STUDY ON EFFECT OF UPFLOW AND DOWNFLOW FORCED AERATION ON COMPOSTING IN A CLOSED SYSTEM USING A SOFTWARE-BASED MODEL

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ABSTRACT

Composting is an aerobic biodegradation process in which organic matter is biologically decomposed and stabilized also generating a nutrient-rich humus-like product. Despite its environmental benefits, conventional composting systems often face operational inefficiencies related to non-uniform aeration, uneven temperature distribution, and moisture accumulation. Two-way forced aeration system can overcome those operational inefficiencies and improve the overall efficiency as compare to traditional composting system. In this study a python based kinetic model was used to evaluate the performance of two-way aeration system and compared with one-way aeration system. The model simulated the temperature, oxygen content, moisture, and volatile solids reduction in the compost with two way directional flow cycles in the compost layers. The simulation code was designed to update the airflow direction dynamically based on the cycle time, in which at first for each hour the direction of the airflow was checked and then the caluculation was started from either bottom or top layer according to the airflow direction. The compost pile was divided in 6 layers and model was run for 28 days with an initial compost mass of 750 kg with 58.9% moisture content, 4% fixed solids, and 48% volatile solids on total solids with 25°C temperature and constant airflow of 5 m^3/m^2h. The two way directional model outperformed the one-way conventional model with enhanced oxygen mass fraction, temperature variations, and moisture content reduction in the compost mass. Compared to the one-way model, the two-way model yielded a 7.18% lower final compost mass (332.2 kg vs. 357.9 kg). It also resulted in a 4.96% reduction in volatile solids (76.6 kg compared to 80.6 kg) and an 18.82% lower moisture content (95.3 kg vs. 117.4 kg). Hence, the layerwise analysis revealed mirror condition of composting parameters change between layer 1 and layer 6, layer 2 and layer 5, layer 3 and layer 4 which confirm a more uniform decomposition pattern under alternating airflow. The shorter 24h cycle duration showed better result than longer 72h cycle with reducing the final compost mass to 316.7 kg and increasing volatile solids reduction to 73.8 kg. The model findings suggest that programming-based two-way aeration enhances composting efficiency, promotes uniform stabilization, and reduces environmental risks compared to traditional one-way systems. The Python modeling approach also offers a cost-effective and scalable tool for advancing sustainable composting practices.

Keywords: *Two-way, aeration, kinetic-model, dynamic-airflow, python*

1. INTRODUCTION

The increasing pace of the world population and consumption has intensified the production of solid waste at the municipal level, and in recent years, the figures are 2.1 billion tonnes, and 3.8 billion tonnes are estimated in the coming 2023 and 2050 respectively. This trend puts a lot of pressure on the collection, treatment, and disposal infrastructure, especially in the low- and middle-income nations where open dumping is still so widespread (Chen et al., 2020; Kaza et al., 2018; Maalouf & Mavropoulos, 2023).

Composting refers to the aerobic biologic breakdown and stabilization of intricate organic substances into a stable humus-like outcome. The end product is a stable, grown up compost which can be stored and used on land without causing environmental damage (Hamoda et al., 1998). Composting is particularly beneficial in the management of manure since it deactivates pathogens, is used as a conditioner in the soil and the risk of environmental pollution is reduced (Larney et al., 2011). In the process, microbial activity produces enough heat to take the system to thermophilic temperatures; the increase in temperature is caused by biochemical oxidation that breaks down complex organics. Composting is therefore a controlled accelerated way of degrading organic waste. With the right conditions (which include temperature, humidity, carbon-to-nitrone (C /N) ratio and air circulation) well controlled, composting can take as short as four to ten weeks to complete. Therefore, the process does not only accelerate degradation, but its mass and volume of the waste also significantly decreases (Walling et al., 2020).

The key factor is aeration strategy: forced aeration could establish vertical gradients in oxygen, temperature, as well as moisture, whereas alternating upflow/downflow system could even out conditions between layers, reduce anaerobic pockets, and stabilize heat release (Bari & Koenig, 2012). Forced aeration systems include two forms of forced draught as a means of controlling the movement of air within compost piles to improve efficiency and stabilize the process (Michel et al., 2022). These systems are in contrast to conventional systems that have unidirectional aeration, and they periodically reverse the direction of flowing air in the compost mass with the aim of ensuring constant temperature, oxygen and moisture levels. In general, two-way forced draught composting provides a significant benefit to sustainable composting, whereby enhanced, faster, smell-free and more qualitative compost can be produced and operators can have a tight control over key process parameters (Cayuela et al., 2006).

Composting process entails various operational aspects which should be taken into account cautiously so as to realize the best outcomes. Bari & Koenig, 2012 set up a mathematical model in order to estimate the composting capacity of biodegradable organic waste. Real composting experiments are often expensive and time-intensive , thus, by using kinetic models, it will be possible to calculate the composting parameters more effectively (Walling et al., 2020). Such calculations have been done previously by using Microsoft Excel, but Excel based models have limitations such as user unfriendly interfaces and change in formula can be done by mistake making it difficult to detect and rectify any mistakes. The need of programming based models is highlighted by such restrictions. In addition, a second composting stage can also be included in the model in order to determine additional degradation. Optimizing important composting factors including airflow rate, ambient temperature, moisture content, and C/N ratio to produce faster decomposition and better compost quality can also be accomplished through the use of mathematical models, often using trial-and-error methods. Python was thus used to create a programming-based kinetic model. The choice of Python was driven by its ability to work well with large volumes of data and its complex computation ability which is usually out of reach to spreadsheet-based applications such as Microsoft Excel. The programming languages are better scaled, have better performance and are more flexible as the complexity of the model increases. Compared to Excel, the data in programming-based models can be easily debugged, the probability of accidental changes in formulas is minimized, and the underlying code is not easily compromised, which guarantees the integrity and reliability of the data.

The main aim of this research is to work out a programming-based model that would simulate the process of temperature, oxygen and volatile solids degradation in composting in the conditions of two-way forced aeration and compare the obtained results with one-way aeration model. Further, this paper compares the composting behavior of various mirrored layers and 24 hours and 72 hours composting.

2. METHODOLOGY

2.1 Model Development

A Python model based on kinetic equations was developed to simulate composting under alternating upflow and downflow (two-way forced) aeration conditions in a closed reactor system. The model was designed to evaluate temperature, oxygen concentration, moisture variation, and volatile solids degradation over time. At the start of the program, all initial parameters were defined, including temperature, heat generation from biodegradable volatile solids (BVS) degradation, specific heat capacities, reaction rate constants, humidity, compost mass and composition, cycle duration, and total simulation time. Preliminary computations determined dry air weight, water and solid masses, individual layer masses, total simulation hours, and vapor inflow. Arrays were created to store hourly and layer-wise variable values.Total 16 arrays were defined in this code. A nested loop structure iterated through time and layers, with airflow direction controlled by the cycle-hour condition. For upflow at the initial hour, baseline values of dry mass, moisture, temperature, oxygen, and volatile solids were initialized, while for subsequent hours and downflow cycles, these values were updated according to composting dynamics and stored. The model finally generated time-series graphs of temperature, moisture, oxygen, and volatile solids, along with comparative charts of initial and final compost composition.Initial conditions were: temperature (T_0) = 25 °C, moisture (M_0) = 58.9 %, fixed solids (FS_0) = 4 %, volatile solids (VS_0) = 48 %, and airflow rate (Q) = 5 $m^3/m^2 \cdot h$. The simulation was run for 28 days with a 1-hour time step ($\Delta t = 1$ h). Alternating airflow direction was modeled by reversing layer computation order every *n* hours (6–72 h cycles) to represent upflow and downflow phases (Figure 1).

2.2 Physio-Chemical Analysis

Different composting parameters like initial temperature, ambient temperature, heat generated by degradation of BVS, specific heat capacity of wet composting material, specific heat transfer co-efficient, relative humidity, initial mass, water contnet ,fixed solid , initial percentage of volatile solid were used as input variables. The basic mathematical model was formulated considering heat balance across the composting mass the previous experimental studies on heat balance for the self-heating test and kinetic analysis of forced aeration composting

2.3 Implementation of Two-Way Forced Aeration

The simulation code was designed to update the airflow direction dynamically based on the cycle time. At each simulation hour, the program first checked whether the airflow should move upward or downward. When the airflow was upward, the calculation began from the bottom layer (layer 1) and progressed sequentially toward the top (layer 6). In contrast, when the airflow direction was reversed, the order of calculation also changed, starting from the top layer (layer 6) and proceeding downward. To implement this, the code created an ordered list of layers for every hour of the simulation. If the airflow was upward, the list followed the natural order of the layers, whereas in the downward phase, the list was reversed. During each step, the program identified the current layer as well as the previous layer in the airflow path, allowing the values from one layer to influence the next. In this way, the interdependence of layers was preserved while maintaining the proper airflow direction throughout the composting process.

```
# Main calculation loop
for hour in range(total_hours):
    if (hour // cycle_hours) % 2 == 0:
        layer_order = list(range(layers))
    else:
        layer_order = list(range(layers - 1, -1, -1))
    for idx in range(layers):
        layer = layer_order[idx]
        prev_layer = layer_order[idx - 1] if idx != 0 else None
```

Flow chart diagram

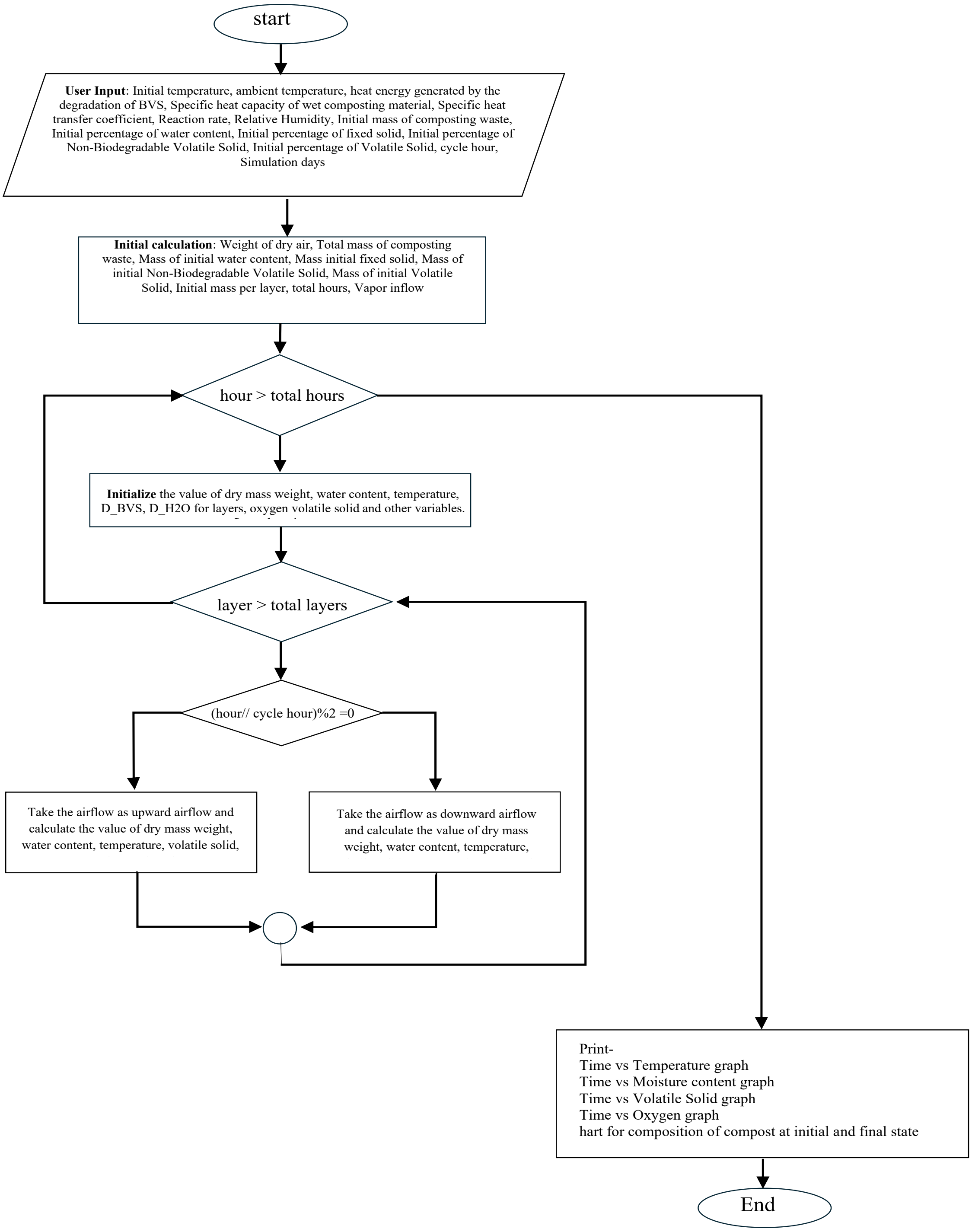

Figure 1 : Flow Diagram of Developed Python-driven Model

3. RESULT AND DISCUSSION

3.1 Comparative Analysis of One-Way and Two-Way Forced Aeration Composting Models

For the same set of input parameters, a comparison was made between the previously developed Excel spreadsheet model for one-way forced aeration (Bari & Koenig, 2012) (Figure 2) and the current programming-based model for two-way forced aeration model (Figure 3).The initial temperature of composting was set as Tci = 25 °C, ambient temperature as Ta = 25 °C, heat energy generated by the degradation of BVS as HL = 13500, specific heat capacity of wet composting material as cpc = 3.4, specific heat transfer coefficient as kc = 0.00005, reaction rate as K_hr = 0.00043, and relative humidity as RH = 0.75. The initial mass of composting waste was 750 kg, with an initial water content of 58.9 %, fixed solids 4 %, non-biodegradable volatile solids 48 %, and volatile solids 48 %. The compost density was 470 kg/m³, height 160 cm, and a constant airflow of 5 $m^3\ m^{-2}\ h^{-1}$ applied continuously for 28 days. Due to one-way airflow in one-way forced aeration, temperature rises faster in the lower layers and decreases toward the top layers. But in two-way forced aeration due to airflow was bidirectional, after a certain period the direction of the airflow changes as a result 1st layer became the last layer and last layer became the first layer so the temperature is more evenly distributed across all layers. The lower layers have more oxygen available due to one-way aeration, whereas the upper layers may have less oxygen, which could decrease microbial activity (Table 1). By distributing oxygen more evenly

Table 1: Comparison between one-way aeration model vs two way python driven model

	One-way forced aeration	**Two-way forced aeration**
Initial Mass of compost	750	750
Final mass of compost	357.9	332.2
Final mass of Total Solid	240.5	236.9
Final mass of Fixed Solid	12.3	12.3
Final mass of Non-volatile Biodegradable Solid	148.0	148.0
Final mass of Volatile Solid	80.6	76.6
Final mass of Water content	117.4	95.3

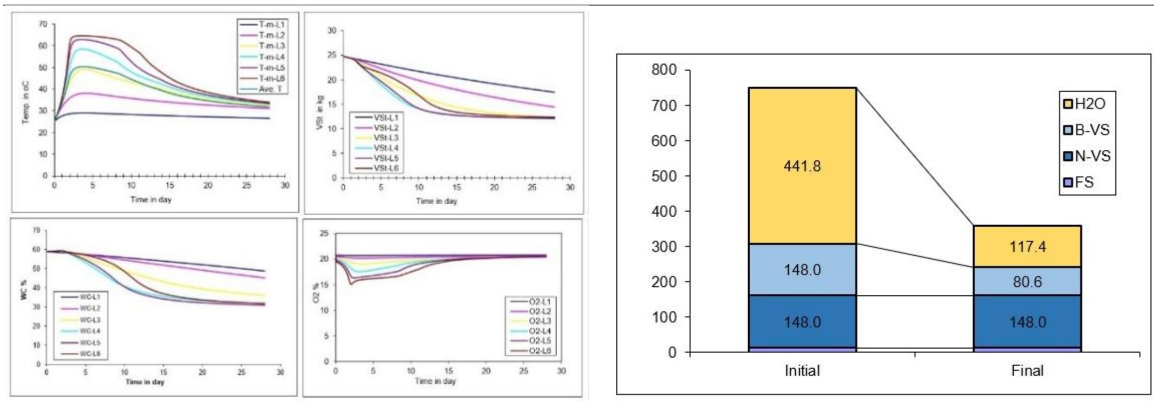

Figure 2 : Different Composting parameters of one-way excel model

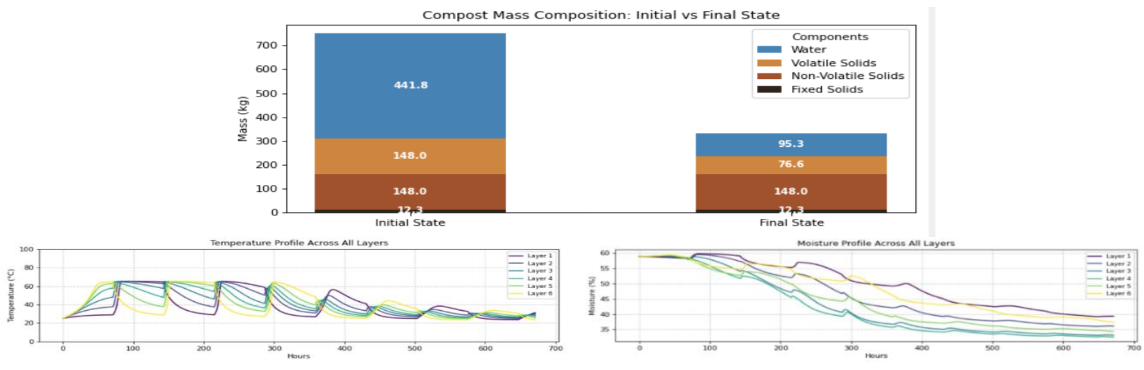

Figure 3 : Different composting parameters of two-way python driven model

throughout the compost heap, two-way aeration increases microbial activity overall. Two-way aeration promotes more uniform degradation across all layers, as airflow reversal ensures previously less-aerated layers receive sufficient oxygen. One-way aeration can cause moisture to accumulate in the upper layers, leading to uneven distribution. Two-way aeration balances moisture content across layers, reducing localized saturation or drying and supporting better microbial activity.

3.2 Comparison between different layers

In this study air is supplied alternately from both side, so that all six layers get better oxygen distribution. The bottom layer decomposed faster and the top layer retained slightly more moisture. Middle layers showed moderate changes in temperature, oxygen and volatile solids. In general, this alternating airflow improves compost stability and minimizes anaerobic zones all six layers. As the direction of air reverses after a certain time the bottom layer acts as top layer and vice versa. So that the alternate layers like (layer 1 and layer 6 (*Figure 4*), layer 2 and layer 5 (Figure 5), layer 3 and layer 4(Figure 6) showed comparable composting properties.As a result, the composting process in these layers is more uniform, aerobic conditions are maintained, and the material stabilizes evenly, reducing the formation of anaerobic zones and ensuring a consistent quality of compost.

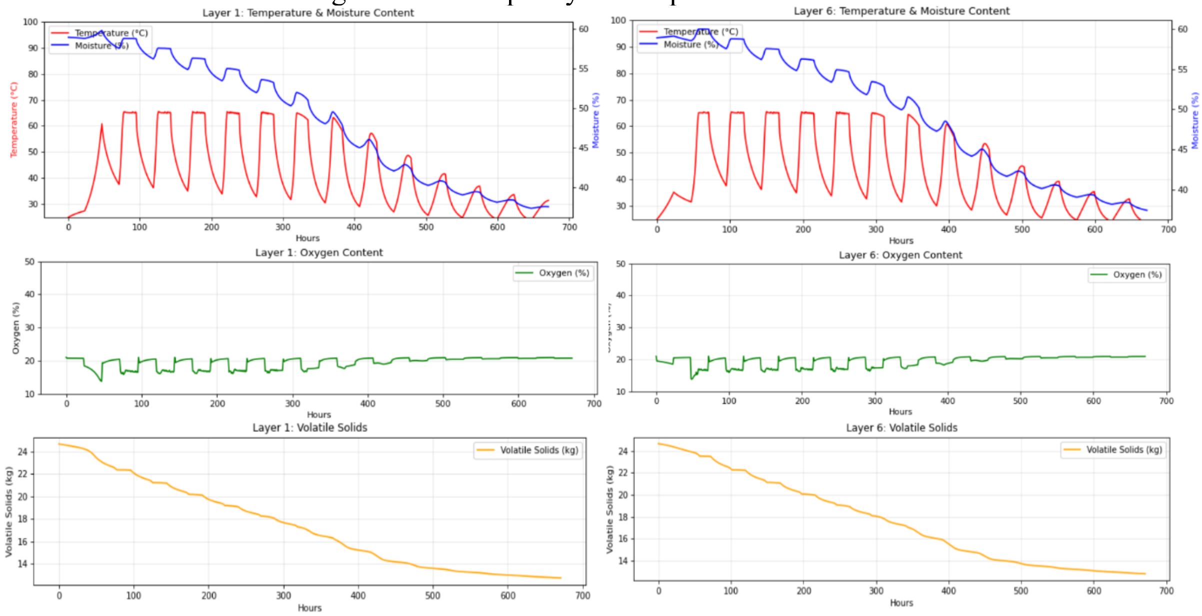

Figure 4 : Comparison of different parameters of composting between layer 1 and 6

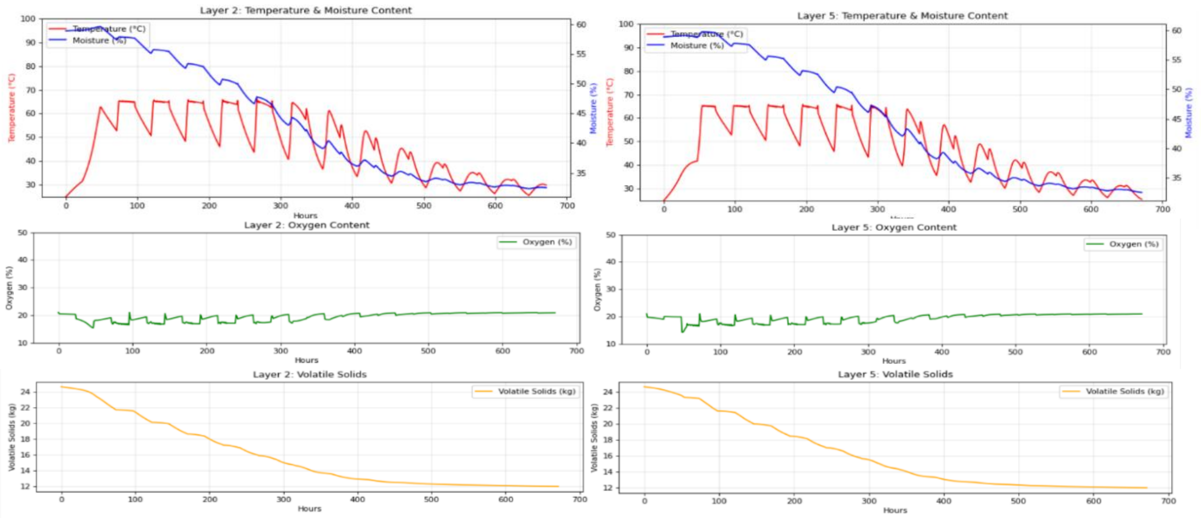

Figure 5 : Comparison of different parameters of composting between layer 1 and 6

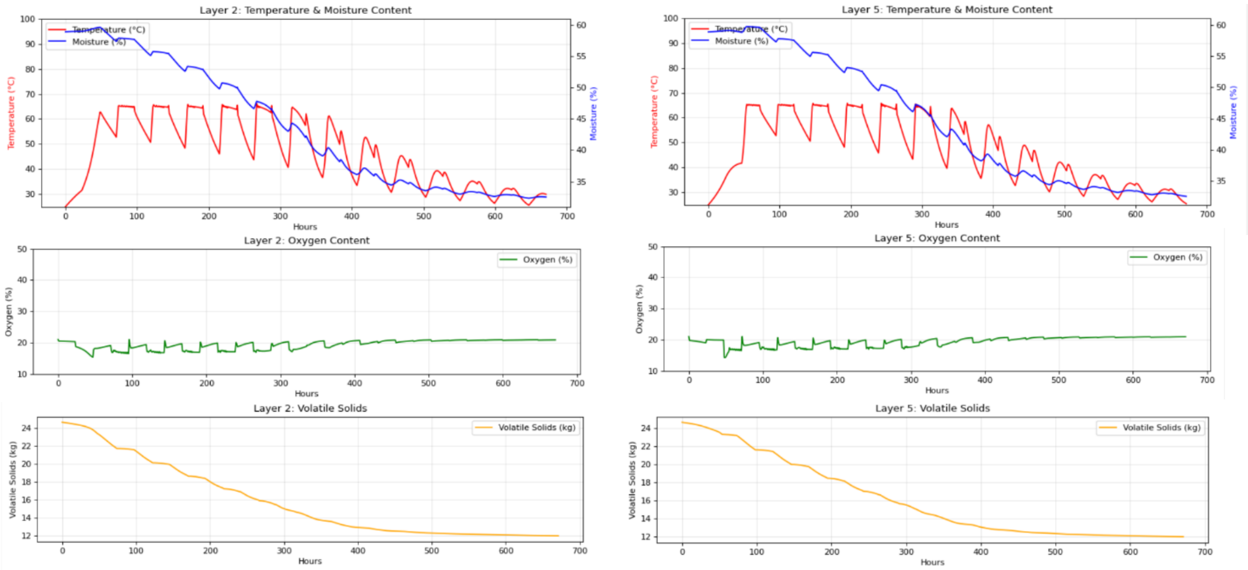

Figure 6 : Comparison of different parameters of composting between layer 1 and 6

3.3 Comparative Analysis of Different Cycle Hours in Two-Way Forced aeration

Two-way forced aeration improves composting by ensuring even oxygen distribution, uniform temperature and moisture, and enhanced microbial activity across all layers, reducing anaerobic zones. The cycle hour influences this effect: shorter cycles promote faster layer alternation, leading to more uniform decomposition and stable compost, while longer cycles may create temporary variations in temperature and oxygen, affecting layer-specific decomposition. If the cycle duration of two-way aeration is reduced from 72 hours to 24 hours, the airflow direction reverses more frequently, causing the compost layers to alternate roles at a faster rate (Figure 7)(Figure 8). This promotes a more even distribution of oxygen, temperature, and moisture throughout the pile, leading to more uniform decomposition and enhanced stabilization of the compost. While the process may accelerate slightly, frequent reversals can also cause greater moisture fluctuations, so careful management is essential to maintain optimal composting conditions (Table 2).

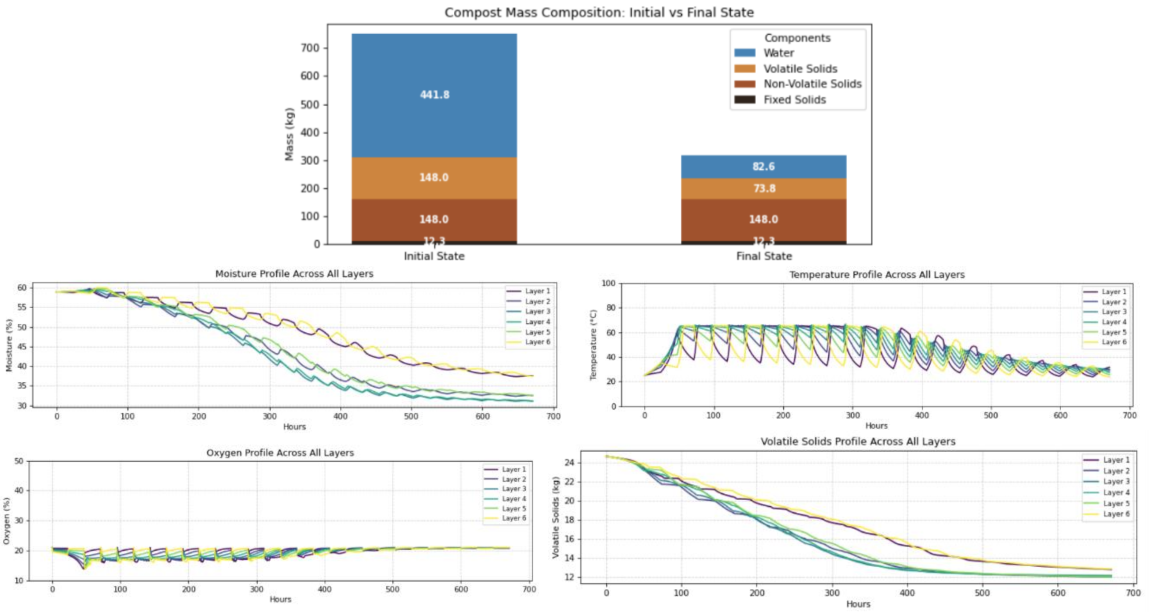

Figure 7 : Composting behaviour of 24 h cycle

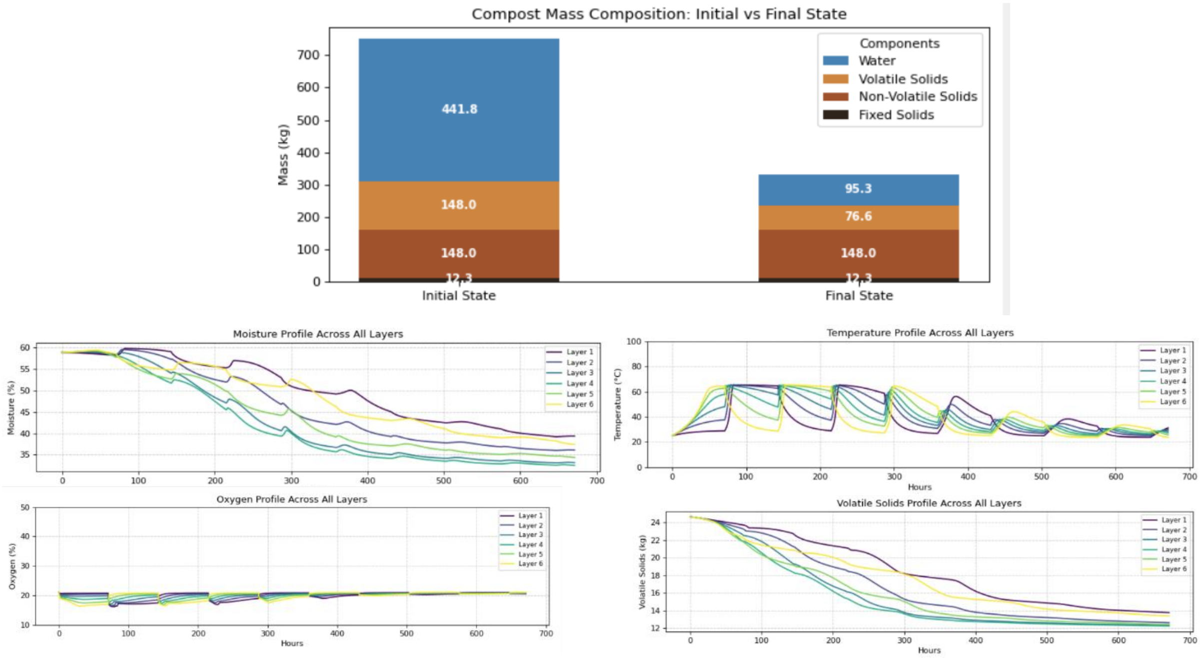

Figure 8 : Composting behaviour of 72h cycle

Table 2 : Comparison between 24h cycle and 72h cycle

	Cycle Hour of 24hr	Cycle Hour of 72hr
Initial Mass of compost	750	750
Final mass of compost	316.7	332.2
Final mass of Total Solid	240.5	236.9
Final mass of Fixed Solid	12.3	12.3
Final mass of Non-volatile Biodegradable Solid	148.0	148.0
Final mass of Volatile Solid	73.8	76.6
Final mass of Water content	82.6	95.3

4. CONCLUSION

The development of a kinetic model based on programming for two-way forced aeration composting represents an important success within the domain of environmentally sustainable waste treatment. By utilizing mathematical modeling methodologies along with computational simulation methods, this kinetic model has the capability to monitor and predict a variety of biochemical and physicochemical reactions that take place in composting.

The model can well describe dynamic changes in temperature, oxygen content, water content, and fraction of relatively volatile solids in diverse layers during composting. On the basis of data obtained using one-way aeration systems, the two-way forced aeration system provided a more uniform environment with enhanced oxygen transfer rate and decomposition efficiency. In addition, compared with traditional programming methods based on which practical industrial models are made, this model system saves costs and labor. Other simulation analysis using stepped aeration or second-stage composting further demonstrated that when involving equal total aeration airflow rate, there was no difference between increased steps and decreased steps in compost stability. These results tend to confirm data obtained using model analysis for compost maturity analysis in the second-stage composting process.

Firstly, to proceed with additional analysis based on these outcomes, optimization studies concerning cycle times or airflow rates in two-way forced aeration systems could be performed. Also, a complete analysis concerning compost quality based on composition, stability, or maturity in phase two composting could be made. Finally, extending the model to incorporate data obtained from sensors or machine learning algorithms could prove to be helpful.

In conclusion, the programming-based kinetic model provides a trustworthy, predictive, and adaptable model which offers optimization possibilities in composting processes relatively more precisely than those obtained using labor-intensive experimental methods.

5. DECLARATION OF USE OF AI

During the preparation of this manuscript, the authors used ChatGPT, Gemini and Grammarly to refine the language and improve the sentence structure of the draft. All scientific content and conclusions were developed by the authors, who have reviewed the finat text and are accontable for its accuracy.

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