duct perforated diffuser, finding that optimized perforation spacing provided more uniform air distribution while reducing the required ventilation flow rate and energy consumption by 18.4%. Yeo *et al.* (2019) optimized the uniform perforation spacing of intake ducts in pig barns, finding that optimized perforation spacing increased the average temperature in the barn while reducing the standard deviation of duct temperatures. Based on the findings of the above study, it is hypothesized that optimizing the perforation structure can specifically address the issue of uneven flow distribution in trough composting systems. The solution is hypothesized to involve the length of the aeration pipes and the large number of aeration orifices. Such adjustments are proposed to effectively improve the uniformity of aeration throughout the composting system.

The intensity of airflow within the compost pile is one of the key factors affecting composting efficiency (Guo *et al.* 2012). Due to the extremely low flow velocity and adverse conditions within the compost pile, the airflow velocity and uniformity within the compost pile are difficult to quantify (Cheng *et al.* 2021). Computational fluid dynamics (CFD) is a viable method for simulating flow fields that has been widely utilized in the field of waste treatment in recent years. Shi *et al.* (2025) simulated the airflow field within a rotary drum composter and found that adding baffles could enhance both the airflow velocity in weak ventilation zones and the microbial community richness within the reactor. He *et al.* (2018) conducted a coupled simulation of gas flow, temperature, and oxygen concentration in a composting reactor, finding that describing the dynamic changes in the composting process based on microbial reaction mechanisms is reasonable. Guo *et al.*

(2023) simulated the aeration process in composting landfills and found that utilizing passive aeration strategies could increase aeration efficiency by 20%, thereby reducing subsequent composting treatment costs. The innovation of this study lies in the development of an integrated CFD model of the flow field in a trough composting system to investigate the impact of perforated structures on the flow field within the composting system. The model's performance was validated through engineering-scale composting experiments, providing a theoretical basis for the design of future composting aeration systems.

EXPERIMENTAL

Model Establishment

The trough composting equipment is located at the Livestock Manure Management Center in Danyang City, Jiangsu Province, China. As shown in Fig. 1, the fermentation tank is a rectangular prism with three sides enclosed and one side open. During operation, the top of the pile is covered with a selective permeable membrane. Figure 2 shows the three-dimensional structure of the composting tank, with dimensions of 15 m in length, 4 m in width, and 1.5 m in height. Aeration pipes are installed at the bottom of the composting tank. The pipes enter from one end of the tank and branch off at the inlet into one intermediate pipe and two side pipes. Each pipe is 15 m long with an inner diameter of 90 mm. Aeration orifices with an inner diameter of 5 mm are distributed at 45° angles on both sides of the pipe, with an adjacent spacing of 5 cm between orifices. Due to the compaction effect of the composting material, the compost pile is modeled as an arched structure.



Fig. 1. (a) Empty composting tank body and (b) compost aeration process

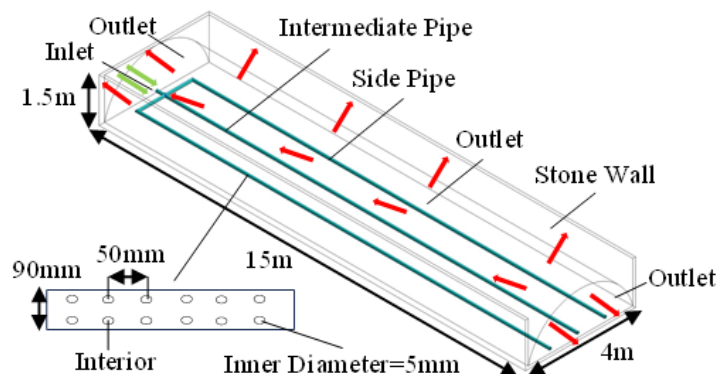


Fig. 2. Three-dimensional schematic diagram of composting trough

Optimization of Aeration Orifice Spacing

Airflow within aeration pipes is affected by friction losses, local pressure losses, and pressure drops across the compost pile, resulting in uneven air distribution across different sections and compromising the uniformity of flow within the compost pile (Joshi *et al.* 2022). To ensure a consistent average airflow rate across the compost pile area, this study achieved this by optimizing the spacing of the perforations in the pipes (Peng *et al.* 2024).

As air flows through a duct, it suffers pressure loss due to friction against the duct walls. The air pressure within the duct gradually decreases as the transmission distance increases. Therefore, it is speculated that reducing the spacing between aeration orifices can improve the overall uniformity of flow within the pipeline. This study added three gradually more closely spaced perforation structures to the uniformly perforated pipe. As shown in Fig. 3, the 15-meter-long pipeline is divided into three sections. In Section A, the spacing between aeration orifices was increased by 0.5, 1, and 1.5 cm (T1, T2, T3); in Section B, the spacing between aeration orifices remained unchanged at 5 cm; and in Section C, the spacing between aeration orifices was reduced by 0.5, 1, and 1.5 cm (T1, T2, T3). The number of aeration orifices remained consistent across all three sections.

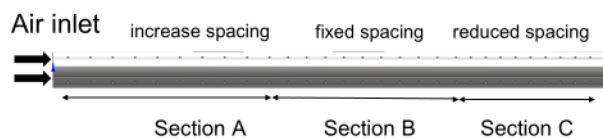


Fig. 3. Optimized design for pipe perforation

Calculation of Porous Medium Parameters

Compost materials consist of a mixture of tiny particles of varying sizes, which generate high airflow resistance in the aeration system during the aeration stage. This resistance produces a more significant pressure drop as the compost pile height increases (Rocha *et al.* 2020). In waste treatment research, compost piles are typically simulated as porous media to model the pressure drop across the airflow (Zambra *et al.* 2012). The viscous resistance coefficient and inertial resistance coefficient were calculated using the Ergun equation (Panigrahi *et al.* 2020),

$$\alpha = \frac{D_p^2}{150} \frac{\varepsilon^3}{(1-\varepsilon)^2} \quad (1)$$

$$C_{VP} = \frac{1}{\alpha} \quad (2)$$

$$C_{IP} = \frac{3.5 (1-\varepsilon)}{D_p \varepsilon^3} \quad (3)$$

where α is the permeability (m^2), D_p is the particle size of the compost material (mm), ε is the bulk porosity, C_{VP} is the viscous resistance coefficient (m^{-2}), and C_{IP} is the inertial resistance coefficient (m^{-1}).

The physical and chemical properties of composting materials change continuously as the composting process progresses, and their resistance coefficient changes accordingly. To ensure the accuracy of the simulation, the air resistance calculations were based on material parameters corresponding to the high moisture content typical of the initial stage

of composting, as high moisture content significantly increases the resistance to aeration airflow. To analyze the distribution of the macroscopic airflow field within the compost pile, this study treats the material as an isotropic porous medium. The simplified assumptions described above have a negligible effect on the simulation of airflow within the pile and are applicable to the quasi-steady-state aeration flow field during the early stages of composting.

In this study, the average particle size of the initial material ranged from 2.6 mm to 2.7 mm, with a porosity of 0.3. Calculations based on the above formula yielded a viscous resistance coefficient of 4.02×10^8 and an inertial resistance coefficient of 34,900 for the composting zone.

Flow Field Simulation and Solution

The fluid transfer method in this study involves air generated by a pressure blower entering through the pipeline inlet, subsequently flowing through aeration orifices in the pipeline to supply oxygen to the compost pile (Külcü 2015). Physical modeling of the compost pile was performed using SolidWorks 2023, with the computational domain divided into the aeration pipe and the compost pile. The model was meshed using an unstructured polyhedral grid, with the mesh skew factor in the computational domain consistently below 0.7 and the orthogonality quality exceeding 0.4. The surface mesh around the aeration orifices was refined to obtain a higher quality mesh, facilitating subsequent airflow field simulations.

The aeration rate of a compost pile is determined by its physical volume. In this study, the aeration rate was set at $0.45 \text{ L} \cdot \text{kg}^{-1} (\text{dry matter}) \cdot \text{min}^{-1}$. The compost material density and initial moisture content were 500 kg/m^3 and 65%, respectively. Based on this calculation, the aeration rate for a 90 m^3 compost pile was $425 \text{ m}^3/\text{h}$, corresponding to a pipeline inlet velocity of 18.54 m/s . This flow velocity was calculated by dividing the volumetric flow rate by the inlet area. The selective permeable membrane at the top of the pile was set to a mass flow outlet condition, with its numerical value matched to the velocity inlet condition. The aeration orifices were set as internal surfaces, which constituted the boundary condition allowing air to enter the compost pile mass through the small orifices. For computational efficiency and accuracy, the turbulence model used the k - ϵ model with a wall enhancement function. Ensure the accuracy of flow simulation in pipelines, pressure-velocity coupling employed the SIMPLE scheme. Pressure, momentum, turbulent kinetic energy, and turbulent dissipation rate were all computed using a second-order upwind spatial discretization scheme. The procedure was to select the steady-state solution method, initialize the model boundaries using the standard initialization method, and set the convergence criterion to all parameter residuals below 0.001. The governing equations in the entire model include the continuity equation and the Navier-Stokes equations,

$$\frac{\partial(\rho_{air})}{\partial t} + \nabla(\rho_{air} \vec{v}_{air}) = 0 \quad (4)$$

$$\frac{\partial(\rho_{air} \vec{v}_{air})}{\partial t} + \nabla(\rho_{air} \vec{v}_{air} \vec{v}_{air}) = -\nabla p + \rho_{air} \vec{g} + \nabla(\vec{\tau}) \quad (5)$$

where ρ_{air} is the air density (kg/m^3), $\vec{v}$ is the airflow velocity (m/s), $\vec{\tau}$ is the shear stress tensor (Pa), p is pressure (Pa), and $\vec{g}$ is the acceleration due to gravity (9.81 m/s^2).

Data and Statistical Analyses

The airflow field within the compost pile and the bottom aeration pipes were analyzed and simulated using Ansys Fluent 2024. The flow field distribution within the compost pile region was plotted using CFD-Post. Plotting Experimental Data Using Origin 2024.

RESULTS AND DISCUSSION

Analysis of Flow Velocity in the Bottom Pipe

Figure 4 shows the velocity distribution across the center cross-section of the pipe for the four perforation methods. Figure 4a shows the flow velocity in the intermediate pipe, with velocities ranging from 0.08 to 10 m/s. The flow velocity decreases with increasing distance from the ventilation inlet, and all ducts exhibit the same downward trend, with the velocity dropping to its lowest point at the end of the duct. Changing the perforation spacing from uniform to gradually denser can increase the flow velocity within the pipe. The comparison results indicate that when the perforation spacing is changed to 1 cm, the flow velocity in the pipe increases the most significantly, while the flow velocity in the uniformly perforated pipe (CK) is the slowest. Figure 4b shows the flow velocity in the side pipe, with velocities ranging from 0.05 to 6 m/s. The trend in flow velocity variation is similar to that observed in the intermediate pipe. Compared to CK, the average velocities at the central cross-section for T1, T2, and T3 increased by 3.7%, 14.9%, and 11.3%, respectively. The velocity in the pipeline, when accounting for friction losses, local losses, and pressure drop across the pile, can generally satisfy the velocity requirements for both the main and branch pipelines in large-scale compost aeration systems.

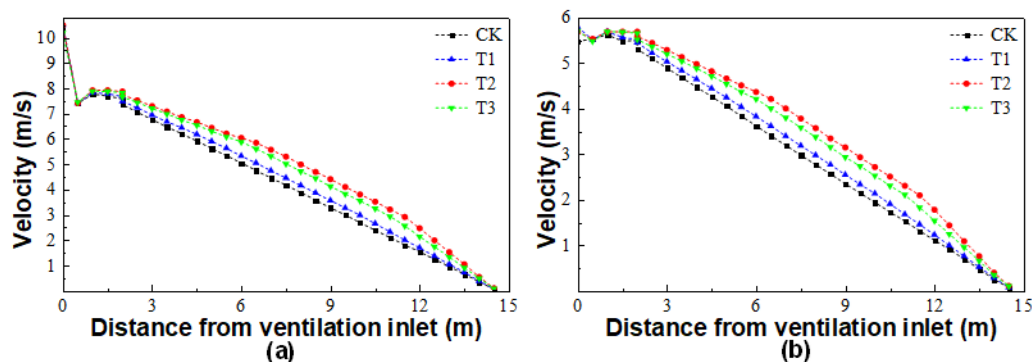


Fig. 4. Pipe flow velocity distribution (a) Intermediate pipeline (b) Side pipeline

Analysis of Flow Velocity at Aeration Orifices

Figure 5 shows the velocity distribution at different locations of the aeration orifices in pipes with four types of perforation methods. As shown in Fig. 5a, the outflow velocity at the aeration orifices of the intermediate pipe ranged from 3.4 to 4.1 m/s. The velocity distribution at the aeration orifices was $T2 > T3 > T1 > CK$. The distribution of flow velocities at the aeration orifices in the front half of the intermediate pipe was unstable, exhibiting significant fluctuations. This was due to turbulent effects within the pipe. In the rear half of the pipe, the distribution of flow velocities at the aeration orifices gradually stabilized, as the pipe was sufficiently long for the airflow to reach an ideal steady-state condition by the time it reached the end. As shown in Fig. 5b, the outflow velocity at the

aeration orifices of the side pipe side ranged between 2.5 and 3.2 m/s, representing a certain degree of reduction compared to the intermediate pipe. The flow velocity distribution at the side pipe aeration orifices was $T2 > T3 > T1 > CK$. The overall flow velocity in the side pipe remained relatively stable, with no significant fluctuations observed. The flow velocity at the aeration orifices near the side pipe inlet shows a decreasing trend. This is because the elbow pipe at the corner has a certain angle, causing the airflow to accumulate on the outer surface of the pipe wall at the corner, thereby affecting the flow velocity at the aeration orifices in that location.

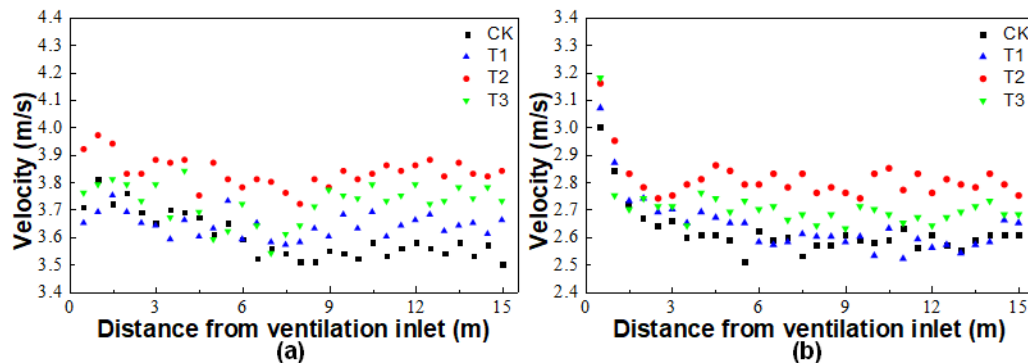


Fig. 5. Flow velocity distribution at aeration orifices in the (a) intermediate and (b) side pipelines

Adjusting the perforation spacing can increase the outflow velocity of the aeration orifices. The flow velocity at the aeration orifices of both the intermediate and side pipes in the gradually dense perforated structure was greater than that in the uniformly perforated structure. This is because the distribution density of the aeration orifices at the front end of the gradually more closely spaced perforated pipe was sparser than that of the uniformly perforated pipe. The flow of gas within a pipe follows the law of conservation of mass. A greater volume of airflow was directed toward the rear section of the duct, which increased the outflow velocity of the aeration orifices in the rear section of the pipeline. Additionally, the front section of the pipeline experienced higher air pressure, and the aeration orifices in this section were able to maintain a relatively stable velocity under the influence of this pressure. Type T2 aeration orifices exhibited the fastest outflow velocity, with the smallest amplitude of velocity fluctuations between the front and rear aeration orifices along the pipeline.

Analysis of Uniformity in Outflow from Aeration Orifices

Figure 6 shows the velocity contour map of effluent from the aeration orifices at the front and rear sections of the central pipeline at the bottom of the compost pile. The outflow velocity from the aeration orifices exhibited a concentric circular distribution. The air velocity gradually increased from the wall surface of the aeration orifice to its center. The velocity was highest at the orifice center, while the flow velocity near the wall surface was nearly 0. The velocity at the front end of the duct was not uniformly distributed, manifesting as a significantly higher velocity in the direction of airflow compared to the inlet direction. The flow velocity at the aeration orifices at the end of the pipeline exhibits a uniform state, with the flow velocity at each aeration orifice being essentially similar. The flow in the latter part of the pipeline has reached a steady condition. Because the area of the aeration orifices is constant and the air density remains unchanged throughout the process, the flow velocity of air through the aeration orifices is directly proportional to the

mass flow rate. Therefore, the uniformity of aeration within the pile can be inferred from the velocity distribution at the aeration ports.

The coefficient of air velocity variation is defined as the ratio of the standard deviation of the air velocity in a plane to its mean value. It is used to measure the uniformity of airflow distribution; the lower the value, the more uniform the airflow distribution. Table 1 shows the calculated mean and standard deviation of the surface flow velocity at all aeration orifices for each of the four pipe sections. Compared with CK, the average flow velocity across all aeration orifice planes increased by 2.4%, 1.9%, and 2.1% for T1, T2, and T3, respectively. Airflow uniformity improved by 3.8%, 12.7%, and 9.7%, respectively. As can be seen, optimizing the spacing between the aeration orifices resulted in only a slight increase in flow velocity, but it significantly improved flow uniformity.

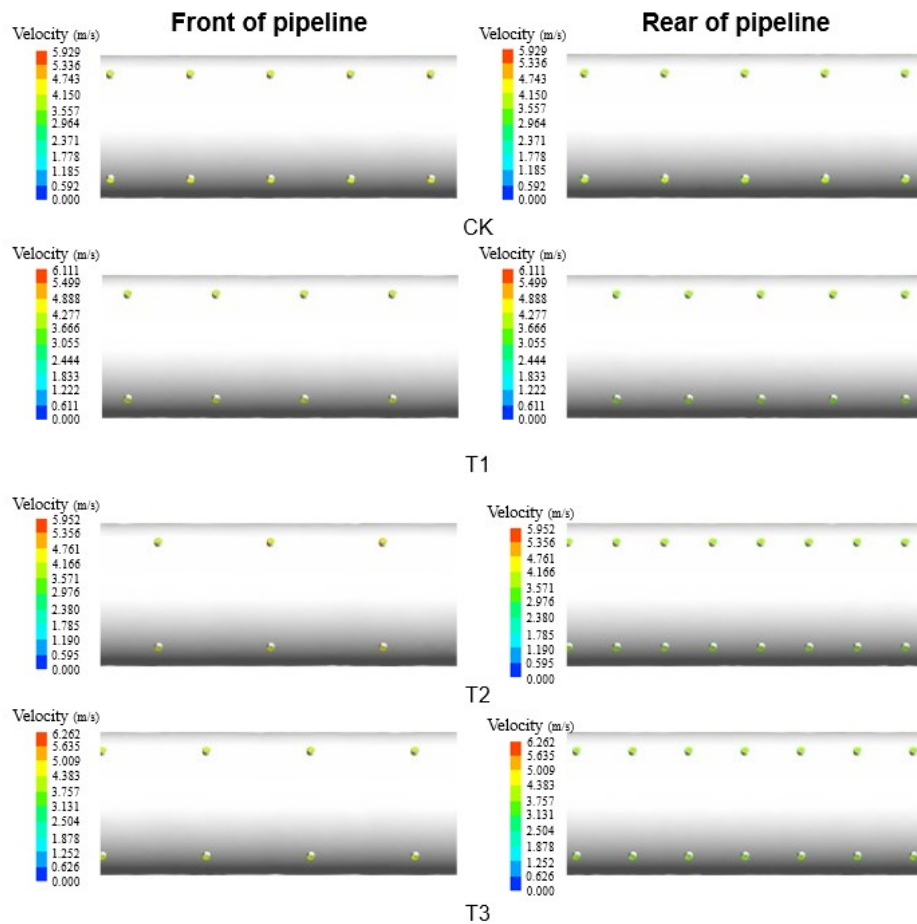


Fig. 6. Velocity distribution at the first and last aeration orifices of pipes with varying perforation spacings

Table 1. Aeration Orifice Flow Velocity Analysis

	Average flow velocity (m/s)	Standard deviation of flow velocity (m/s)	Coefficient of air speed variation (CASV)
CK	4.068	0.957	0.235
T1	4.157	0.941	0.226
T2	4.137	0.848	0.205
T3	4.145	0.878	0.212

Analysis of the Airflow Field within the Compost Pile

The oxygen content and distribution uniformity within the compost pile are related to airflow velocity. A uniform distribution of gas flow velocity within the compost pile can reduce the formation of anaerobic zones. Figure 7 shows the contour lines of airflow at different cross-sections within the compost pile for four types of pipe perforation methods. Cross-sections were taken from the front, middle, and rear sections of the compost pile. These three positions represent the three sections of the compost pile along its length. The apparent velocity of the air flow within the compost pile was relatively slow, approaching 1×10^{-3} m/s. After entering the compost pile through the aeration orifices, the air flow maintained a relatively high velocity. However, as the air encountered friction with the compost particles, causing a pressure drop, the rate at which the gas velocity decreased increases exponentially (Cheng *et al.* 2024). At lower flow rates, air primarily supplies oxygen for fermentation within the pile through diffusion, with the gas concentration gradient within the pile being the main driver of this diffusion (He *et al.* 2020). If the airflow velocity within the compost pile is too high, heat loss will become the dominant factor, requiring an extremely large pile volume to reach the ideal composting temperature (Luangwilai *et al.* 2018). Lower airflow velocity reduces heat loss while meeting oxygen supply requirements.

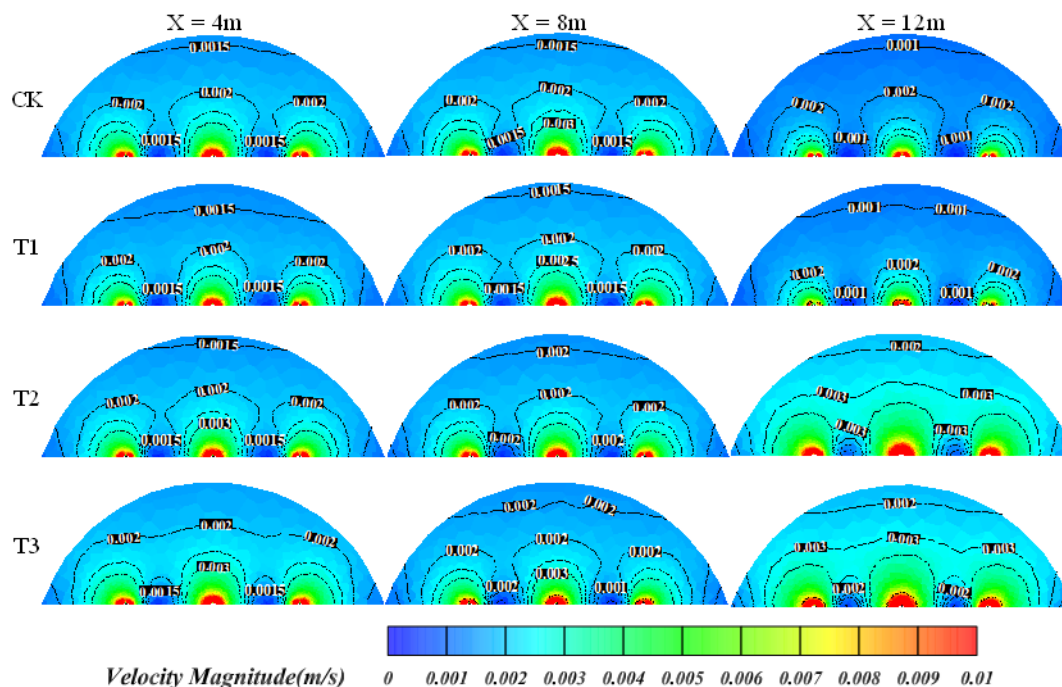


Fig. 7. Velocity distribution across each plane within the compost pile

A weak ventilation zone exists in the area adjacent to the pipes at the bottom of the compost pile, where the air velocity is less than 1×10^{-3} m/s. This is because the angle of the aeration orifices causes less airflow accumulation in this area, resulting in lower flow velocity. This is similar to the airflow at the bottom of a silo storage system (Nwaizu and Zhang 2021). Modifying the spacing of the aeration orifices can improve the flow velocity in this area. The air flow velocity at the bottom of the compost pile is superior in T2 and T3 compared to CK and T1. Increasing the spacing between orifices can effectively reduce low-flow velocity zones between pipes, thereby minimizing anaerobic fermentation in

these areas.

A uniform distribution of airflow velocity within the compost pile ensures that oxygen is delivered steadily to all parts of the pile. Compared with CK, the CASV values for T1, T2 and T3 increased by 1.3%, 2.1% and 1.8% respectively in the X=4 m plane; by 7.6%, 13.8% and 10.2% respectively in the X=8 m plane; and by 13.7%, 28.4% and 22.6% respectively in the X=12 m plane. Optimising the spacing between perforations increased the air supply intensity in the rear section of the compost pile, reduced areas of weak ventilation, resulted in a more uniform local airflow distribution, improved the uniformity of oxygen distribution within the compost pile, and ensured that fermentation proceeds normally. When the perforation spacing was set to T2, the uniformity of airflow within the compost pile was optimized.

Case Verification

To validate the feasibility of the aforementioned simulation design methodology and the accuracy of the simulated data, this study conducted further case studies for verification. The actual dimensions of the pile structure refer to the parameters in Figs. 1 and 2. Optimization of the perforated structure for bottom aeration pipes employed a spacing of 1 cm. The aeration mode for the compost pile employed continuous aeration, with the flow velocity at the pipeline inlet set to approximately 20 m/s. A total of 30 flow velocity sampling points were taken on each of the four planes along the length of the compost pile. When the aeration system was operating stably, an anemometer was used to measure the flow velocity at each point. Measurements were taken twice at each location, and the average value was calculated.

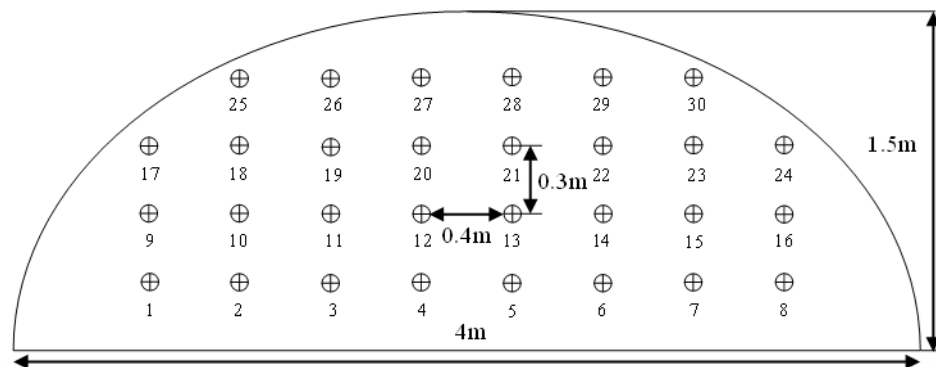


Fig. 8. Diagram of measurement points

Table 2 shows the root mean square error, mean absolute error, and mean relative error between measured and simulated values at four planes (X = 3, 6, 9, and 12 m) within the compost pile. The RMSE and MAE values for the four plane measurements and the simulated values were both lower than the order of magnitude of the flow velocity itself, indicating that the simulation results from the CFD model used in this study were highly accurate. The CASV values for the CK, T1, T2, and T3 planes were 1.12, 0.64, 1.56, and 1.09, respectively. The standard deviation of the CASV was 0.38, indicating that the variation in airflow uniformity across different regions within the compost pile was small, and that the overall airflow distribution within the compost pile was relatively uniform.

Figure 9 shows the comparison between actual measured values and simulated values within four planes of the compost pile. Actual measurements at all wind speed monitoring points exhibited certain discrepancies from simulated values, but the overall trend in flow velocity remained largely consistent. No measurement points showed significant discrepancies between measured and simulated values. The average relative error between the measured and simulated airflow velocities on each plane ranged from 4.9% to 7.3%, with an overall average relative error of 6.5%. In practical engineering applications, the relative error should not exceed 20% (Qian *et al.* 2023). The compost flow field model established by this research institute and its boundary condition settings generally correspond to the flow distribution within trough compost piles.

Table 2. Statistical Indicators of Each Plane

YZ section location	RMSE (m/s)	MAE (m/s)	MRE
X=3m	1.22×10^{-4}	1.14×10^{-4}	7.3%
X=6m	1.16×10^{-4}	1.15×10^{-4}	7.9%
X=9m	1.35×10^{-4}	1.29×10^{-4}	6.2%
X=12m	1.4×10^{-4}	1.36×10^{-4}	4.9%

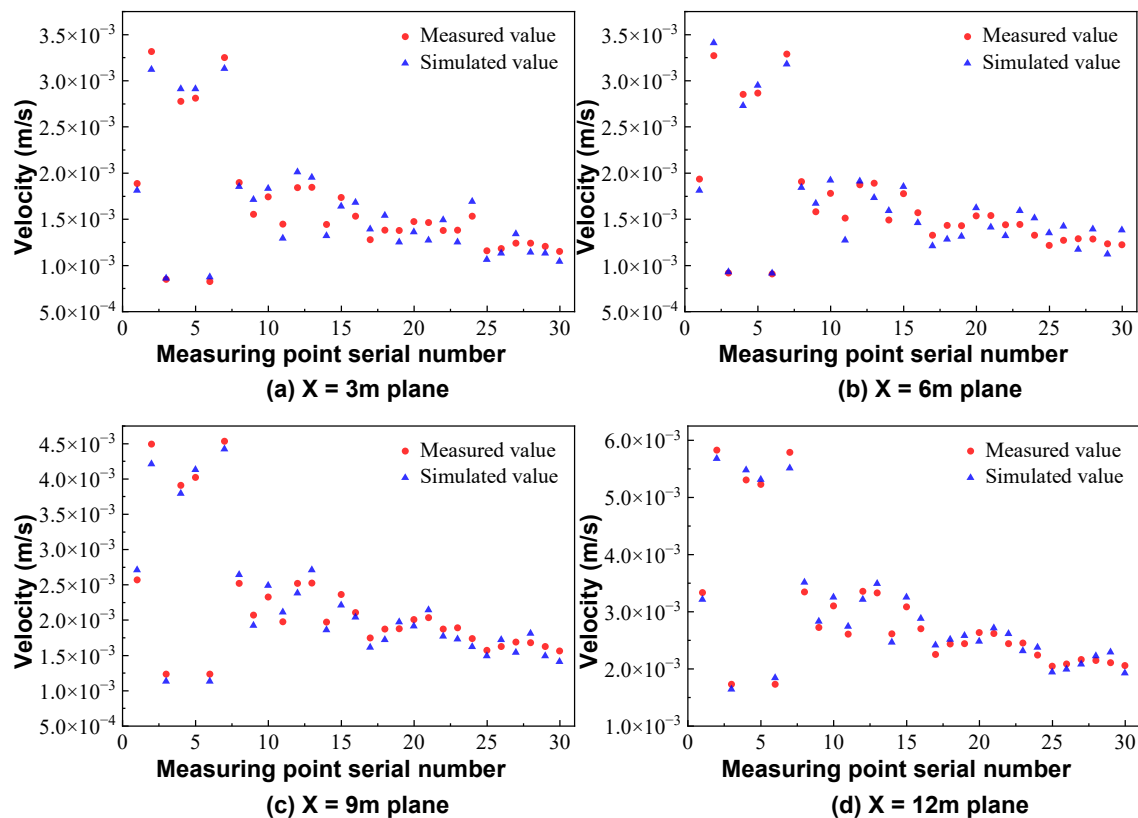


Fig. 9. Comparison of measured flow velocity values with simulated values

CONCLUSIONS

1. It is reasonable to describe the flow field within the trough compost pile and the flow in the bottom aeration pipes using computational fluid dynamics. The average relative error between the actual flow velocity within the pile and the simulated value was within 10%. The flow model and boundary conditions proposed in this study can be extended to trough composting systems of varying scales. This provides theoretical support for the structural design of the forced aeration system at the bottom of trough composting facilities.
2. Changing the spacing of the perforations in the pipes from uniform to gradually more closely spaced increased the flow velocity in the bottom pipes and improved the uniformity of flow within the aeration orifices and the compost pile. When the spacing was adjusted to 1 cm, the average flow velocity within the pipes increased by 14.9%, the flow uniformity at the aeration orifices improved by 12.7%, and the flow uniformity in the front, middle, and rear planes of the compost pile increased by 2.1%, 13.8%, and 28.4%, respectively. The improved airflow uniformity within the composting system provides a more favorable fermentation environment while reducing the formation of anoxic zones.

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