Thermal Environment Monitoring and Model Development of an Enclosed Vertical-Type Composting Facility

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Abstract: This study focused on the development of a scaled-down model for an enclosed vertical-type composting facility designed to efficiently manage space and odors. Through thermal environment monitoring, we observed that the temperature rose to 67 °C on the first day of composting and gradually decreased to 28.9 °C as the composting progressed. Temperature variations based on height were analyzed by dividing the facility into layers. The validation of the model was conducted by comparing actual measurements with model data using contour maps, resulting in a correlation coefficient ($R^2$) of 0.8, indicating the high reliability of the model. The findings demonstrated the effectiveness of the model in identifying and addressing issues in enclosed vertical-type composting facilities. Furthermore, it is anticipated that the model, which analyzes thermal environments, can be applied to automated operation systems for enhanced efficiency.

Keywords: composting; livestock odor management; manure; numerical analysis model

1. Introduction

The increase in meat consumption among the South Korean population has led to a rise in the number of livestock being raised. With Korea’s arable land area being only 1547 thousand hectares, which accounts for just 15% of the total land area, it is challenging to manage the growing volume of livestock manure [1]. The production of livestock manure has been steadily increasing, from 49,868 thousand tons in 2014 to 50,260 thousand tons in 2017 and reaching 51,886 thousand tons in 2021. The proper management of livestock manure is crucial as its inappropriate disposal into water bodies can lead to severe environmental issues. Methods for treating livestock manure include composting, liquid fertilization, and purification processes, with approximately 75% of the manure generated in Korea being treated through composting [2,3].

Composting is one of the methods that minimizes environmental impacts while biologically stabilizing organic matter, turning organic waste into a resource. The traditional composting method involves piling compost into cone-shaped heaps and periodically turning them. To enhance efficiency, an additional method involves injecting air through pipes installed at the bottom of the compost pile [4]. In Korea, continuous agitation composting facilities, which fill compost into a trench (U-shaped) structure and stir it daily with a mixer installed at the top, are widely distributed for the efficient processing of livestock manure in confined spaces [5]. However, this method occupies a large area, leading to increased construction costs, and has the disadvantage of making it difficult to capture odors [6]. The odorous substances generated during the composting process can lead to complaints from nearby areas, necessitating the installation of facilities for odor reduction [7].
Recently, enclosed vertical-type composting facilities, which offer higher space utilization and easier odor capture than continuous agitation composting facilities, have been recognized as a superior alternative for the treatment of livestock manure. Enclosed vertical-type composting facilities are cylindrically designed, with blades attached to an internal axis that continuously rotate, stirring the compost. This equipment introduces air through holes located at the bottom or on the rotating blades to supply air to the compost. This technology is widely utilized, and in Korea, approximately 163 farms were equipped with these facilities in 2022 at a total cost of about USD 18.56 million through local government subsidies [8,9].

Despite active research on enclosed vertical-type composting facilities, there is a lack of study on the internal temperature changes caused by the heat generated during the composting process. This deficiency makes it difficult to effectively monitor the composting process in enclosed vertical-type composting facilities in the field [10,11].

To address this issue, the development of a numerical analysis model and a computer program that can analyze the internal state is needed. By using a numerical analysis model, it is possible to identify changes in the thermal environment of the compost pile, which can help in devising appropriate operational strategies for enclosed vertical-type composting facilities [12]. Numerical analysis models can be utilized to calculate fluid dynamics and changes, thereby analyzing various environmental conditions within facilities. Such models can be effectively applied in research concerning air flow within livestock buildings, the diffusion of harmful gases, and the improvement of mixing efficiency in biogas facilities. This suggests that it can play a crucial role in enhancing livestock productivity through monitoring and analysis [13–15].

Few studies have been conducted on composting using computational fluid dynamics (CFD). However, composting process modeling is relatively rare as it presents challenges in incorporating biochemical reactions, internal aeration, and thermal diffusion. Moreover, even when models are developed, there is a significant scarcity of fundamental data necessary to validate the accuracy of these models. A study was performed to model the dynamic changes in oxygen concentration and temperature inside a compost pile during the composting process [16]. Additionally, research was conducted on a CFD model to explain the dynamic temperature changes and spatial distribution within a compost pile when composting food waste [17]. Furthermore, an analysis of gas flow generated during the composting process in a composting facility was carried out to study the internal gas turbulence and stagnation within the facility [18].

This study was conducted with the goal of monitoring and analyzing temperature changes occurring inside enclosed vertical-type composting facilities during the composting process and, based on these data, developing a thermal environment model.

2. Materials and Methods

2.1. Experimental Subject

The subject of the experiment, an enclosed vertical-type composting facility was installed at a swine farm located in Dangjin City, Chungcheongnam-do. This reactor is cylindrically designed with a height of approximately 10,000 mm and a diameter of about 4000 mm. It is equipped with 8 rotating blades inside, which serve to stir the compost by making one rotation per hour. At the bottom of the reactor, pipes are installed to supply air to the compost pile, with the air supply rate set at 150 L·m⁻³·min⁻¹. The material for composting is added from above and slowly moves downward through the facility for mixing [19]. The raw material used in the enclosed vertical-type composting facility was pig manure that had been separated into solids and liquids using a decanter (Figure 1a).
When taking an operational, full-scale enclosed vertical-type composting facility as a research subject, several issues arise. First, direct investigation in a facility processing large volumes of manure poses significant risks to researchers. Second, the enclosed structure makes it difficult to see inside, complicating temperature measurements at consistent points. Third, to monitor the internal thermal environment from the beginning of the composting process, artificial conditions must be set; however, pausing an operational facility to remove all manure and then restarting it is practically challenging. Lastly, the physical properties of composting materials vary from farm to farm, and external temperature changes make it difficult to obtain consistent results during model validation. To address these issues, a device reflecting the blade position, number, air supply rate, and rotation speed of an operating enclosed vertical-type composting facility was constructed and used for experimentation (Figure 1b).

2.2. Monitoring of Thermal Environment Inside Enclosed Vertical-Type Composting Facilities

This experiment was conducted over 8 days in a separate space measuring approximately 60 m² (5 m × 12 m) under constant temperature conditions of 25 °C. The experimental reactor designed to monitor the internal thermal environment of the enclosed vertical-type composting facility was fabricated at a scale of 1/100 of the actual size, with a height of 1000 mm and a diameter of 400 mm. The reactor’s internal shaft was designed with 7 attached stirring blades, with the rotation rate set at 1 rotation per hour, and the air supply rate was set at 150 L m⁻³ · min⁻¹. Pig manure separated into solids and liquids using a decanter was used as the substrate, and the 125 L reactor was filled nearly to capacity with this manure.

Temperature sensors were installed to precisely measure the temperature changes that occurred during the composting process based on height and position. K-type thermocouples were used for temperature measurement, and the recorded temperature data were logged using a data logger (GL840, Graphtec, Tokyo, Japan). The sensors were divided into 4 layers: the bottom (B) layer located 100 mm above the reactor’s base, the middle bottom (MB) layer at 350 mm, the middle top (MT) layer at 600 mm, and the top (T) layer at 900 mm. To accurately measure temperature changes at different depths, a total of 5 points from the center to the outer edge of the reactor were selected for the temperature measurement. Each layer had 5 temperature measurement points, making a total of 20 points in the entire reactor where temperature measurements were taken (Figure 2).
To analyze the spatial distribution of temperature and compare it with the validation data of the temperature model, a contour map of temperature distribution was created using Surfer 22.0 software. The temperature values used in this process were based on the average temperatures measured from the four reactors. Table 1 presents the results of the analysis of the characteristics of the sewage used in the experiment, including pH, EC (electrical conductivity), elemental analysis (C, N, S, H), total solids (TS), and volatile solids (VS).

Table 1. Material properties of pig manure at the initial stage of the experiment (average ± S.D.).

<table>
<thead>
<tr>
<th>Item</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.2 ± 0.0</td>
</tr>
<tr>
<td>EC (μs/cm)</td>
<td>1969 ± 0.0</td>
</tr>
<tr>
<td>Total solid (%)</td>
<td>30.31 ± 0.0</td>
</tr>
<tr>
<td>Volatile solid (%)</td>
<td>89.21 ± 0.0</td>
</tr>
<tr>
<td>Carbon (%)</td>
<td>40.4 ± 0.0</td>
</tr>
<tr>
<td>Nitrogen (%)</td>
<td>2.2 ± 0.0</td>
</tr>
<tr>
<td>Sulfur (%)</td>
<td>1.0 ± 0.0</td>
</tr>
<tr>
<td>Hydrogen (%)</td>
<td>5.8 ± 0.0</td>
</tr>
</tbody>
</table>

2.3. Design of Thermal Environment Model for Enclosed Vertical-Type Composting Facility Using CFD

The model development involved creating an exterior that matched the conditions of the actual reactor and establishing a porous zone to replicate the compost inside the reactor. The exterior of the model was created using Ansys SpaceClaim 2022 R1, based on the design drawings of an experimental enclosed vertical-type composting facility. The reactor’s bottom part featured sixteen 2 mm diameter air inlets, which were streamlined in this model to four 20 mm diameter inlets for efficiency. The flow rate of the air being discharged and the incoming air was measured, and the inlet size was adjusted accordingly in the simplified model. On the top of the reactor, there exists a 30 mm diameter outlet through which the air entering from the inlets passes through the compost layer, and this
was implemented identically in the model. The exterior walls were set to be made of stainless material, like the actual experimental model. Further details of the model’s boundary conditions are listed in Table 2.

Table 2. Boundary conditions of numerical analysis model.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity coefficient</td>
<td>435,560,000 m$^{-2}$</td>
</tr>
<tr>
<td>Coefficient of inertia resistance</td>
<td>18,150 m$^{-1}$</td>
</tr>
<tr>
<td>Porosity coefficient</td>
<td>0.3</td>
</tr>
<tr>
<td>Inlet velocity</td>
<td>0.088 m·s$^{-1}$</td>
</tr>
<tr>
<td>Wall density</td>
<td>8000 kg·m$^{-3}$</td>
</tr>
<tr>
<td>Wall specific heat</td>
<td>515 J/kg·k</td>
</tr>
<tr>
<td>Wall thermal conductivity</td>
<td>15.5 W/m·k</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>25 °C</td>
</tr>
</tbody>
</table>

A porous zone was established inside the model to simulate the compost layer. The porosity, viscosity coefficient, and inertial resistance coefficient within this porous area were set based on preceding research [16,20,21]. The viscosity resistance coefficient and inertial resistance coefficient in the porous media follow Equations (1) and (2).

$$\frac{1}{\alpha} = \frac{150}{D_p^3} \frac{(1 - \epsilon)^2}{\epsilon^3}$$  \hspace{1cm} (1)

$$C_2 = \frac{1.75}{D_p} \frac{1 - \epsilon}{\epsilon^3}$$  \hspace{1cm} (2)

where $D_p$ denotes the average size of compost particle and $C_2$ denotes the inertial resistance coefficient. Referencing earlier studies, the average size of the compost particles, $D_p$, was determined to be 2.5 mm, and the porosity hypothesis constant, $\epsilon$, was set at 0.3 m$^3$·m$^{-3}$ [22,23].

2.4. Grid Independence Test

When designing a grid, the smaller the size of the grid, the higher the accuracy, but this also leads to a significant increase in computation time and the possibility of errors due to unnecessary details. To evaluate grid independence, CFD simulations are run multiple times. The numerical analysis is compared with reference analyses or field data, allowing for the determination of an error metric that represents the difference between the two values. The error metric can be measured by methods such as RMS (root mean square) and maximum error and can also be determined by quantitatively measuring the physical quantities of the object [24].

Grid independence evaluations can be performed using various methods, including the Richardson extrapolation method, grid convergence index, and grid refinement study. Out of these, the grid refinement study method was utilized to evaluate grid independence. To reduce the computation time while improving the accuracy of the calculations, an analysis of skewness based on grid size and an evaluation of independence for sectional average temperatures were conducted. The grids for analysis were set to sizes of 1, 3, 5, 7, and 10 mm.

The analysis of the number of grid cells according to grid size showed that there were 840,403 grid cells at 1 mm, 96,221 at 3 mm, 34,125 at 5 mm, 17,765 at 7 mm, and 8742 at 10 mm. The skewness values were 0.61 at 1 mm, 0.56 at 3 mm, 0.46 at 5 mm, 0.49 at 7 mm, and 0.49 at 10 mm. The lowest skewness value of 0.46 at 5 mm indicated the highest model quality, with a lower number of grid cells than at 1 mm and 3 mm, serving as an indicator for efficient simulations (Figure 3).
Figure 3. Analysis of the number of grids with grid size for the grid independence test.

The grid independence evaluation conducted for temperatures across different sections revealed that in the B layer, the temperature was 43.8 °C at the 1 mm grid size, 44.0 °C at 3 mm, 44.1 °C at 5 mm, 44.3 °C at 7 mm, and 44.3 °C at 10 mm. In the MB layer, the temperature was 61.1 °C at the 1 mm grid size, 61.1 °C at 3 mm, 61.0 °C at 5 mm, 61.0 °C at 7 mm, and 61.4 °C at 10 mm. In the MT layer, the temperature was 64.2 °C at the 1 mm grid size, 64.1 °C at 3 mm, 64.0 °C at 5 mm, 63.9 °C at 7 mm, and 63.2 °C at 10 mm. In the T layer, the temperature was 46.5 °C at the 1 mm grid size, 46.6 °C at 3 mm, 46.6 °C at 5 mm, 46.7 °C at 7 mm, and 47.9 °C at 10 mm (Figure 4).

Figure 4. Evaluation of temperature variations in layers according to grid size: (B) bottom layer; (MB) middle bottom layer; (MT) middle top layer; (T) top layer.

3. Results and Discussion
3.1. The Thermal Environment monitoring of Enclosed Vertical-Type Composting Facilities

A temperature rise occurs due to the decomposition of organic matter by microbes during the composting of livestock manure and serves as the best indicator of the composting process, with the optimal composting temperature being 55 to 60 °C [25]. For the composting period, a contour map was created using temperature data from 20 points installed inside the reactor to observe temperature changes over time and by location. The analysis focused on how the thermal environment inside the enclosed vertical-type composting facility changed throughout the composting period. On Day 0, the beginning of the experiment, the temperature range uniformly rose to between 32.0 °C and 35.0 °C. By Day 1, during the peak of the composting period, the temperature in the compost pile
reached its highest, ranging from 36.7 °C to 67.2 °C. Following Day 2, the temperature gradually decreased, and by Day 7, it was measured between 28.9 °C and 37.2 °C. Based on the temperature changes according to location, the MT layer recorded the highest temperatures throughout the experimental period. The next highest layer was MB, while the B and T layers were found to be lower than the other locations. On Day 1, the deepest temperature increase, driven by the heat from the decomposition of organic matter within the compost, resulted in a difference of more than 20 °C between the core and the bottom part. However, as the composting period progressed, this variance reduced to less than 5 °C by the final day (Figure 5).

Figure 5. Changes in the thermal environment inside the compost during the composting period.
At the start of the composting process, the temperature inside the compost pile rose due to the heat generated by microbes decomposing biodegradable material. As the biodegradable material remaining in the manure was exhausted, the temperature gradually decreased [26]. The experiment spanned 8 days, with the mixing blades inside the reactor operating continuously without any breaks, leading to a composting period that was not extended. This outcome aligned with the tendency observed in other studies using continuously stirring reactors, where the duration of composting was similarly brief [27].

In typical composting experiments, the compost located at the innermost part usually exhibits the highest temperature. However, in this experiment, the highest temperature points were observed at two locations. This occurrence is attributed to the lower stirring efficiency at the innermost part where the axis is situated compared to other areas [28]. Nevertheless, continuous stirring is expected to maintain adequate temperature conditions for pathogen destruction, suggesting that there should not be stability issues related to pathogens [29].

Temperature variations by height indicated that the B layer was measured to have a relatively lower temperature compared to other sections, a condition attributed to the air supplied from the piping located at the bottom of the reactor. The introduction of air into the bottom part of the compost pile resulted in deviations, yet during the hottest phase, on Day 1, the lowest temperature of the B layer was recorded at 36.7 °C, and on the last day, Day 8, the temperature at the same spot was observed to be 35.2 °C. These observations suggest that the factors determining the temperature at the bottom part of the compost pile lean more towards the inflow of air and conductive heat from the bottom than the heat generated by microbial activity [30]. It was also noted that the temperature in the T layer decreased due to the heat conducted from the lid of the reactor (Figure 5).

During the composting period, the decomposition of organic matter generates approximately 16–19 MJ of energy per 1 kg of volatile solids throughout the period [31]. The temperature change associated with the composting period began at 35 °C on Day 0, reaching a peak of 53 °C on Day 1. Throughout the experiment, the temperature gradually decreased back to 35 °C, showing a consistent pattern of change at all heights, including the T, MT, MB, and B layers. Since the temperature within the composting reactor varies by height, there is a need to closely analyze the temperature changes at the same height [32]. The T layer, located at the top of the reactor, displayed a temperature range of 34 to 50 °C, the MT layer from 36 °C to 66 °C, the MB layer from 35 to 60 °C, and the B layer from 30 to 38 °C. On Day 0, the average temperature across the different height sections was relatively small, between 34 and 36 °C, but on Day 1, the temperature range expanded to 38 to 66 °C, showing a significant difference of about 28 °C between the B and MT layers. The increase in microbial activity was identified as the primary cause of temperature rise during the composting period. Based on temperatures indicative of high microbial activity, the most active composting sections were listed in order of MT, MB, T, and B layers (Figure 6).
3.2. Simulation Model Validation and Analysis

The analysis of the correlation between the distance from the center of the compost pile and temperature change showed a significant variation in temperature from Day 0 to Day 1, reaching a peak before stabilizing. Based on these results, model validation was conducted using Day 1 data, where microbial activity was highest and temperature diffusion from the center of the compost pile was most evident.

A grid refinement study was conducted to evaluate the impact of grid size on the formation of structures within the model. To verify the shape of the grid formed inside according to the grid size, the model was filled with grids of different sizes to check the density. When the grid size was 1 mm, the number of grids was the highest at 840,403, while at 5 mm it was 34,125, and at 10 mm, it was 8742. Upon evaluating the density for each grid size, the result with the lowest skewness value of 0.46 at 5 mm suggests that a grid size of 5 mm is the most efficient (Figure 7a). Additionally, when the model was constructed with a grid size of 5 mm, the assessment of the shape and density by checking the grid composition at different locations revealed that the grids were well formed and robust at the outlet, compost pile, and inlet areas (Figure 7b).
Figure 7. Evaluation of density and internal grid configuration by grid size: (a) internal density of the model by grid size; (b) grid formation at different internal locations with a 5 mm grid size.

The results were found to be at a similar level to numerical analysis studies on reactor modeling using livestock manure. The structures built for processing livestock manure should prevent the accumulation of residues, and therefore, it is believed that most structures operating in the field have simple configurations [33,34].

The temperature simulation results of the model were implemented in the form of contour maps, which were compared with contour maps created based on actual measured temperature values. The legend was set identically, representing the temperature range with a maximum value of 70 °C in red and a minimum value of 30 °C in blue. Due
to the inability to implement conductive heat in the map using measured temperature values, 20 mm on both sides was omitted when creating the map with model temperature values. The distribution of temperature changes was presented in a gradient form. Upon comparing the two maps, the high completeness of the model was evident. Both maps showed that the highest temperatures were at the center of the compost, gradually decreasing as the distance from the center increased. The low temperatures at the reactor’s ceiling and floor due to the influx of external air and conductive heat were also well represented (Figure 8). The validation of the simulation model was conducted through an analysis of the correlation between the temperature values measured in the reactor and those calculated by the simulation model. The x-axis represented the measured temperature values, while the y-axis showed the simulation temperature values at the same locations. The analysis of the correlation between the two temperature values resulted in an $R^2$ value of 0.8 (Figure 9).

![Figure 8](image-url)  
(a) measured in experiment; (b) computed in CFD.
4. Conclusions

This study aimed to develop a scaled-down model of an enclosed vertical-type composting facility that occupies less space and enables odor management compared to traditional composting facilities and to monitor its thermal environment for model development. The thermal environment monitoring showed that the temperature rose significantly on the first day of the composting process, allowing the arrangement of composting activity within the enclosed vertical-type composting facility in the order of MT→MB→T→B layers. The reliability of the model was confirmed by producing contour maps and conducting a correlation analysis between the generated model data and actual measured data, resulting in an $R^2$ value of 0.8. The developed model is expected to be useful for identifying and exploring improvement measures for internal issues in enclosed vertical-type composting facilities. Furthermore, it is anticipated that the model, which analyzes thermal environments, can be applied to automated operation systems for enhanced efficiency. However, it was challenging to characterize the properties of porous media, and the assumptions of the model need further optimization.

Author Contributions: H.-J.S. and D.-H.L. generally conducted the field monitoring, experimental analysis, methodology, and data interpretation. H.-J.S. undertook the writing, conceptualization, and interpretation of the data. I.-H.S. designed and supervised the experiment. All authors have read and agreed to the published version of the manuscript.

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