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Optimizing Aeration for Enhancing Biodrying Efficacy of Municipal Solid Waste in Tropical Climate Condition

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Abstract

This study investigated the influence of aeration and its optimum operation for the biodrying of municipal solid waste (MSW). A series of lysimeter experiments were conducted to determine MSW's moisture content, temperature, and gas emissions during its biodrying treatment at different aeration rates over 14 days. Results indicated that low-to-moderate aeration rates of 0.3-0.5 L/min facilitated a balance between water evaporation by heat generated from biological activities and advective removal of evaporated water from the waste matrix. In contrast, higher aeration rates primarily relied on physical drying, resulting in rapid initial moisture loss but potentially inhibiting microbial activities. The optimal aeration was determined at 0.3 L/min, achieving a minimum low heating value (LHV) of 11.4 MJ/kg and reducing the moisture content to less than 30% within 7 days. These findings suggest that optimizing aeration rates can significantly enhance the efficiency of the biodrying of MSW in tropical climate condition. The data from this study could be used to promote sustainable waste management practices in regions with similar climatic and waste composition characteristics as Thailand.

Keywords : Biodrying; Mechanical Biological Treatment; Municipal Solid Waste; Waste-to-Energy; Refuse Derived Fuel

Introduction

Global climate change, attributed to anthropogenic activities, has intensified the need for sustainable waste management practices. Municipal solid waste (MSW) contributes significantly to greenhouse gas (GHG) emissions, including open burning and landfill emissions. These activities release methane, a potent greenhouse gas with a relatively short atmospheric lifetime but a high global warming potential [1]. As in many developing countries, MSW management faces challenges in Thailand due to rapid urbanization and inadequate waste management infrastructure. In 2023, the daily generation of MSW has reached approximately 73,840 tons, representing a 5% increase from the previous year [2]. The organic composition of this waste, particularly the high content of food waste (approximately 40%), poses significant challenges for traditional waste management strategies, especially in a humid tropical climate.

Improper management of food waste poses a significant threat to the environment. Food waste decomposes anaerobically, which produces methane (CH_4), a potent greenhouse gas with a global warming potential approximately 28 times greater than carbon dioxide (CO_2) [3]. While Thailand has implemented policies to promote a circular economy for plastic waste [2], challenges persist in food waste management due to the absence of a clear, dedicated policy framework in Thailand to address food waste management, waste segregation, and the efficient utilization of food waste [4]. Such food waste signifies a global challenge and highlights inefficiencies in resource allocation. Food waste contributes to approximately 8-10% of global GHG emissions with a global average generation rate of 86 kg/capita/day, among which food waste generation in Thailand (79 kg/capita/ day) was comparable to those observed in neighboring countries [5]. This situation poses a significant challenge to achieving Sustainable Development Goal 12.3, which aims to halve per capita global food waste at the retail and consumer levels by 2030.

Thailand has implemented various waste management strategies to address these challenges, including mechanical biological treatment (MBT) with biodrying [6]. Biodrying is a process that involves the controlled biological degradation of organic matter within the waste and the removal of moisture through evaporation. This technology provides significant benefits, such as creating refuse-derived fuel (RDF) and reducing GHG emissions [7-9]. Moreover, MSW biodrying is generally accomplished within a short period, i.e., less than 20 days; hence, it can be considered a compact and energy-efficient process [10, 11]. According to studies by Payomthip et al. (2022) and Sutthasil et al. (2018), the biodrying process can reduce GHG emissions by 84-93.3% compared to those of landfilling [12, 13]. It also produces RDF with a higher calorific value, which cement plants can use as an alternative fuel source [9, 14, 15]. Unfortunately, only 12.6% of the RDF produced by waste management was used in cement facilities due to the potential negative impact on clinker quality from low-quality RDF input [16, 17].

Despite the potential benefits of biodrying, several challenges and knowledge gaps persist. The optimal aeration rate for biodrying depends on waste characteristics [12], climatic conditions, and waste density [18, 19]. To establish proper operating conditions for biodrying of MSW in tropical climate condition, this study investigated the effect of aeration on moisture content, temperature profiles, and gas emissions. It determined the optimum rate for maximizing moisture removal and enhancing the heating value of RDF. The study offers valuable insights into the biodrying process, which can be integrated into sustainable waste management strategies for developing countries in tropical regions.

Materials and Methods

Experimental Design and Preparation

This study investigated the biodrying of MSW in Thailand, focusing on the effect of the aeration rate. A set of lysimeter experiments was performed to examine biodrying performance under varied aeration rates of simulated mixed waste materials representing landfilled waste to gain insight into physical changes together with their associated gas emissions.

This research used an acrylic column with a diameter of 0.2 m and a height of 0.6 m covered with thermal insulation to prevent heat losses. Each column was equipped with a perforated base connected to an aeration system to distribute air. The orifice with a 6.35 mm diameter was installed at the center of the lysimeter for inner gas sampling. Meanwhile, the exhaust gas was collected from the top of the lysimeter for emitting gas evaluation. The temperature and moisture content inside the waste material were measured in the middle of the lysimeter, as described in Figure 1. The range of airflow rates to each column was adjusted using this system with a compressor and flow regulators.

Experiments were designed using a simulated waste mixture representing the typical composition of MSW in Thailand, in which food waste was the predominant component at 45%, follows by paper, plastic, yard waste, textile and other at 12%, 6%, 5% and 7%, respectively [2]. The size of the simulated waste was reduced to about 10 cm and mixed manually. After the preparation, 2.9 kg of simulated waste was loaded into each lysimeter, and its compaction density was 340 kg/m^3.

While porosity and size distribution are recognized as factors in biodrying, these parameters were not measured in this study. This decision was primarily due to the focus of this research on the impact of aeration rates on biodrying performance. We acknowledge that the absence of these measurements may limit a comprehensive understanding of the physical changes within the waste matrix. Furthermore, output waste composition was not measured as the primary objective of this study was to evaluate the effect of aeration rates on MSW biodrying. However, the initial composition was controlled to replicate the MSW composition found in Thailand.

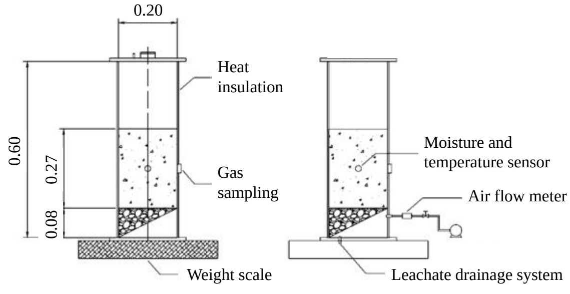

Figure 1 Configuration and cross-sections of simulated lysimeters

Aeration Rate Selection

Six different aeration rates were studied, ranging from 0.1 to 2.0 L/min, as described in Table 1. These rates were selected based on a review of prior research on the biodrying process. It was intended to be used as the theoretical underpinning for the study and literature on optimal conditions for maximal moisture removal and microbial activity. An air pump was installed to provide different aeration rates into each lysimeter, with silicon tubing of 6.35 mm diameter connecting the pump to the perforated base of each column. The inlet air supplied by the air pump had an average temperature of 30°C with approximately 60% moisture content, representing the ambient room temperature of the laboratory, under an atmospheric pressure of 1 atm. The aeration was applied continuously for 14 days, maintaining a constant flow rate from the bottom to the top of the waste material. A control lysimeter was included to simulate passive aeration (natural ventilation), and by allowing ambient air to enter and exit freely without forced airflow, to provide a baseline for comparison with the lysimeters subjected to forced aeration.

Table 1 The aeration provided for the lysimeter

Code	A	B	C	D	E	F	G
Aeration rate (L/min)	0.1	0.3	0.5	0.7	1.0	2.0	-

Measurement and Analysis

The measurements comprised temperature, moisture content, inner gas, and gas emissions as follows:

Temperature Measurement:

Each lysimeter contained a port through which testers could insert temperature sensors at the center, which were recorded using a data logger to get a temperature profile. The temperature measurements monitored the thermal profile of waste periodically because this parameter is critical to characterize the microbial activity and effectiveness of the biodrying process. The data collected made it possible to analyze and explain how, by different aeration rates, the temperature distribution profiles inside the lysimeter lead to moisture evaporation and microbial activity.

Moisture Content and Low Heating Value Measurement:

The initial and final waste materials were analyzed for water content and LHV using air-dried at 105°C for 24 h. (ISO-5068-1 standard) and Bomb Calorimeter (ASTM D 5865-11a standard), respectively. The moisture content of waste material during the experiment was tracked using moisture sensors (EN 61326-1:2013, EN 50581:2012 standard) and recorded by a data logger. This method is frequently employed in studies on waste processing to control drying technologies and calculate moisture retention after the treatment of wastes [12, 14, 17].

Gas Sample Analyses:

Gas samples at the mid-depth of waste layer and emitting gas at the top of the lysimeters were collected along the experimental period and analyzed for CO_2, CH_4, and nitrous oxide (N_2O) concentrations using gas chromatography (GC) equipped with flame ionization detector (FID) and electron capture detector (ECD). These gases were used to indicate biological activities occurring in the waste layer: CO_2 corresponds to aerobic respiration, CH_4 indicates anaerobic conditions and N_2O points to incomplete denitrification processes. Monitoring these gases was essential to evaluate the environmental impact of the biodrying process.

Process Efficiency Evaluation:

The primary objective of biodrying is to reduce moisture content while minimizing organic matter loss. Various researchers have used the biodrying index to evaluate the efficiency of the biodrying process [12, 17, 20]. In this study, the biodrying index was calculated as the ratio of carbon loss (measured by CO_2 and CH_4 emissions) to water loss. This index measures the extent to which the process relies on biological degradation versus physical drying. A higher biodrying index indicates a more significant contribution of biological processes to moisture reduction.

Data Analysis

The information gathered from measuring temperature and moisture levels underwent statistical examination to pinpoint variations across aeration levels. A regression analysis was used to show the link between aeration rate and moisture reduction, and an analysis of variance was used to establish the significance of the differences among the rates. A normalized approach was employed to assess the overall efficiency of the biodrying process through moisture removal, increasing LHV, and weight reduction. All data analysis was carried out using data analysis through Excel for Windows.

Results and Discussion

The experiment was conducted to examine the effects of aeration on waste materials through the biodrying process by investigating basic phenomena; hence, optimal aeration on tropical MSW was achieved.

Effect of Aeration on Waste Characteristics

Temperature, Moisture Content Profiles and Their Implications

As a vital factor in the biodrying process, temperature directly influences the microbial activities responsible for the biodegradation of organic matter, which subsequently releases heat for evaporating moisture. Throughout the 14 days of this experiment, the temperature and moisture content profiles within the lysimeters changed considerably depending on airflow conditions. Figure 2 shows the temperatures and moisture observed at different aeration rates.

The temperature inside waste materials varied between 36 and 44°C in all lysimeters. The statistical analysis reveals an insignificant difference between the temperature profile over the entire biodrying period in the lysimeters operated under different aeration rates ($p > 0.05$). However, significant differences were observed in the moisture content of waste between the lysimeters, thus suggesting the impact of the aeration rate on moisture removal from waste.

Regarding the temperature profile, higher initial temperatures were observed in low-to-moderate aeration rates (0.1 to 0.5 L/min), likely due to intense microbial activities. Subsequently, a decline in temperature was noted, followed by a secondary rise, possibly attributed to the degradation of more recalcitrant organic matter by thermophilic microorganisms. Interestingly, the lysimeter

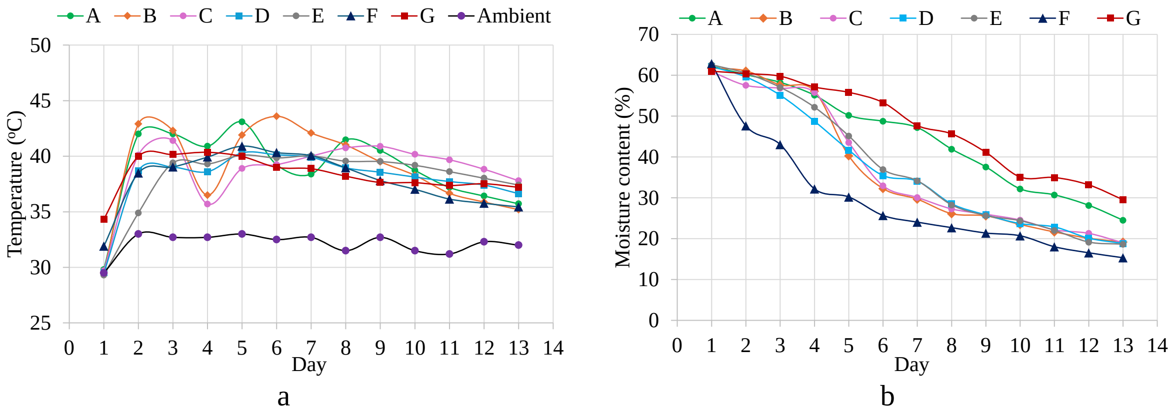

Figure 2 The profiles of temperature (a) and moisture content (b) during biodrying process

with upper moderate-to-high aeration rates (0.7 to 2.0 L/min) shows similar trends in temperature profiles as the control lysimeter. This could be attributed to excessively high aeration, leading to rapid moisture loss and hindering microbial activity. Nevertheless, high aeration rates did not accelerate the process to the thermophilic phase due to increased convective heat loss, which counteracted the heat generated by microbial activities [21, 22], leading to a lower temperature.

While upper moderate-to-high aeration rates show similar trends in temperature profiles, the trends in daily moisture content were observed in different directions. In the highest aeration rates (F – 2.0 L/min), the moisture content decreased rapidly in the initial stages, primarily due to physical drying, as the high airflow rate facilitated moisture evaporation. The moisture level in this lysimeter can reach 30% within 5 days, while over 40% was observed in other lysimeters. In contrast, other aeration rates (0.3 to 2.0 L/min) exhibited a slower moisture reduction rate, indicating a balance between biological and physical drying processes. The lowest aeration lysimeter (A – 0.1 L/min) shows a similar trend as the control lysimeter. The moisture content gradually decreased starting on day 5 of the experiment. In low-aeration conditions, moisture transport within the waste material may be limited, hindering evaporation, whereas moderate aeration can improve moisture transport. However, the evaporation rate may be limited if the airflow is insufficient to overcome the resistance to moisture diffusion within the waste material. In fact, temperature can influence moisture evaporation. Notwithstanding, the relatively similar temperature profiles across different aeration rates suggest that temperature may not be the primary driver of moisture loss in this case.

While the moisture content profiles varied significantly across different aeration rates, the temperature profiles exhibited a more complex and non-linear relationship with aeration. As depicted in Figure 3, the maximum temperature was observed in lysimeter B (0.3 L/min) on day 2, whereas the minimum temperature was recorded in lysimeter E (1.0 L/min) on the same day. On day 4, the lowest temperatures were attained in lysimeters B and C (0.3 L/min and 0.5 L/min). This non-linear behavior suggests that increasing the aeration rate does not always result in a commensurate increase in temperature. In some instances, excessive aeration can even suppress microbial activities, leading to decreased heat generation. This can occur when the airflow is too strong, leading to excessive drying of the waste material and hindering the growth of microorganisms. As a result, the biodegradation process is slowed down, and the temperature within the waste material decreases.

When comparing the relationship between temperature and decreasing moisture content (Figure 4), it is observed that the highest aeration rate exhibited a rapid initial decrease in moisture content, reaching 40% on day 1, followed by a gradual decline. Concurrently, the temperature increased to a maximum on day 5 and then gradually decreased. This suggests that in the initial stages, biodrying processes were dominant, with microbial activities contributing to heat generation and moisture reduction. However, as the moisture content decreased significantly, advective removal of moisture, driven by airflow, became more prominent. The excessive aeration rate is likely to reduce microbial activities under low moisture content conditions, leading to a decline in biological activities; thus, removing water through evaporation from releasing heat would be imited.

For low-to-moderate aeration (lysimeter B to D – 0.3, 0.5, and 0.7 L/min), a similar trend was observed, which suggests that the initial temperature rise was likely due to the degradation of readily biodegradable materials, while the subsequent decrease may be attributed to the degradation of more recalcitrant substances. However, three aeration rates of B, C, and D achieved the targeted moisture content of produced RDF set by end users at 30% within 7 days, as illustrated in Figure 5. However, selecting an appropriate aeration rate for the biodrying process in practical operation would also depend on other factors such as energy and equipment costs. In this context, the lysimeter B could be considered the most appropriate condition as it could achieve the desired end-user product while creating lower environmental impacts. However, further analysis and optimization studies may be necessary to definitively conclude the optimal aeration rate for specific waste types and operational conditions. Notwithstanding, even though the moisture content in lysimeter F reached 30% on day 5, it could be dried only through advective removal from the waste matrix without a significant contribution from biodrying phenomena.

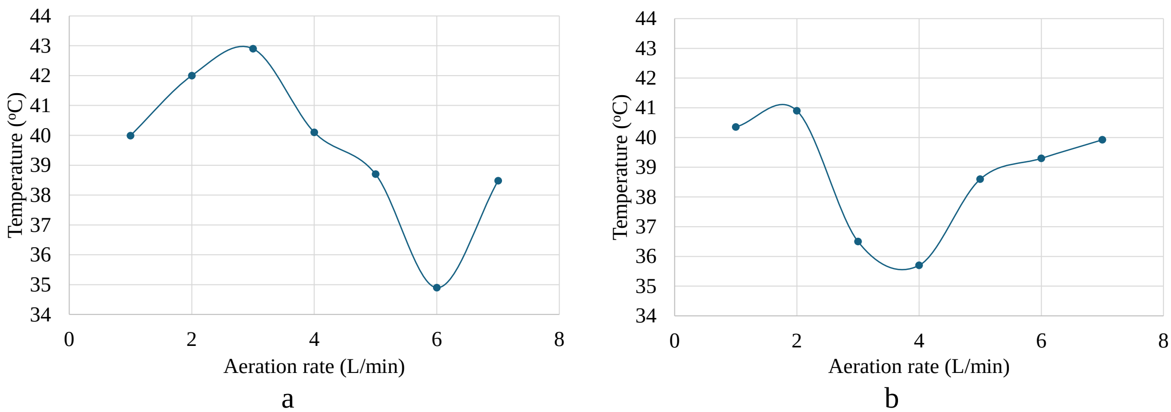

Figure 3 The relationship between the temperature change period and aeration rate on day 2 (a) and day 4 (b)

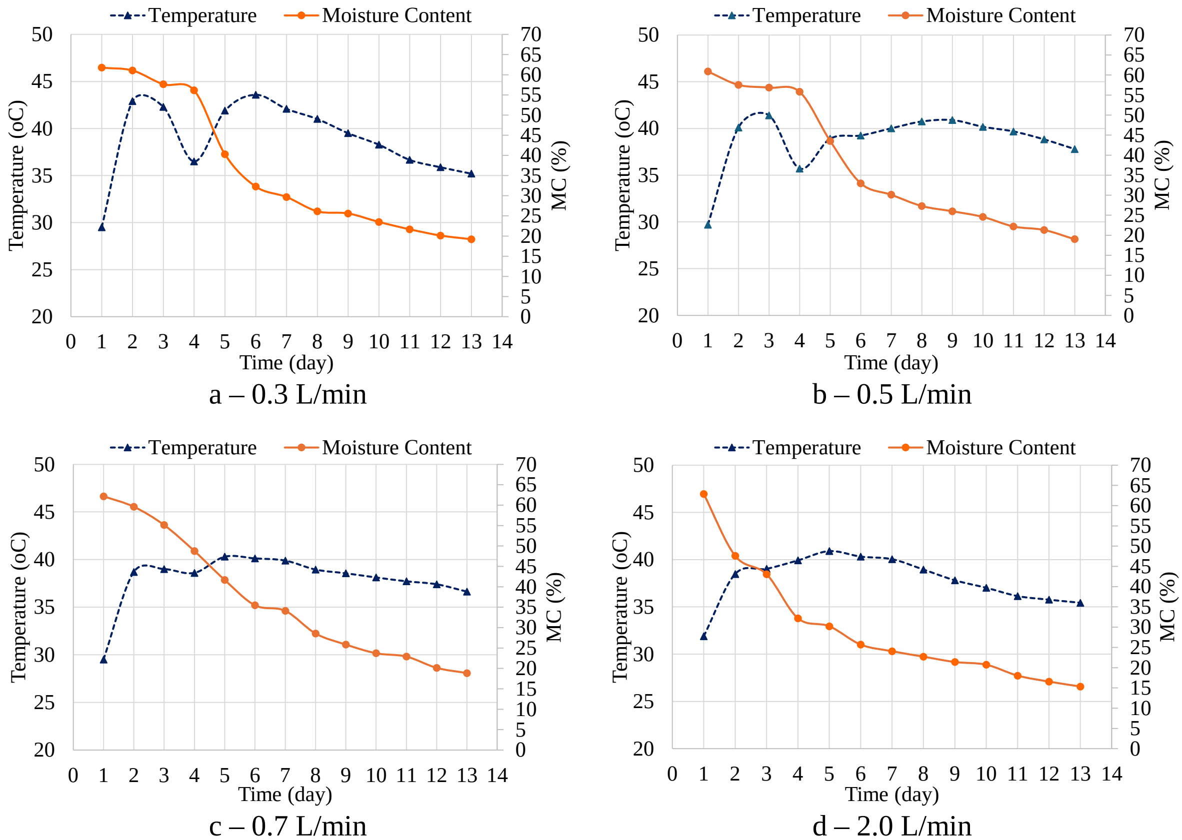

Figure 4 The variation of moisture content and the temperature in lysimeter with 0.3 (a), 0.5 (b), 0.7 (c), and 2.0 L/min (d) aeration supplied

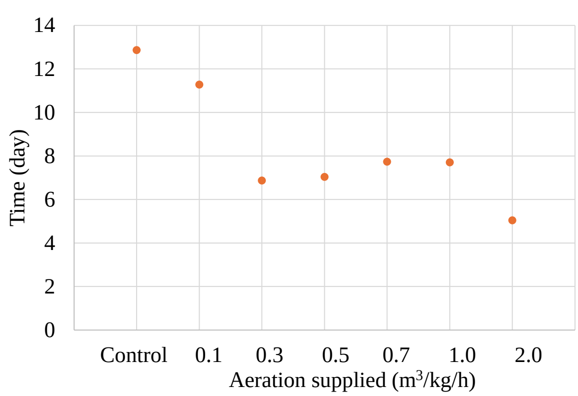

Figure 5 The correlation between the time to achieve target RDF qualities set by end-users and the aeration rate

Gas Concentration Inside Waste Material

The production of greenhouse gases, including CO_2, CH_4, and N_2O, was closely linked to the biodrying process. CO_2 emissions were highest in the initial stages, reflecting active microbial activity. Subsequently, CO_2 levels decreased as organic matter was consumed and microbial activity decreased. Figure 6 illustrates the variation of gas inside the waste materials among lysimeters B, C (low-to-moderate aeration), and F (highest aeration). The highest CO_2 levels were observed in lysimeter C, particularly on the 3rd day. This peak indicates a period of intense microbial activity that the moderate aeration rate could drive. However, it is essential to note that this peak is a transient phenomenon, and as readily biodegradable organic matter is consumed, the rate of CO2 production decreases.

In contrast, lysimeter F exhibited the lowest CO_2 levels, indicating excessive aeration can accelerate moisture evaporation, potentially limiting the growth of certain microorganisms' growth and reducing CO_2 production. Moreover, lysimeter B showed intermediate CO_2 levels, suggesting a balance between the evaporation of water by heat generated from biological activities and the advective removal of evaporated water from the waste matrix. However, it should be noted that the relationship between aeration rate and CO_2 production is complex and can be influenced by various factors, including waste composition, initial moisture content, and environmental conditions. Further research is required to clarify the mechanisms inside waste material for effective biodrying.

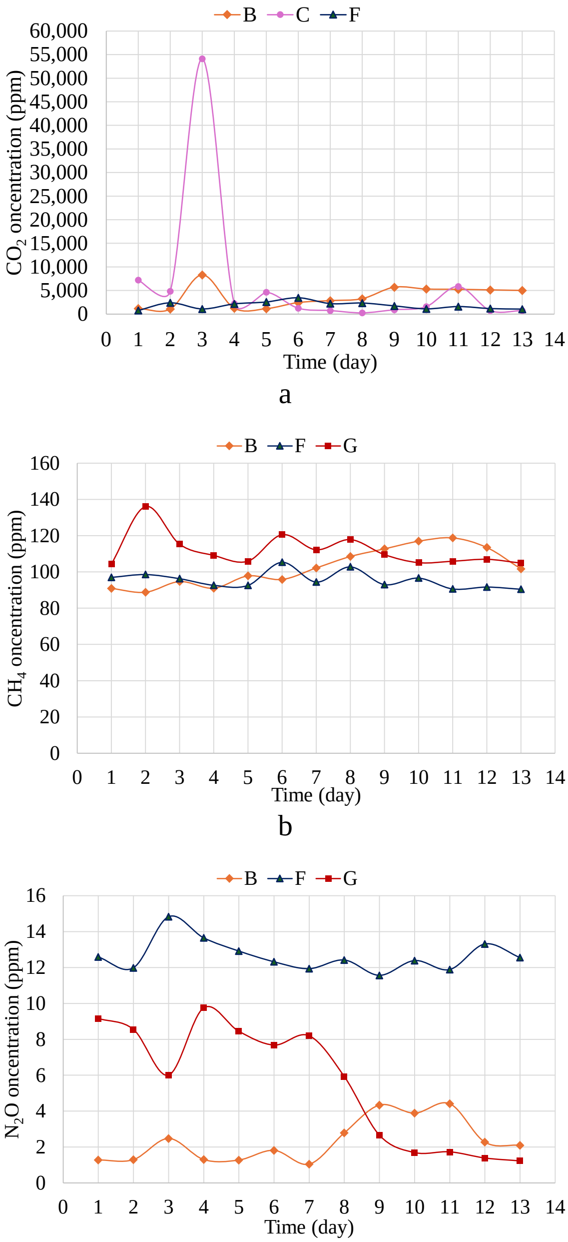

Figure 6 The variation of CO_2 (a), CH_4 (b), and N_2O (c) gas inside the waste materials

The comparison of CH_4 gas production among lysimeters B, F, and G shows that the CH_4 concentration profiles varied across different aeration rates. However, statistical analysis showed non-significant differences among the lysimeter operation conditions ($p > 0.05$). It should be noted that even though the statistical analysis did not reveal significant differences in CH_4 concentrations, it is crucial to consider the underlying biological and environmental factors that may influence CH_4 production. Further research is needed to fully understand these factors' complex interactions and optimize biodrying processes for efficient waste management and reduced greenhouse gas emissions.

Regarding N_2O inside the lysimeter, the statistics show a significant difference among the lysimeters ($p < 0.05$). Lysimeter F shows a higher and more stable N_2O concentration, indicating that a high aeration rate promotes nitrification. In contrast, a decreasing trend over time was observed in lysimeter G, which could result from the limited oxygen availability, inhibiting nitrification and favoring denitrification. Lysimeter B exhibits a relatively stable N_2O concentration with some fluctuations. This suggests a balance between nitrification and denitrification processes.

Weight Loss and Heating Value

The weight loss of the waste was directly correlated with moisture reduction. The heating value of the biodried waste increased significantly, making it a potential feedstock for energy recovery. Normalization was used to compare the effects of different aeration rates on the moisture content, low heating value, and weight loss. Each triangle represents a different treatment, with the vertices representing the percentage reduction in moisture, the increase in low heating value, and the percentage weight loss, as illustrated in Figure 7. No leachate was observed throughout the experimental period, which aligns with the findings of previous studies [23]. Please note that the highest aeration rate was not included in the calculation because the loss in moisture content was mainly due to the advective removal of moisture under high airflow conditions rather than the evaporation of water from heat generated by biological activities.

The figure shows that moisture content decreases and LHV increases with increasing aeration rates. This suggests that increased aeration can promote microbial activity, leading to higher energy content in organic matter. However, more aeration can decrease LHV, as observed in certain lysimeters. This might be affected by the inhibition or nutrient loss associated with increased oxygen. Low-to-moderate aeration rates (0.3 and 0.5 L/min) showed greater normalized efficiency scores, suggesting a more balanced combination of biological and physical drying processes. The highest LHV achieved was 11.4 MJ/kg and 13.3 MJ/kg after 7 days and 14 days in the lysimeter with 0.3 L/min aeration, meeting the end-user standard of at least 10.5 MJ/kg LHV for RDF utilization in power plant [16].

These rates resulted in significant moisture reduction with minimal organic matter loss and yielded optimum biodrying conditions.

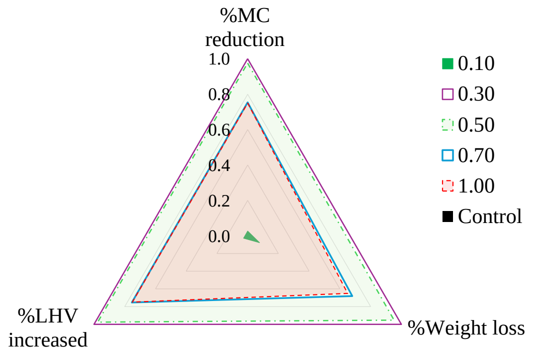

Figure 7 A comparison of process efficiency among different aeration rates on day 7

Optimal Aeration Rate for Biodrying and its Index

From Figure 8, the lowest aeration rate (0.1 L/min) resulted in minimal water loss due to limited airflow and reduced microbial activities. However, this condition also led to a higher carbon loss, suggesting inefficient biodegradation and potentially anaerobic processes. In contrast, the high aeration rates of 1.0 and 2.0 L/min led to increased CO_2 emissions, implying that physical drying dominated biological processes. While these higher aeration rates showed higher carbon loss, they resulted in similar levels of water loss as the low-to-moderate aeration rates of 0.3 and 0.5 L/min.

These low-to-moderate aeration rates demonstrated a better balance between biological and physical drying processes. These rates resulted in higher water loss with lower carbon loss through CO_2 and CH_4 emissions, indicating more efficient biodegradation and reduced organic matter loss. The optimal biodrying index was observed at 0.3 L/min, suggesting a balance between microbial activity and moisture removal.

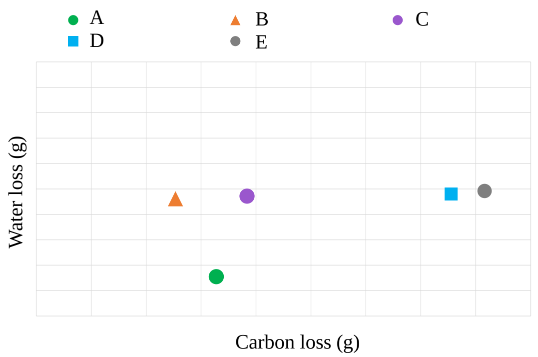

Figure 8 The correlation between C loss in terms of CO_2 emission loss and water loss

Conclusions

This study examined the effects of aeration rate on the biodrying of MSW in Thailand, a representative of tropical developing countries. The findings of this research contribute to the advancement of waste-to-energy technologies, explicitly highlighting the potential of biodrying as a suitable treatment option for regions with climatic conditions and similar waste management challenges to Thailand. The results demonstrated that aeration significantly influenced the lysimeters' moisture reduction, temperature profile, and gas emissions. It was found that low-to-moderate aeration (0.3 and 0.5 L/min) promoted a biodrying process, combining biological and physical drying phenomena. Under high aeration condition (2.0 L/min), rapid initial moisture loss resulted from the dominance of active moisture removal. In contrast, the evaporative removals due to heat released from microbial activities were limited. The study recommends maintaining an aeration rate of 0.3 L/min as optimal for the biodrying process in this study. This rate balanced moisture removal, microbial activity, and gas emissions, producing efficient biodrying and high-quality biodried products. Further research is needed to assess how these findings can be implemented and explore the potential for scaling up the technology, including the effects of different waste compositions and seasonal variations on biodrying performance. Moreover, developing monitoring and control systems to optimize aeration rates and environmental conditions can significantly enhance the effectiveness of biodrying processes.

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