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Aeration Optimization for the Biodrying of Market Waste Using Negative Ventilation: A Lysimeter Study

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Abstract: This study investigates the optimization of aeration rates for the biodrying of market waste using negative-pressure ventilation. Market waste, characterized by a high moisture content (MC) and rapid decomposition, presents challenges in waste management. Over 12 days, three aeration rates (ARs) of 0.2, 0.4, and 0.6 m^3/kg/day were examined, and the most effective continuous ventilation configuration was identified in terms of heat generation, moisture reduction, and biodrying efficiency. The results indicate that the most effective AR for heat retention and moisture removal was 0.2 m^3/kg/day, achieving a 6.63% MC reduction and a 9.12% low heating value (LHV) increase. Gas analysis showed that, while AR 0.2 supported high microbial activity during the initial 7 days, AR 0.6 sustained higher overall CO_2 production due to its greater aeration rate. The findings also suggest that the biodrying of market waste with a high initial MC can achieve significant weight loss and leachate generation when paired with a high aeration rate of 0.6 m^3/kg/day, with a 69.8% weight loss and increased waste compaction being recorded. The study suggests that variable ARs can optimize biodrying, making market waste more suitable for conversion to refuse-derived fuel or landfill pre-treatment and improving waste-to-energy processes and sustainability.

Keywords: negative-pressure ventilation; moisture-content reduction; thermal efficiency; biodrying; waste management

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1. Introduction

Global urbanization, combined with rising populations, has driven a steep surge in municipal solid waste (MSW) generation and increasingly complex waste compositions, leading to severe environmental and health hazards while also hindering economic development [1,2]. Ineffective waste management practices can cause significant environmental problems, including greenhouse gas emissions, soil contamination, water pollution, and disease outbreaks [3,4]. Market waste—containing food scraps, vegetable peels, and other discarded items from markets—poses a particular waste management challenge due to its high levels of organic content, rapid decay, and high waste volume [5]. In many developing nations, this mismanaged organic waste is often disposed of in sanitary landfills or open dumps due to convenience and cost factors, further aggravating environmental issues such as methane emissions from the anaerobic decay of waste [6,7]. Market waste also causes waste management issues due to its high moisture content (MC) and low density, commonly resulting in leachate spills, odor problems, and pest infestation [8,9]. Given its unique characteristics, this type of waste requires efficient and effective treatment to mitigate its harmful environmental impacts while also allowing sustainable energy recovery to be implemented [10].

Composting or biodrying of the biodegradable component of municipal organic waste has become a widely acknowledged strategy compared to alternative disposal options for reducing its size and volume, and it efficiently removes moisture and partially stabilizes waste [11]. This approach is well suited to processing waste with a high MC, leveraging microbial heat for evaporating water and thus shrinking the waste's volume while boosting its energy recovery potential. Unlike conventional waste processing methods, biodrying can effectively reduce waste weight and volume through moisture loss, thus helping to minimize waste overflow from landfills [12,13] while simultaneously preserving most of the organic matter's calorific content [14]. The characteristics of the end product of this process make biodrying a suitable pre-treatment before landfill disposal or refuse-derived fuel (RDF) production, and it can be used as an alternative fuel in cement plants. RDF is used locally with a well-established production system in Thailand, making it suitable for temporary storage and helping to reduce transportation costs while extending landfill lifespans [15].

Despite these advantages, biodrying systems still require optimization, especially in terms of their aeration rate (AR), to help maximize the effectiveness and efficiency of biodrying while minimizing energy consumption and organic matter breakdown [16]. Aerobic aeration accelerates decomposition, reduces odor, lowers methane (CH_4) emissions, and provides heat for biodrying, making it suitable for organic waste management. The process progresses from mesophilic to thermophilic stages, resulting in increased moisture reduction and pathogen removal. The use of aerobic aeration in a biodrying system creates mainly carbon dioxide (CO_2) and minor volatile organic compounds that, when correctly managed, can be safely discharged into the atmosphere with minimal impact on the environment when compared to anaerobic processes' CH_4-rich emissions. The MC of MSW affects biodrying, with high moisture impeding oxygen (O_2) transmission but low moisture limiting microbial activity [17]. While negative aeration helps promote the loss of water relative to volatile solids (VSs) [18,19], positive aeration can enhance moisture evaporation and reduce leachate production, but it may cause an uneven moisture distribution due to the effects of condensation and restricted airflow in the compacted waste [20]. Previous studies have explored various aspects of biodrying optimization, including the impacts of varying ARs, the use of bulking agents, co-biodrying with other waste materials, leachate recirculation, and moisture control [19–23]. For instance, Slezak et al. (2019) discovered that, if waste does not self-heat, the biodrying process will be inefficient, and the applied aeration will result only in waste stabilization [24].

Despite these advances, the ideal ARs for biodrying market waste remain unknown. Optimized aeration configurations are crucial to improving the effectiveness of market waste biodrying because of this waste type's high organic content and other unique characteristics. This study seeks to address this limitation by testing various ARs and configurations in order to identify the best AR for biodrying market waste. Optimizing the treatment of market waste requires a thorough understanding of the dynamics of aeration in the biodrying process. Effective aeration promotes microbial activity, which is necessary to biodegrade organic matter and produce the heat needed to drive moisture evaporation. In this study, three different ARs were tested (0.2, 0.4, and 0.6 $m^3/kg/day$). Overall, the findings of this work will help improve the effectiveness of biodrying procedures and offer essential insights into the ideal configuration for biodrying market waste, which will, in turn, help promote more widespread deployment of this technique. The important problem of market waste disposal in metropolitan areas could be solved with the help of newfound insights into more affordable and environmentally friendly waste management techniques. Furthermore, by producing high-quality fuel from refuse, the enhanced biodrying process may help contribute to the global transition from fossil fuels to renewable energy sources.

2. Materials and Methods

2.1. Overview of the Study Framework

This study explores how varying ARs affects the biodrying of market waste under negative aeration. In this work, three lysimeters were configured with different aeration levels. The primary aim involved identifying the most effective AR to optimize the biodrying process over 12 days. A typical sample of market waste was used as the feedstock in this study. Three lysimeters were configured using a negative-pressure system, with monitoring points established to collect measurements throughout the experiment. In the aeration experiments, the AR values were varied, and key parameters were monitored to assess the system's performance. Material analysis, including both proximate and ultimate analysis, was performed to evaluate the characteristics of the waste. The performance of each configuration was evaluated by integrating the temperature, measured weight, and elevation loss and calculating the water and carbon balance and the biodrying-air ratio to assess the efficiency of the biodrying process.

2.2. Waste Sampling Site

The Praeksa Mai dumpsite in Samut Prakan, Thailand, was selected as the waste sampling site for this study. Although waste in Thailand is typically classified into municipal, industrial, household, and hazardous waste [25], this site receives MSW daily from 18 municipalities. Only 12% of the waste sent to this landfill is classified correctly as organic, recyclable, or combustible, while the rest is directly sent to the landfill [26]. Additionally, the rapid decomposition of market waste results in the production of a substantial volume of leachate that flows toward collection sites, serving as the primary source for pre-treatment. Moreover, improper waste segregation at this site exacerbates the challenge of market waste and, thus, must be managed effectively. The feedstock preparation step involved collecting approximately 300 kg of market waste, which was then transported to Eastern Energy Plus Co., Ltd. for the experiment. Figure 1 shows the location of the market waste collection site and an example of the typical characteristics of this waste type.

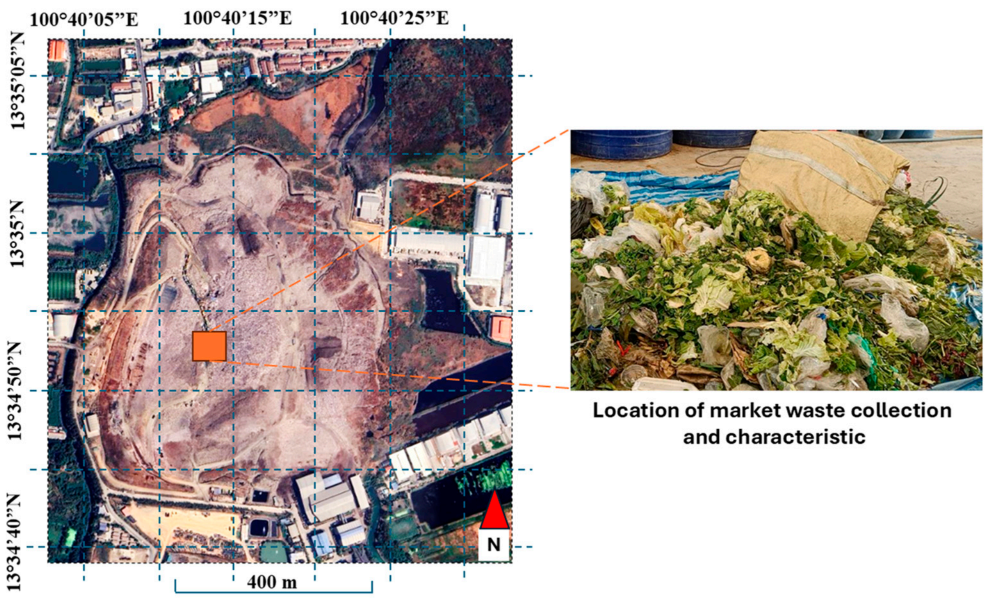

Figure 1. Aerial view of waste sampling site at Praeksa Mai dumpsite and image showing typical characteristics of the studied market waste.

2.3. Feedstock Preparation

A total of 150 kg of market waste was initially categorized based on its composition. The market waste sample was homogenized using the quartering method specified in the American Standard Test Method (ASTM) D5231-92 standard [27]. This approach involves dividing, blending, and repeating the procedure until a sample accurately representing the whole is obtained. Before biodrying, two 1.5 kg samples of market waste and one 0.5 kg sample of organic waste were gathered for examination. The MC was determined using a thermogravimetric analyzer (TGA801; LECO Corporation, St. Joseph, MI, USA) following the ASTM D7582-15 standard [28]. The high heating value (HHV) was measured using a bomb calorimeter (AC-500 calorimeter, LECO®, St. Joseph, MI, USA) according to the ASTM D2015-00 standard [29], and it was then converted into a low heating value (LHV). The organic material was analyzed to determine its carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) following the ASTM D-5373-14 standard [30]. To assess the changes in characteristics and quality improvements resulting from the biodrying process, identical tests were conducted on the biodried products from each lysimeter [31].

2.4. Lysimeter Configuration and Monitoring

Lysimeters were used throughout the experiment to biodry the market waste samples. Each lysimeter was 1.5 m tall and 0.5 m wide. A metal plate was placed under the ventilation pipe at the bottom to support the feedstock. This plate was carefully positioned to stabilize the raw material. The system's base housed ventilation pipes, condensation pipes, and blowers responsible for generating airflow. Leachate was collected at the lysimeter's base using a U-trap pipe with a diameter of 5.08 cm. Perforated pipes with a 20 mm diameter were inserted at heights of 0.2, 0.6, and 1 m from the base to measure the lysimeter's internal gas. The lysimeter configuration was based on data from Bhatsada et al. (2023) [31]. Figure 2 shows the schematic design of the lysimeter in more detail.

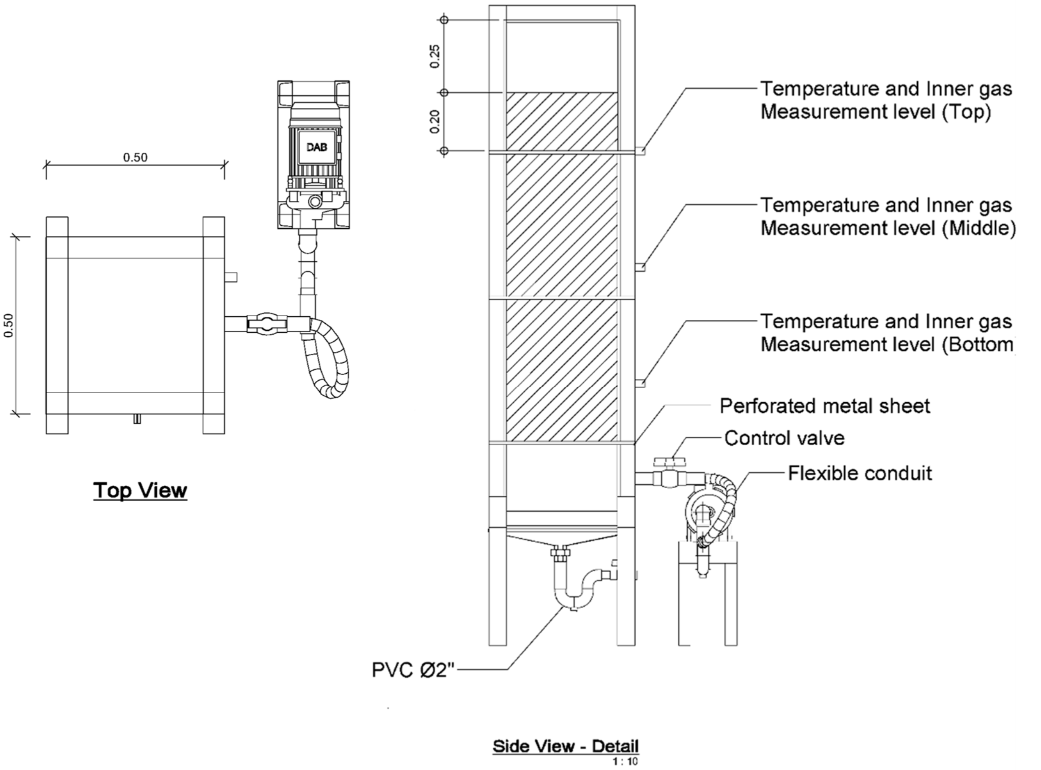

Figure 2. Schematic of lysimeter design.

The experiment's temperatures were monitored at heights of 20, 60, and 100 cm using type-K thermocouples, which have a measurement range from −270 °C to 1327 °C. An additional sensor was placed outside the lysimeter to capture the ambient external temperature. A data logger (Graphtec GL200A Midi Data Logger; DATAQ Instruments, Akron, OH, USA) recorded temperatures every hour. Daily O_2, CO_2, CH_4, hydrogen sulfide (H_2S), and nitrogen (N_2) measurements were collected at three different heights within the lysimeters, as well as in the ambient air and exhaust, using a Biogas 5000 gas analyzer (Geotechnical Instruments International, Ltd., Berlin, UK). The average daily surrounding air contained 0% CH_4, 0% CO_2, 20.9% O_2, 0 parts per million of H_2S, and 79.1% N_2. The height of the feedstock inside each lysimeter was measured using a tape measure. Additionally, the aeration capacity in each lysimeter was assessed by using an airflow meter to measure the velocity of air passing through the perforated pipe near the control valve.

2.5. Experimental Setup

Lysimeters were configured with AR values of 0.2, 0.4, and 0.6 m^3/kg/day, as indicated in Table 1. These values corresponded to specific proportions of the feedstock's mass and the cross-sectional area of the ventilation pipes. The feedstock density varied in the range of 146–150 kg/m^3. The feedstock's density was varied based on the fixed feedstock height and the cross-section of the lysimeter to achieve an overall weight of 43–50 kg. The feedstock's LHV was 1766 cal/g, and its initial MC was 76.22%. The lysimeters were supplied with continuous negative aeration, ensuring uniform airflow during the experimental period (12 days).

Table 1. Experimental design conditions.

Conditions	Lysimeter 1	Lysimeter 2	Lysimeter 3
Aeration rate, m^3/kg/day	0.2	0.4	0.6
Air flow rate, m/s	0.05	0.1	0.15
Weight, kg	44.28	43.86	44.99
LHV, cal/g	1766	1766	1766
MC, %	76.22	76.22	76.22

2.6. Performance Indicators

2.6.1. Temperature Integration Index

The total daily variations in temperature within the matrix and ambient temperatures were determined using the temperature integration (TI) index as a comprehensive measure of thermal performance during the biodrying experiment. TI was calculated according to the equations in Zhang et al., 2008a and 2008b [32,33].

$$\mathrm{TI} = \sum_{i=1}^{n} (\mathrm{Tm} - \mathrm{Ta}) \cdot \Delta \mathrm{t} \quad (1)$$

where Tm and Ta are the matrix and ambient temperatures at day i, respectively, and Δt is the time element. The daily waste density changes were calculated based on the equations from Bhatsada et al. (2023) [31].

2.6.2. Biodrying–Air Ratio

The biodrying–air ratio is calculated according to the equation from Payomthip et al. (2021) by dividing the AR fed to the biodrying operation by the composting stoichiometric air demand to explore the interaction between the composting and biodrying operations [34]. Aeration helps facilitate the aerobic biodrying process by ensuring that sufficient air is present for decomposition. This explanation links biodrying and composting, with biodrying playing a crucial role in composting. The biodrying–air ratio, or B.A. ratio, reflects the relationship between the air supplied for biodrying and the stoichiometric air required for composting.

The stoichiometric aeration requirement for composting was determined here based on the elemental composition, with the feedstock's elemental composition containing proportions of C, H, O, and N of 5.81%, 38.51%, 51.44%, and 4.24%, respectively. This requirement indicates the amount of O_2 required for bacteria to break down the organic material, consistent with the stoichiometric AR. The stoichiometric AR was calculated using the chemical reaction between organic material and O_2. Additionally, since organic oxidation demands relatively little O_2, the O_2 needed for nitrification was not considered. The aeration demands were estimated by converting each feedstock's elemental composition into a molecular formula as $C_2H_{127}O_{11}N$.

An essential measure for biodrying processes is the B.A. ratio. While lower B.A. ratios may result in insufficient moisture loss through aeration, higher B.A. ratios may promote physical drying. Payomthip et al. (2022) stated that physical drying occurs when the B.A. value exceeds 1.55; thus, the B.A. value should not exceed this threshold for composting [34]. As shown, the B.A. value in all the experiments (Table 2) was below 1.55 in this investigation.

Table 2. Biodrying–air ratio.

Parameter	Unit	Experiment		
		AR 0.2	**AR 0.4**	**AR 0.6**
Aeration rate	$m^3/kg/day$	0.2	0.4	0.6
Stoichiometric air demand	$m^3/kg/day$	0.62	0.62	0.62
B.A. ratio	%	0.32	0.65	0.97

2.6.3. Water and Carbon Balance

Water-balance equations were used to estimate the moisture removal and metabolic water generation during biodrying. The formulas were based on Ham et al. (2020), while the calculation steps followed Bhatsada et al. (2023) [18,35].

The water mass created via bioactivity and organic digestion is called metabolic water creation. The moisture in the biodried product is represented by the water buildup [18]. Assuming complete degradation of the organic matter, the ratio of H_2O to CO_2 was calculated as 62/2, a value that can be utilized to determine the amount of metabolic water [35].

The carbon balance was computed based on the amounts of carbon in the feedstock, air, exhaust gas, leachate, and final product. The carbon balance can be calculated using the following equations:

$$\text{C in feedstock} + \text{C in air} = \text{C in exhaust gas} + \text{C in leachate} + \text{C in biodried product} \quad (2)$$

$$\text{C in feedstock} = \text{initial mass of feedstock} \cdot (1 - \text{MC})\% \quad (3)$$

$$\text{Mass of C in } CO_2/CH_4 = \text{mole of C} \cdot \text{molecular weight of C} \quad (4)$$

$$\text{C in biodried product} = \text{final mass of biodried product} \cdot (1 - \text{MC})\% \quad (5)$$

where the moles of C in CO_2 and CH_4 can be calculated using the ideal gas law based on the volume of gas, which can be obtained by multiplying the gas concentration with the airflow rate. The carbon in the leachate was calculated by multiplying the TOC amount (mg/L) by the volume of leachate (L).

2.6.4. Biodrying Index and Weight Loss

To assess the biodrying efficiency, the biodrying index was determined as the ratio of the changes in organic content and water losses using the following equations [32,33].

$$\text{total organics losses at time}_t = WM_0 - WM_t - W_{t\ loss} \quad (6)$$

$$\text{water losses at time}_t = (WM_0 \cdot w_0) - (WM_t - w_t) \quad (7)$$

where WM_0 (kg) and WM_t (kg) are the wet materials at the initial time and time$_t$, respectively, while w_0 (%) and w_t (%) are water contents at the initial time and at time$_t$, respectively.

The weight loss during the biodrying process was calculated using the following equation:

$$W_{loss,n} = (W_0 - W_n)/W_0 \cdot 100 \quad (8)$$

where $W_{loss,n}$ is the weight loss (%) on n days, W_0 is the initial weight, and W_n is the weight measured on n days.

3. Results

3.1. Temperature Evolution

The temperature profiles of the three lysimeters, each subjected to different ARs (0.2, 0.4, and 0.6 m^3/kg/day), were monitored over the 12-day biodrying period (Figure 3). The results show significant variations in temperature evolution between the studied aeration rates. Three qualitative phases of temperature evolution are identified in the biodrying process: rising, declining, and steady [23]. Additionally, the temperature values can also be classified into quantitative phases: the mesophilic phase, which begins at room temperature and gradually rises to 35 °C to 40 °C, is marked by bacterial bioactivity; it then transitions into moderately thermophilic temperatures of 40 °C to 45 °C before reaching the main thermophilic phase, in which the waste reaches its maximum evolution at temperatures between 55 °C and 70 °C [36].

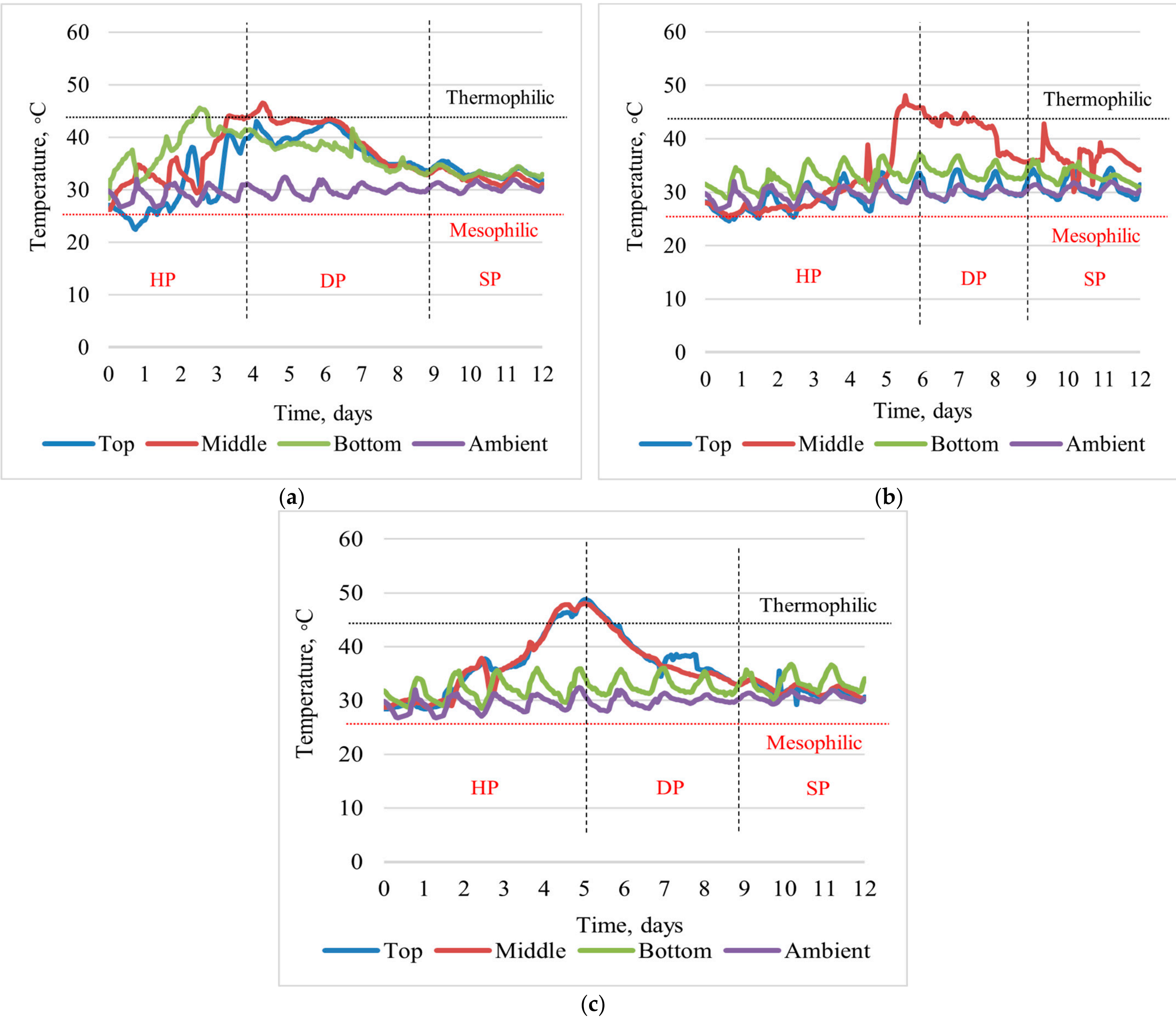

Figure 3. Temperature evolution under different aeration rates: (**a**) AR 0.2, (**b**) AR 0.4, and (**c**) AR 0.6 (HP—heating phase, DP—declining phase, SP—stable phase).

The lysimeter with an AR of 0.2 m^3/kg/day showed a rapid temperature rise, entering the thermophilic phase in less than two days and maintaining temperatures over 45 °C for an extended time until day 6. The highest recorded temperature in this lysimeter was 46.5 °C. The observed sustained temperatures above room temperature suggest strong microbial activity and efficient biodrying. Compared to the 0.2 m^3/kg/day AR lysimeter, the lysimeter with an AR of 0.4 m^3/kg/day took the longest to reach the thermophilic phase. This configuration showed modest biodrying efficiency by reaching a peak temperature of 48.1 °C and sustaining thermophilic conditions for a shorter period. The lysimeter with an AR of 0.6 m^3/kg/day showed a comparatively slow temperature increase, with the peak temperature of 48.7 °C occurring on day 5. Beyond this point, this lysimeter did not maintain thermophilic conditions for a prolonged time, suggesting that microbial activity and heat retention were less effectively achieved in this configuration.

A statistical analysis using one-way ANOVA was carried out in order to determine significant differences between the temperature layers and the ambient air across all lysimeters. The p-value of 0.85 indicates that the difference between the top layer of AR 0.4 and the ambient temperature is not statistically significant. The high p-value for the AR 0.4 top layer indicates that the temperature there is more similar to the ambient air, but other layers or ARs may retain more heat or have more variability, resulting in lower p-values and greater temperature disparities.

The temperature profiles emphasize the importance of aeration in preserving the ideal conditions for microbial activity. The lysimeter with an AR of 0.6 m^3/kg/day exhibited the highest temperature during the rising phase on day 5; however, the lysimeter with an AR of 0.2 m^3/kg/day achieved the longest duration of thermophilic conditions, indicating that this AR minimized heat loss caused via excessive ventilation while simultaneously providing sufficient O_2 to support microbial activity.

3.2. Temperature Integration

Figure 4 shows the TI of the three biodrying stages. The temperature evolution trends are shown in the higher TI value of AR 0.2 (1668 °C) compared to AR 0.4 and AR 0.6 (816 °C and 690 °C). Of the three studied ARs, AR 0.2 had higher TI values during the heating phase, indicating stronger microbial activity and heat production. AR 0.2 also sustained significantly higher TI values than AR 0.4 and 0.6 during the declining period. The TI value of AR 0.6 was much lower than that of AR 0.2, suggesting less heat buildup and potentially faster cooling. The TI value of AR 0.4 is marginally higher than that of AR 0.6 but much lower than that of AR 0.2, indicating reduced heat retention. All of the lysimeters' TI readings were almost the same during the steady period. These findings are corroborated by the results of Payomthip et al. (2022), who reported that the TI value of the MSW biodrying process decreased when the AR feed rate was too high [34]. This is because the determination of the optimal AR must be performed on a per-feedstock basis, as the characteristics of each feedstock vary, and the optimal AR will differ accordingly.

Higher TI values occur due to better heat retention and increased microbial activity, which are particularly evident at lower ARs (e.g., AR 0.2). In contrast, the results for AR 0.6 illustrate that higher aeration levels contribute to increased heat dissipation through ventilation. This highlights the need for a balanced aeration strategy that provides sufficient airflow to enhance microbial efficiency while minimizing heat loss, which is essential for effective biodrying. Lowering the AR during the cooling phase could optimize heat preservation, as the goal of biodrying is to create a system that produces sufficient heat from microbial activity and retains that heat effectively throughout the drying process.

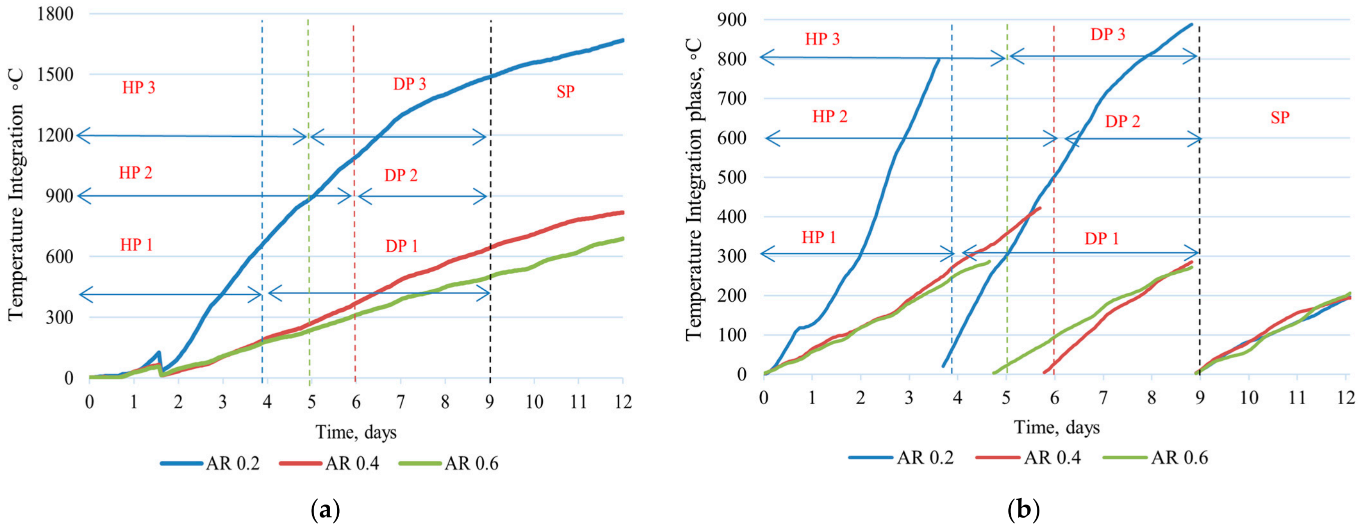

Figure 4. Plots showing the (**a**) temperature integration index and (**b**) temperature integration index by phase during biodrying (HP—heating phase, DP—declining phase, SP—stable phase).

3.3. Gas Concentrations and Generation

Gas analysis was conducted daily to monitor the concentrations of key gases (CO_2, O_2, and CH_4), providing insights into microbial activity and aeration efficiency throughout the experiment, as shown in Figure 5. The significant increase in CO_2 levels over the first few days implies strong microbial decomposition, followed by a corresponding reduction in CO_2 levels when the microbial activity declines. Microbial activity was low in the upper and middle levels of the lysimeter but high in the lower part of the apparatus.

The observed high CO_2 concentrations in the lowest layer of all three lysimeters confirm high levels of microbial activity and the breakdown of organic materials in this area. As the experiment progressed, changes in the waste height caused the upper and middle measurement pipes to no longer be in contact with the waste, leaving only the lowest pipe capable of consistently sampling the waste pile. Toward the end of the experiment, the CO_2 levels stabilized in the bottom layer, which suggests a decline in microbial activity caused by a lack of readily degradable organic waste. The highest CO_2 concentrations were observed in the lysimeter with an AR of 0.2 $m^3/kg/day$ from day 1 to day 7 which is consistent with the temperature evolution results. The increase in CO_2 levels in the AR 0.4 lysimeter was only observed after day 5, with moderately low concentrations recorded until the end of the experiment. In the AR 0.6 lysimeter, the CO_2 concentration peaked on days 6–8, correlating with the observed temperature profiles. Higher observed O_2 levels during the declining phase indicate lower O_2 usage in this phase, likely due to decreased microbial activity. Of the three studied configurations, the 0.2 $m^3/kg/day$ lysimeter had the lowest O_2 levels during this phase, followed by the 0.6 $m^3/kg/day$ lysimeter, which implies the occurrence of vigorous aerobic decomposition. The CH_4 concentrations remained low in all the lysimeters (0–0.1%), indicating that aerobic conditions were effectively sustained throughout the biodrying process in all three configurations, which is essential for reducing greenhouse gas emissions.

The volume of CO_2 produced in each lysimeter during the experiment was calculated using the average concentration across all three layers, as shown in Figure 5d. Higher aeration rates led to more CO_2 being produced, as shown in the AR 0.6 lysimeter, although the CO_2 concentration was relatively lower at higher aeration rates. Although the lysimeter with an AR of 0.2 $m^3/kg/day$ initially showed high CO_2 concentrations in the first seven days, its low aeration rate limited total CO_2 generation over time. In contrast, the AR 0.6 lysimeter, with a higher aeration rate, maintained a consistent CO_2 generation pattern from day 3 until the end of the experiment, resulting in greater overall CO_2 production.

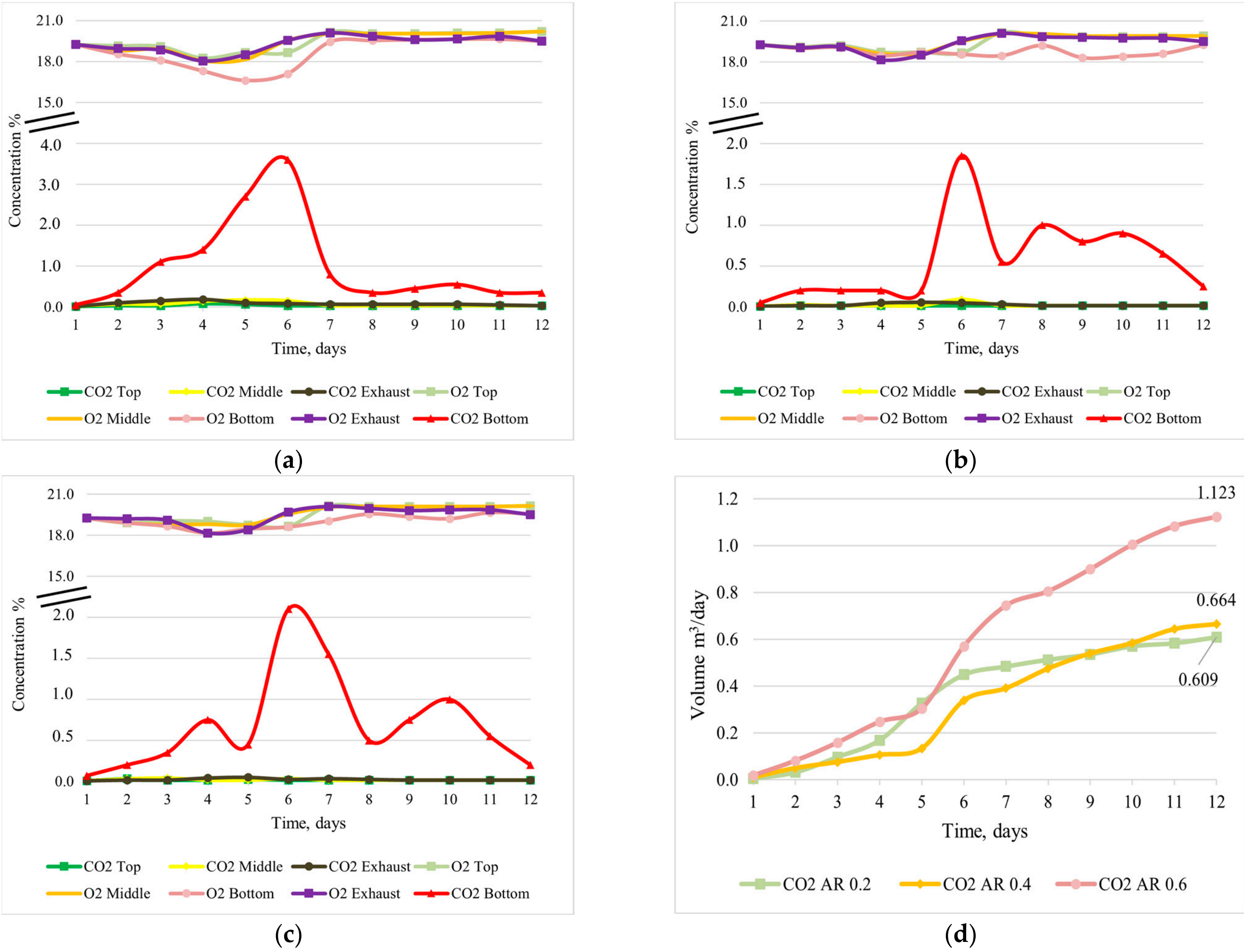

Figure 5. Observed CO_2 and O_2 concentrations during the biodrying process for (**a**) AR 0.2, (**b**) AR 0.4, and (**c**) AR 0.6; (**d**) average CO_2 generation in all three lysimeters.

3.4. Physical Changes

All the lysimeters showed a significant drop in waste height over the first few days, as illustrated in Figure 6a, indicating compaction induced via significant moisture loss and microbial activity. The rates of height change varied, with AR 0.6 exhibiting the fastest rate of decline. Following the experiment, the AR 0.2, AR 0.4, and AR 0.6 elevations were 0.21 m, 0.19 m, and 0.14 m, respectively. This indicates that the AR 0.6 lysimeter exhibited the greatest decrease in waste matter, most likely due to increased water removal through leachate generation and more waste compaction. Increasing microbial activity leads to significant moisture loss and organic matter decomposition, which causes the first noticeable drop in elevation recorded across all the lysimeters. This is consistent with the recorded temperature profiles, which reveal that high temperatures indicate active microbial metabolism. The calculated matrix density during the experiment increased steadily with minor fluctuations from the beginning of the trial, except for AR 0.2, where a density drop was observed during the decreasing period.

In addition, the success of the biodrying process can also be measured in terms of the weight loss and moisture reduction indicators, which are shown in Figure 6b.

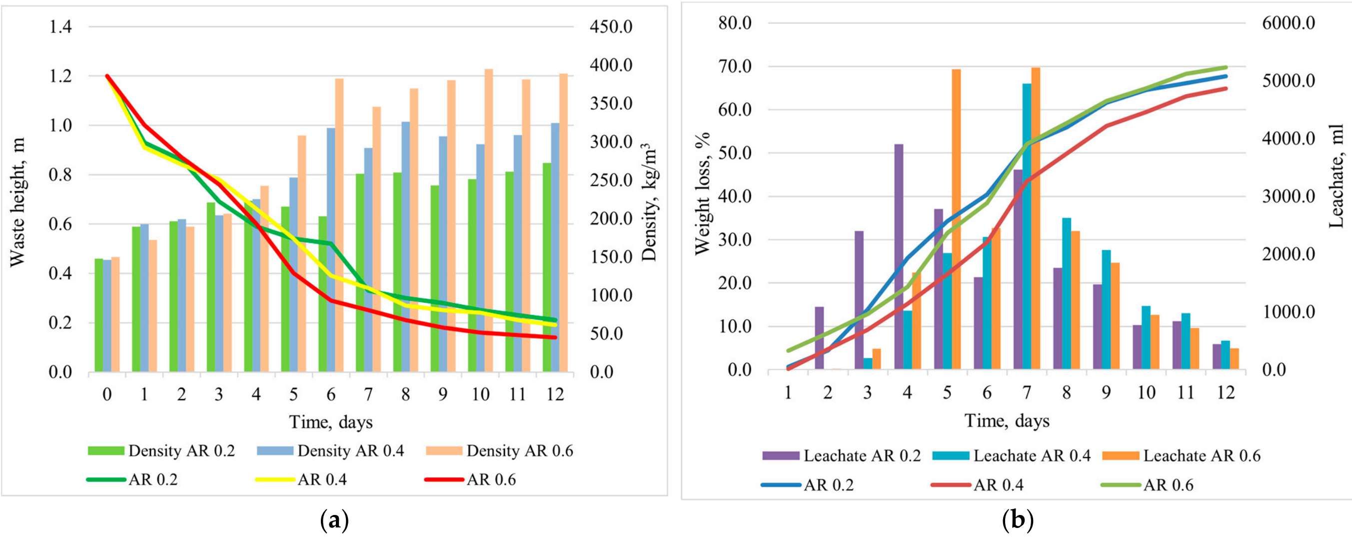

Figure 6. Plots showing physical changes throughout the experiment in (**a**) daily density and waste height and (**b**) weight loss and leachate production.

In terms of weight loss, the AR 0.6 lysimeter exhibited the highest weight loss of 69.8%, followed by 67.7% in the AR 0.2 lysimeter and 64.9% in the AR 0.4 lysimeter. This indicates that a moderate AR was insufficient to facilitate effective moisture evaporation and organic matter decomposition.

Regarding leachate generation, higher leachate output relates to more significant weight loss, indicating efficient moisture removal and higher microbial activity levels. AR 0.6 produced the most leachate with 21.23 L, followed by AR 0.2 with 20.52 L, and AR 0.4 with 17.77 L. However, AR 0.2 also displayed more significant weight loss than AR 0.4, with a more efficient moisture removal process implied by the temperature evolution. The weight loss patterns and leachate formation indicate that AR 0.6 can achieve effective leachate production, whereas AR 0.2 achieved better moisture removal through evaporation, improving the biodrying process.

3.5. Fuel Quality

The results regarding weight loss, leachate generation, and moisture reduction reveal that, although higher ARs can boost water removal via leachate production, lower ARs more effectively drive moisture removal from the waste matrix by evaporation, thus enhancing the biodrying process. The differing performance of each AR, each showing notable reductions in weight and MC, highlights the need to fine-tune aeration to improve the overall efficiency of the biodrying method based on the characteristics of the feedstock. In addition, the LHV of the biodried product, which corresponds to the MC, is a key parameter to assess its suitability as RDF. Accordingly, the increase in LHV in the biodried product was calculated for each AR.

The MC reduction was most pronounced in the 0.4 m^3/kg/day lysimeter, achieving an 8.84% reduction, followed by 6.63% in the 0.2 m^3/kg/day configuration and 2.74% in the 0.6 m^3/kg/day lysimeter. These results suggest that the moisture-reducing capacity may vary, based on the differing feedstock characteristics and organic content, initial MC, and residual water in the pores. The LHV increased by 9.12% in the 0.2 m^3/kg/day lysimeter, 7.11% in the 0.6 m^3/kg/day lysimeter, and 4.7% in the 0.4 m^3/kg/day lysimeter. The greater increase in LHV at lower ARs suggests more efficient preservation of the organic material's calorific value, as indicated by greater increases in the heating value for AR 0.2 and 0.6. The lowest rise was seen for AR 0.4, indicating that, although this experimental configuration successfully decreased moisture, the increase in heating value was only marginal. The LHV results show that the organic material's energy content was generally better retained at lower ARs. This is an important discovery for the real-world use of biodrying in waste-to-energy systems since it shows that AR optimization can improve product quality. Figure 7 comprehensively compares the performance of different aeration rates in accordance with the temperature integration index (°C), CO_2 production (m^3), MC reduction (%), LHV increase (%), and weight loss (%). These parameters provide a holistic view of the system's efficiency in terms of both drying and energy recovery. They illustrate an important discovery for the real-world use of biodrying in waste-to-energy systems since they show that AR optimization can improve product quality.

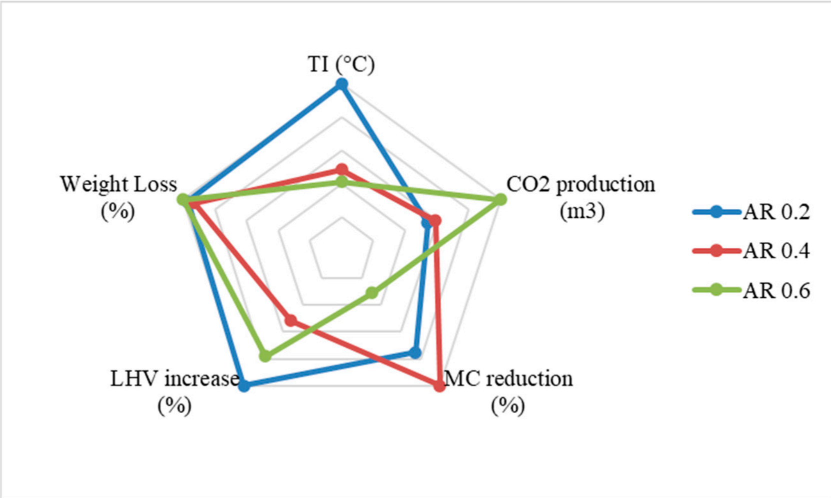

Figure 7. Radar chart comparing the performance of different aeration rates.

Removing leachate reduces free water; however, due to the high initial MC of the feedstock, the overall percentage reduction may be lower, as a considerable amount of water remains in the material. The water eliminated as leachate is mostly unbound (free) water; however, much of the remaining water may be in the form of bonded water, which is more difficult to remove during biodrying. Even after the leachate has been removed, this bound water remains within the organic material, contributing to the overall MC of the final product. The air temperature and relative humidity also influence the removal mechanisms for unbound and bound water. As a result, these are also critical variables that must be considered during biodrying, potentially influencing the transport dynamics of the biodrying reactor [37].

3.6. Water Balance

The capacity of the three lysimeters to remove water through several mechanisms—such as leachate formation, water vapor air flow, metabolic water generation, and water buildup—was investigated using the approach described in Section 2.6.3. As shown in Figure 8, AR 0.2 and AR 0.6 achieved better performance than AR 0.4. The AR 0.2 configuration was the most successful at extracting water via leachate because its feedstock contained the most water. In contrast, the AR 0.6 configuration was the best at removing water via airflow, indicating superior efficiency of the reactor's ventilation system or air movement through the system. The highest biological activity level was likewise demonstrated by AR 0.6, which led to the breakdown of organic matter and metabolic water production. Despite the applied water removal processes, AR 0.4 retained the most water, suggesting that this configuration operated less effectively than the other reactors.

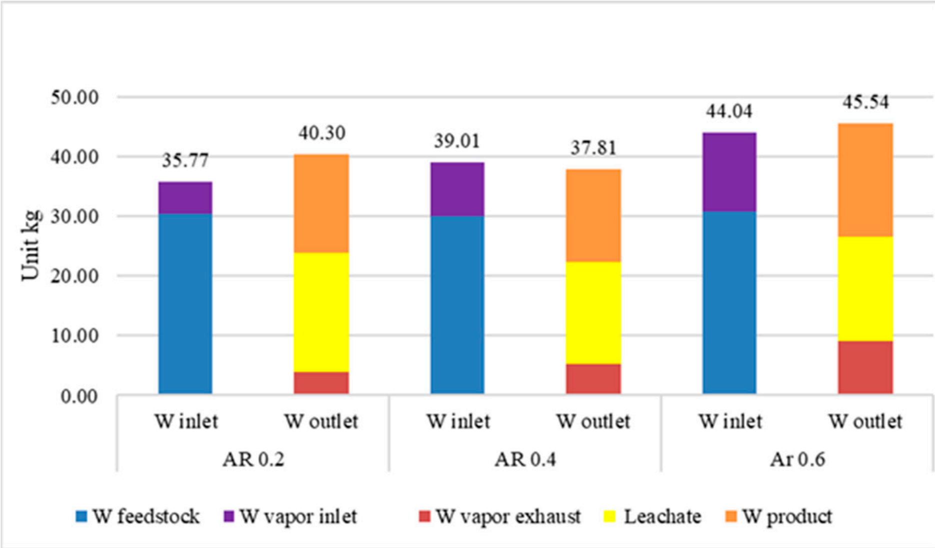

Figure 8. Schematic showing water balance calculation for the three studied lysimeters.

3.7. Carbon Balance

Figure 9 shows the full C balance for the experiment using the biodried product's elemental composition containing proportions of C among lysimeters 1, 2, and 3 as 5.71%, 5.54%, and 5.61%, respectively. As shown, higher ARs led to a rise in the C content of the exhaust and ambient air. The AR 0.2 and AR 0.4 configurations had the highest C level in the leachate. The mass balance analysis for C in the feedstock, air, product, leachate, and exhaust for all three configurations reveals minimal differences between the initial and final conditions in all three lysimeters. In terms of the remaining C in the biodried product, the AR 0.6 configuration consumed the highest amount of C in the experiment, with the least C remaining in the final product from this lysimeter. Overall, the minor observed variations show that all three scenarios achieve good C balance maintenance.

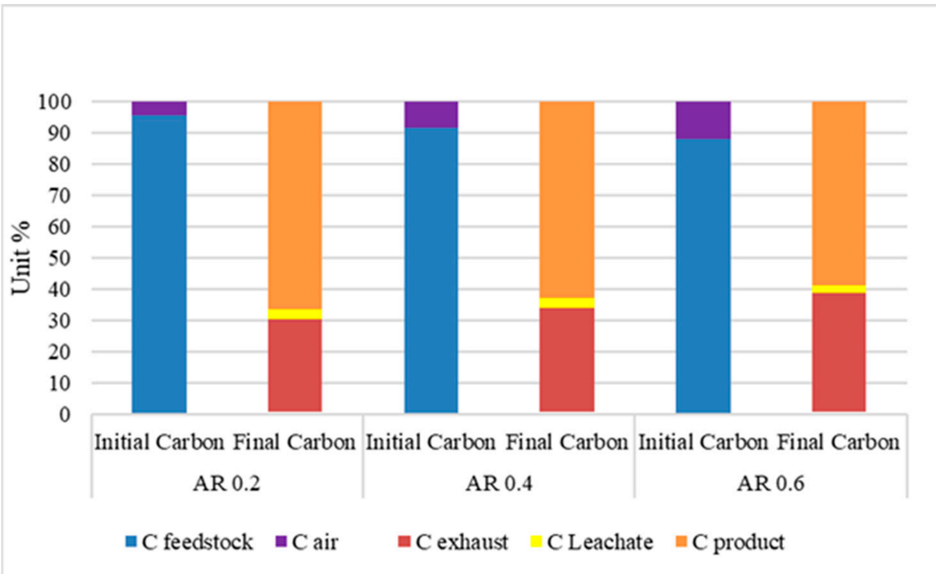

Figure 9. Schematic showing the calculated carbon balance for the three lysimeters.

3.8. Biodrying Index

The main aims of the biodrying process were to remove more water while retaining the organic material in the feedstock; therefore, the amount of water removed per kilogram of organic material consumed can be used as a metric to gauge the effectiveness of this process. A lower biodrying index is generally considered better for biodrying because it indicates that more moisture has been removed while minimizing the degradation of organic content, which helps preserve the energy value of the dried material.

Table 3 illustrates that AR 0.4 exhibited the smallest organic loss at 2.6 kg and the greatest water loss at 14.63 kg, in contrast to AR 0.6, with the highest organic loss of 3.01 kg and the lowest water loss of 11.89 kg. The fact that the biodrying index value is lowest (0.18) at AR 0.4 indicates that a moderate AR is best for reducing the index, followed by AR 0.2 with an index of 0.2 displaying a similar performance. These findings are inconsistent with those of Bhatsada et al. (2023), who reported that higher AR values lower the biodrying index more [31]. However, the difference in the pattern observed here is likely explained by the differences in initial MC and the amount of degradable material in the feedstock used in each lysimeter: AR 0.4 had the lowest content of degradable organics (39.47 kg), followed by 39.86 kg and 40.49 kg for AR 0.2 and AR 0.6, respectively.

Table 3. Biodrying index.

Parameter	Unit	AR 0.2	AR 0.4	AR 0.6
Water loss	kg	13.92	14.63	11.89
Organic loss	kg	2.81	2.60	3.01
Biodrying index		0.20	0.18	0.25

4. Discussion

4.1. Comparisons with the Literature

The findings of this study align with previous research, highlighting the crucial role of optimizing ARs for enhancing biodrying efficiency. For example, Payomthip et al. (2022) reported similar outcomes in which lower ARs supported better heat retention and increased microbial activity, leading to more efficient biodrying [34]. This is reflected in the elevated temperatures and CO_2 levels observed in the 0.2 m^3/kg/day lysimeter in this study, which indicate vigorous microbial decomposition of the feedstock and significant heat production.

Additionally, Zhang et al. (2020) highlighted that excessive aeration may lower biodrying efficiency by causing heat loss, a trend consistent with the relatively poor performance of the AR 0.6 lysimeter in the present study [21]. The lower temperatures and minimal moisture loss in the 0.6 m^3/kg/day lysimeter suggest that excessive aeration can stifle microbial activity and reduce heat retention, ultimately lowering the overall efficiency of the biodrying process. In the case of biodrying feedstock types with a high initial MC, such as market waste, it is crucial to consider various indicators that can demonstrate the efficiency of the biodrying process. In this experiment, involving the biodrying of market waste, the 0.2 m^3/kg/day AR lysimeter achieved excellent heat retention, as shown by the temperature evolution and TI. The elevated CO_2 concentrations recorded within the first seven days of the experiment also led to the effective decomposition of waste material and improved moisture removal. However, higher aeration also enabled the peak temperature level to be reached on day 5, with the greatest generation of CO_2 during the latter phase of the experiment. Although the AR 0.6 lysimeter was inferior in terms of moisture removal and LHV increase compared to the AR 0.2 lysimeter, the weight loss patterns and leachate formation indicate that the AR 0.6 configuration also improved the compaction of the waste during biodrying.

4.2. Mechanisms and Implications

The effectiveness of the 0.2 m^3/kg/day AR for the biodrying of market waste can be attributed to an appropriate balance at this AR between providing sufficient O_2 for microbial activity and minimizing the heat loss from excessive ventilation. The significant microbial activity levels at this AR generated substantial metabolic heat, which was effectively retained within the lysimeter, promoting the thermophilic conditions essential for efficient biodrying.

The higher CO_2 concentrations and lower O_2 levels recorded in the 0.2 m^3/kg/day lysimeter indicate active microbial decomposition, which is crucial to achieving effective moisture evaporation and organic matter stabilization during biodrying. The minimal CH_4 production from all the lysimeters also confirms that aerobic conditions were maintained at all the studied ARs, preventing anaerobic decomposition and associated greenhouse gas emissions.

The significant weight loss and moisture reduction observed at the optimal AR demonstrate the potential of this method for practical applications in market waste management. By reducing the MC and increasing the LHV of the biodried product, this process also enhances the waste's suitability for conversion into RDF, thereby contributing to more sustainable waste-to-energy solutions.

4.3. Economic and Environmental Impact

Adjusting the aeration levels in biodrying could lead to cost savings by reducing the energy required for aeration, thus improving the efficiency of the biodrying process. Lowering ARs cannot increase the output of the biodried product, which also reduces the operational expenses linked to managing aeration systems. In terms of environmental impact, using biodried waste as RDF is a viable option due to its increased calorific value and lower MC relative to the waste feedstock. This supports the idea of a circular economy by converting waste into an energy source, thus reducing the dependence on fossil fuels and decreasing greenhouse gas emissions associated with waste disposal.

4.4. Limitations and Future Research

Although this study provides valuable insights into the optimal ARs for the biodrying of market waste, there are nonetheless several limitations that could be addressed in future studies. Since this study was conducted for only 12 days, experiments with a longer duration could help in understanding long-term biodrying processes. Furthermore, analyzing the effects of other waste compositions and ambient conditions would help optimize aeration techniques for the biodrying of a wide range of different feedstocks in varying environments.

In terms of industrial applications, future research on the optimal ARs for large-scale biodrying plants would help determine the economic feasibility of this technique on a large scale. The cost of various aeration systems and the extent to which they improve drying efficiency could also be estimated to reduce energy use. Furthermore, examining the scalability of the optimized ARs and adapting them to different types of organic waste would potentially broaden the generalizability of this approach.

4.5. Practical Applications

The outcomes of this study have important implications for waste management plants seeking to fine-tune their biodrying processes. Based on this study's results, in comparison to discontinuous aeration, the optimal AR of 0.2 m^3/kg/day improved the efficacy of the biodrying process and stabilization of the biodried product while also reducing leachate production and improving the material's quality for RDF applications. In waste-to-energy plants, lower heating values are feasible to meet combustion chamber requirements; thus, alternative fuels from MSW are continuously used. MSW's high MC and organic proportion can produce low energy gain during thermal conversion [15]. Furthermore, using this optimized AR has key benefits in terms of environmental protection by helping to satisfy legal discharge standards in waste treatment and also more broadly supporting efforts to apply sustainable waste management methods.

5. Conclusions

In conclusion, this study emphasizes the crucial importance of adjusting ARs to optimize the effectiveness of the biodrying process for market waste under negative ventilation. By systematically testing three different ARs (0.2, 0.4, and 0.6 m^3/kg/day) over 12 days, this research identified that the most appropriate AR for moisture removal was 0.2 m^3/kg/day. This optimal rate achieved sustained high temperatures within the thermophilic range, which are essential for efficient biodrying. Gas analysis revealed that AR 0.2 supported high microbial activity during the initial 7 days, indicating strong biodrying efficiency early in the process. However, due to its higher aeration rate, AR 0.6 was able to sustain greater CO_2 production over time, leading to an overall higher total CO_2 output. In addition, the biodrying of market waste with a relatively high initial MC under the studied ARs cannot achieve significant MC reductions and LHV increases. The lysimeter with an AR of 0.6 m^3/kg/day also demonstrated superior weight loss and water removal as leachate, achieving a significant 69.8% weight loss and greater waste compaction than the other experiments. Additionally, both ARs resulted in substantial increases in the LHV of the biodried product with increases of 9.12% and 7.11% for the AR 0.2 and AR 0.6 lysimeters, respectively, enhancing the suitability of the biodried product for RDF applications. These outcomes highlight the potential of implementing variable ARs for optimizing the conversion of market waste into a valuable energy resource, thus contributing to sustainable waste management practices. From an economic perspective, lower AR values reduce operational costs associated with continuous ventilation and enhance the overall efficiency of the biodrying process. Environmentally, this AR optimization helps reduce greenhouse gas emissions by maintaining aerobic conditions throughout the process, thereby preventing CH_4 production. This research provides a strong foundation for further studies to refine biodrying strategies and explore their scalability in large-scale applications. Future research should extend the duration of the experiment to gain insights into longer-term biodrying dynamics and also assess the impact of different waste compositions on the process. In summary, this study's findings have significant implications for sustainable waste-to-energy solutions, offering a practical approach to managing market waste more effectively in alignment with global environmental and economic goals.

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