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Investigating the Impact of Aeration and Leachate Recirculation for Biodrying of Food and Vegetable Waste from the Market

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Abstract

The increasing production of waste from the market presents significant challenges for waste management, necessitating efficient treatment methods like biodrying. This study examines optimizing biodrying methodologies for the treatment of fruit and vegetable waste collected from market sources, emphasizing the nuanced impact of leachate recirculation within zero discharge systems. Aimed at bolstering the efficiency of converting market refuse into a biodried product suitable for integration into the waste-to-energy framework, our research meticulously assessed the performance of three lysimeters, arranged in parallel, under distinct aeration rates: Lysimeter 1 with an aeration rate of 0.2 m^3/kg/day, followed by Lysimeters 2 and 3 with 0.4 m^3/kg/day and 0.6 m^3/kg/day respectively. Lysimeter 1 emerged as the front-runner, showcasing better performance metrics across CO_2 concentration, weight reduction, leachate volume, and temperature profiles. Notably, it achieved a remarkable 5.97% moisture content (MC) reduction at the lowest aeration rate of 0.2 m^3/kg/day. The controlled aeration strategy employed in Lysimeter 1 facilitated significant organic content transformation and led to an impressive 317% boost in heating value, surpassing the results of Lysimeters 2 and 3, which recorded MC losses of 7.97% and 2.47%, respectively. These findings highlight the critical importance of optimizing aeration rates and the detrimental effects of leachate recirculation on the biodrying process. They advocate for future research endeavors to refine aeration rates further and exclude leachate recirculation, aiming to produce a biodried product that meets the moisture loss and heating value requirements for the cement industry's RDF standards. This study contributes valuable insights towards enhancing biodrying efficiency, with significant implications for waste management and energy recovery practices.

Keywords : Biodried Product; Waste-to-Energy; Biodrying Efficiency; Controlled Aeration; Leachate Return

Introduction

Municipal solid waste (MSW) production is increasing due to urbanization as well as the complexation of MSW composition, which remains one of the key challenges [1-3]. MSW is typically disposed of in sanitary landfills or open dumps, particularly in low- and middle-income nations, for convenient and economic reasons [4]. On the other hand, poor waste management at these locations has resulted in several environmental issues, including the emission of greenhouse gases (GHGs) and pollution of water and soil [5]. GHG emissions from MSW are relatively low, with landfills being the primary source due to the anaerobic decomposition of organic waste, which produces methane (CH_4). Aerobic decomposition of organic waste emits carbon dioxide (CO_2) but to a lesser extent than methane from anaerobic processes. Market waste, including food and non-food-related waste [6], presents significant challenges to waste management, characterized by high waste mass but low density, and rapid decomposition, which can lead to environmental and sanitary problems, i.e., infestation of insects, odor, and leachate spilling on the surrounding [7]. Centralized wholesale marketplaces in developing nations generate segregated organic waste, hindering efficient waste treatment [8]. By 2050, food and green waste will account for over 50% of all waste in low- and middle-income nations [9]. Many countries continue to generate a considerable amount of mismanaged organic waste, particularly in those where agriculture is the primary source of revenue [10].

In Thailand, waste is categorized into four types: municipal, industrial, household hazardous waste, and hazardous waste [11]. However, there are no separate collection and treatment systems for market waste, further creating environmental threats [12]. Thailand employs three main waste disposal methods, incorporating composting, combustion, and disposal on land, while the solid waste problem is still considered a prime environmental concern [13, 14]. Thailand's waste management system is currently facing issues such as garbage overflow in landfills due to increased waste generation with population growth and subsequent improper disposal [15-18]. Innovative waste management technologies are needed to efficiently handle market waste, such as food waste in Vietnam and Thailand, reducing moisture content (MC) for efficient disposal and energy recovery from solid waste [19, 20]. Refuse-derived fuel (RDF) synthesis eliminates MC and non-combustible elements, resulting in a cost-effective and safe burning product for cement kilns or biomass boilers. Alternative fuels are crucial for reducing fuel prices and enhancing GHG emission reduction. [21, 22]. In Thailand, most cement plants use the local RDF-3 standard, which sets a minimum threshold of 4,500 kcal/kg [23]. In waste-to-energy plants, lower heating values are feasible to meet combustion chamber requirements; thus, alternative fuels from MSW are continuously used [24]. MSW's high MC and organic proportion can result in low energy gain during thermal conversion [25].

Mechanical biological treatment (MBT) processes, including composting, biostabilization, and biodrying, are widely used to manage, convert, and transform MSW [26-28]. Due to the continuous increase in solid waste generation, which shortens landfill lifespans, treating solid waste through methods such as composting and biodrying can significantly reduce the volume of waste destined for sanitary landfills, thereby extending their lifespan [29]. Biodrying is a promising solution for treating organic waste efficiently, reducing volume, MC, and GHG emissions. It ensures environmental sustainability by reducing landfill waste and mitigating leachate leakage. Biodried products can recover energy from high calorific values, but aeration rate is crucial [30].

Biodrying reactors are based on a combination of physical and biochemical processes and are designed as open tunnel halls or rotating drums. On the biochemical side, aerobic biodegradation of easily decomposable organic materials occurs. Aeration is used to remove convective moisture effectively. Although the reactor architecture and biochemical process are similar to composting, the specific operation differs greatly [30]. Lysimeters are increasingly used to investigate the effects of climate change on land and water resources. Lysimeter experiments provide more accurate leaching test results than static leaching tests [31]. Thus, lysimeters are commonly used in biodrying experiments because they can accurately measure moisture content and other parameters critical to biodrying.

Moisture in MSW significantly affects biodrying, with high moisture levels preventing oxygen (O_2) transmission and low moisture levels preventing microbial activity [32]. Organic waste decomposition is hindered by O_2 shortage, necessitating biodrying, and natural aeration. Positive or negative forced aeration ensures O_2 availability, with negative aeration causing more extensive water loss-to-volatile solids ratios [33, 34]. Positive aeration in an open-top lysimeter arrangement can improve moisture evaporation and reduce leachate generation; nevertheless, this can cause non-homogeneous moisture distribution due to condensation and, given the compacted waste, insufficient air movement through the waste matrix. Biodrying evaporates water from biological waste, but leachate can form, requiring careful control before discharge into aquatic bodies [35]. Leachate recirculation enhances biodrying efficiency by maintaining moisture levels, promoting biological decomposition, and enhancing heat generation while managing rates and frequency for optimal process conditions [36]. Zhang et al. (2009) found that pH-neutralized leachate recirculation enhances total water removal and organics degradation in a hydrolytic-aerobic bio-pretreatment for MSW [37].

For this study, 'market waste' refers to food and vegetable waste collected from market sources. Despite advances in waste management technologies, there is still a significant gap in our understanding of biodrying processes, mainly when applied to market waste. With its high organic content, market waste poses particular challenges and potential for biodrying procedures. However, current research focuses primarily on generic organic waste streams, ignoring the complexities of market waste biodrying. The effect of leachate recirculation on a biodrying process is quite limited, as the quantity of leachate and the minimal MC for biodrying operations that inhibit biodegradation have not been widely identified. On the other hand, if the water concentration is too high, it plugs the waste pores, making the process anaerobic [38]. With high MC, market waste generates large quantities of leachate during biodrying. Recirculating leachate containing nutrients and organic matter can improve organic material degradation, generate metabolic heat for efficient moisture removal, and reduce the need for external management and treatment. This study aims to (1) determine the optimal aeration rate for biodrying market waste, (2) assess the impact of leachate recirculation on microbial activity and heat generation, and (3) evaluate the overall efficiency of different aeration rates and leachate recirculation practices. This study introduces a novel approach by integrating different aeration rates and leachate recirculation practices in a zero-discharge system. The expected impact includes enhanced biodrying efficiency and improved waste management practices, contributing to sustainable environmental management.

Materials and Methods

Feedstock preparation

Market waste, including mainly vegetable and fruit residues, was collected from Eastern Energy Plus Co., Ltd. in Samut Prakan province, Thailand, as part of the feedstock preparation process. The trials in this study were conducted from November 3rd to November 18th, 2023, with an average relative humidity of 30-50% and a temperature range of 25-33°C. The market waste utilized as feedstock was typically similar in composition. Plastic bags comprised 6.84% of the non-biodegradable components, while packaging and plastic tubes comprised 0.54%. Organic waste included up to 91.25% of the degradable materials, with milk cartons and paper waste accounting for 1.37%. The market waste stockpile was homogenized using the ASTM D5231-92 standard's quartering process, a straightforward method that involves splitting, mixing, and repeating until a representative sample is obtained. A total of 18.5 kg of market waste was collected and analyzed before biodrying, including two 1.5 kg samples of market waste and one 0.5 kg sample of organic waste. The MC, volatile solid (VS), and ash were measured using an ASTM D7582 thermogravimetric analyzer (TGA801; LECO Corporation, St. Joseph, MI, USA). The high heating value (HHV) was determined using an ASTM D240 bomb calorimeter (AC-500 calorimeter, LECO®, USA), then converted to LHV. The organic material included carbon (C), hydrogen (H), oxygen (O), nitrogen (N), chlorine (Cl), sulfur (S), and ash content studies. The feedstock's physical and chemical properties – weight, and bulk density, which were measured before each experiment – the MC, Ash content, low heating value (LHV), and MC were 90.23% (by wt), 1.07% (by wt), 47.5 kcal/kg, and 0.03% (by wt), respectively. The characteristics of feedstock were similar to those of Hanrinth and Polprasert. (2016) regarding MC and organic content: MC 89.36% and 88.46% w/w of organic matter for vegetable residue, fruit peel, and food debris derived from the fresh-food market [39].

Experimental design

The feedstock quantity in each lysimeter varied 45.35, 62.98, and 66.65 kg for Lysimeters 1,2 and 3 with waste densities of 151.16, 209.92, 222.16 kg/m^3 at a feedstock elevation of 1.2 m. The aeration rate was set as 0.2, 0.4, and 0.6 kg/m^3 with the associated proportion of feedstock's mass and cross-sectional area of ventilation pipes, transforming the air flow rates to be 0.05, 0.14, and 0.23 m/s, respectively. Recirculation of leachate was carried out from day 1-6. All the experiments lasted 15 days.

The purpose of the leachate recirculation on the decomposition of market waste in the biodrying process can be the stage that Lysimeter 1 was the low aeration and density conditions that are close to anaerobic digestion similar to landfill conditions [40] – leachate recirculation helps to provide leachate volume reduction and leachate dilution; Lysimeters 2 and 3 were the sufficient aeration consistent with stoichiometric value – leachate recirculation supports the acceleration of degradation processes associated with high oxidizable organic matter from recirculated leachate, minimize pollutants by provide a stabilized leachate generation. To prevent the low oxidizable organic matter from returning to the digestion process, the recirculation period was limited to day 6 [41].

Operating mode

This experiment used a 1.5-meter-high lysimeter for biodrying processes, incorporating leachate recirculation. A metal plate stabilized the raw material, while ventilation pipes, condensation pipes, and blowers created airflow. Leachate was collected using a U-trap pipe, and interior gas was measured using 20mm diameter perforated pipes. This apparatus was created using data from a study by Bhatsada et al. (2023). Figure 1 illustrates the lysimeter's schematic design in more detail.

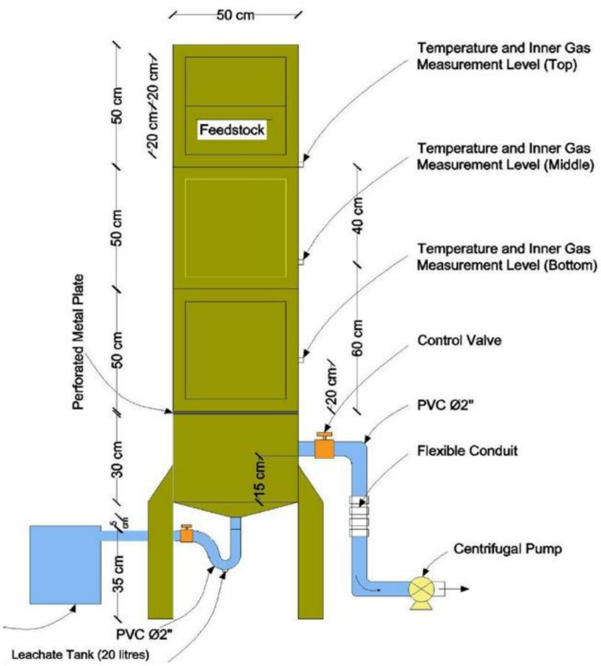


Figure 1 Schematic of lysimeter design [42, 43]

Monitoring parameters and performance indicators

Temperatures were measured at 20, 60, and 100 cm heights using type-K thermocouples (temperature range: -270 °C to 1,327 °C). Another sensor was inserted outside the lysimeter to detect the ambient temperature. A data logger (Graphtec GL200A Midi Data Logger; DATAQ Instruments, Akron, OH, USA) was used to record the temperature hourly. The concentration of O_2, CO_2, CH_4, hydrogen sulfide (H_2S), and Nitrogen (N_2) at three levels within the lysimeters, in the ambient air, and the exhaust were measured daily with a Biogas 5000 gas analyzer (Geotechnical Instruments International, Ltd., Berlin, UK). In addition, the ambient air was concentrated in 0%, 0%, 20.9%, 0 ppm, and 79.1% of CH_4, CO_2, O_2, H_2S, and N_2, respectively. The feedstock height inside the lysimeter was measured vertically with a tape measure. The daily control of aeration rates in each lysimeter (m^3/kg/day) were measured in air velocity through the 1 × 3 cm hole perforated pipe using an airflow meter.

Temperature integration (TI) index was used to calculate the accumulated daily difference between the matrix and ambient temperatures.

$$TI = \sum_{i=1}^{n}(T_m - T_a).\Delta t \qquad (1)$$

where T_m and T_a are the matrices and ambient temperatures at day I, Δt is the time element [37].

The aeration and leachate flow were in the same direction that was introduced at the top to the bottom of the lysimeter. However, the end location was different following Figure 1. The all-leachate generation in the collected system was daily upward, and some of them were accumulated in the lysimeter. To determine the leachate recirculation pattern, the accumulation of leachate within the process can also be considered.

$$L.A_n = L.\ Gen_n + L.Re_{n-1} \qquad (2)$$

where $L.\ A_n$ is leachate accumulation in n days, and $L.\ Gen_n$ and L. Ren-1 are leachate generation and recirculation.

The settlement rate within the waste pile can be determined with changes in elevation during biodrying. The elevation change can be calculated using daily measurements of the waste height.

$$\text{Elevation Change (\%)} = (H_{n-1} - H_n / H_{n-1}) \times 100 \qquad (3)$$

where H_n is the waste height (m) in n days, and H_{n-1} is the waste height (m) from the previous day's measurement.

Statistical analysis

The significant difference in three trials was performed with 95% confidence using one-factor variance analysis (ANOVA) in Excel 2010 to assess the temperature differences between the layers and the ambient environment with a significance level (cutoff p-value) of 0.05 [33].

Results and Discussion

Leachate recirculation

The biodrying of market waste using a zero-discharge system involved collecting and returning leachate from each lysimeter daily from day 1 to day 6 as shown in Figure 2. The amount of leachate accumulation was equal to that of generation on day 7 and afterward. Lysimeter 1 started producing on day 2, while Lysimeters 2 and 3 had significantly higher leachate generation and return amounts. This phenomenon indicates that although the leachate generation experienced

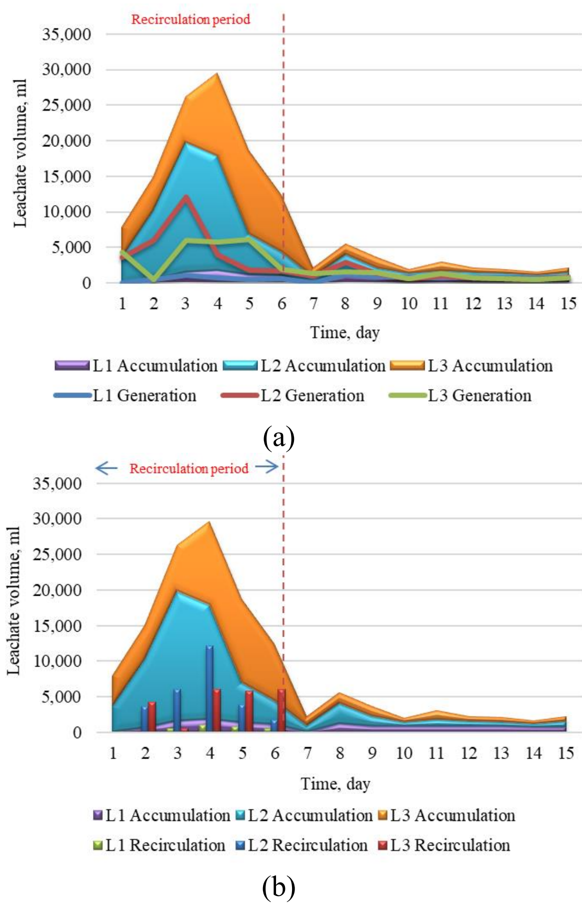


Figure 2 (a) Leachate accumulation vs generation and (b) Leachate accumulation vs recirculation during biodrying (L1 = lysimeter 1, L2 = lysimeter 2, L3 = lysimeter 3)

a declining trend due to high-temperature formation within the waste matrix, much higher volumes were accumulated due to recirculation. During the non-recirculation period, leachate generation decreased steadily to a stable generation quantity. Bilgili et al. (2012) investigated the effect of leachate recirculation in four landfill test cells. The quantity of leachate decreased by 29.7%, 37.8%, and 22.5% in three recirculated cells, while there were no changes in the quantity of the control cell. The more significant decrease in leachate quantity can be explained by the effect of evaporation of the waste temperature and the effect of air-drying the waste [44].

The accumulated leachate volume was superior to other feedstocks since market waste mainly comprises organics with high MC. Sutthasil et al. (2022) discovered that waste with high initial MC levels of 70-80% showed abnormal leachate formation and evaporation. This could be due to the high water content of the waste, which created an overflow of leachate outflow and impaired drying effectiveness [45]. According to Awasthi et al. (2018) and Wijerathna et al. (2024), moisture levels exceeding 80% can cause anaerobic respiration, limit compost porosity, and produce leachate and unpleasant odors [46, 47]. Ma et al. (2021) reported that the larger amount of leachate recirculation increased the waste MC and thus was suitable for microorganism growth in semi-aerobic reactors [48]. Ma's study supports the present study that sufficient aeration stimulates the decomposition (high leachate generation) by Lysimeters 2 and 3. Luo et al. (2019) varied the concentration of leachate recirculation effects on solid waste degradation by observing that the organic reduction increased gradually with increasing water replacement [49]. The study found that leachate generation increased due to high accumulation and recirculation but decreased after day 3 and continued until day 6. This correlation mirrors Calabrò et al.'s (2018) study, suggesting that leachate recovery mirrors generation as long as it remains at the landfill bottom [50]. Consequently, the present study decreased the belatedness trend of leachate recirculation due to some leachate accumulating in the bottom waste.

Temperature evolution during biodrying

Temperature evolution is divided into three stages: heating, high-temperature maintenance, and cooling. Heating rapidly raises the temperature, while high-temperature maintenance is steady, affecting water evaporation and organic deterioration [51, 52]. During the process of biodrying market waste, the temperature evolution was quite different from a typical biodrying system, when the heating phase was reached within days 1-2, followed by the declining phase (days 3-5) and the stable phase (days 6-15) (See Figure 3). This phenomenon can be explained by the recirculation of leachate into the lysimeters from day 1 to day 6. Moreover, temperature patterns separate the different stages of its evolution; mesophilic is characterized by bacterial bioactivity and temperatures starting from ambient temperature and a gradual rise to between 35 °C to 40 °C; transitions into the thermophilic phase where waste achieves maximum evolution at temperatures of 55 °C to 70 °C [52]. While microbial activity can enhance the decomposition of organic matter [53], providing a condition suitable for thermophilic microorganisms' growth could accelerate the thermophilic phase's start, leading to an increase in the biodegradation of organic matter [54]. Lysimeter 1 reached the thermophilic stage on day 2 in an experiment due to a lower aeration rate and leachate influence, unlike other lysimeters. The results indicated a high biodegradation process from substantial microorganism metabolism, and stability was achieved in the mesophilic phase after day 5. The study's findings were consistent with Zaman, B. et al. (2021). This indicated a temperature rise from around 43 °C on the second day, followed by a drop to 39 °C on the third day, utilizing a low airflow of 2.88 m^3/kg/day [38, 55]. The middle layer of Lysimeter 1 has optimal conditions for microbial activity, moisture reduction, and organic matter decomposition, leading to increased heat production during biodrying. The top and middle layers have higher temperatures and larger waste weights, while the bottom layer collects water, indicating insufficient microbial activity for biological stability. This is consistent with the findings of Jalil et al. (2016), who used solid waste samples such as food scraps, papers, plastics, and wood. This denotes a lack of sufficiently large microbial activity required to achieve circumstance biological stability following the biodrying procedure [54]. Lysimeter 3's top and middle layers were cooler due to increased ambient heat transfer, while the intermediate layer's maximum aeration rate of 0.6 m^3/kg/day enhances dry air and heat dissipation.

The temperature fluctuations in layers were explained by the recirculation of large amounts of leachate at a high aeration rate during the heating phase. Sutthasil et al. (2022) investigated the biodrying process of domestic waste in tropical Asian climatic conditions by adding 135 ml/day of water for 15 days. The study observed that the temperature increased from days 1-2 and remained at approximately 30 °C until day 7. Then, the temperature ascended again on day 8, shifting suddenly to the declining phase [45]. Temperatures in all lysimeters dropped until day 5, stabilizing, indicating a certain equilibrium in the biodrying process, possibly suggesting the completion or stabilization of specific stages. Kumar et al. (2008) investigated the impact of leachate recirculation in waste in a bioreactor. They observed that the starting temperature recorded at various depths lowers with leachate recirculation, demonstrating the cooling effect of leachate recirculation [56]. Biodrying increases microbial activity due to high temperatures and rich organic materials. As substrates decrease and microbial populations saturate, decomposition rates stabilize, leading to thermal equilibrium. The optimum temperature range for biodrying in this experiment was found to be 45-60°C, enhancing moisture evaporation and stabilizing organic matter. Temperatures below this range may prolong the process, while temperatures above it can cause excessive heat generation. Based on the results, we can conclude that the experiment can be terminated after day 10 instead of going until day 15.

The temperature differences between waste layers were analyzed in terms of the homogeneous temperature layers. A p-value > 0.05 implies acceptance of the null hypothesis, suggesting equality in mean temperatures among the layers. However, a p-value of ≤ 0.05

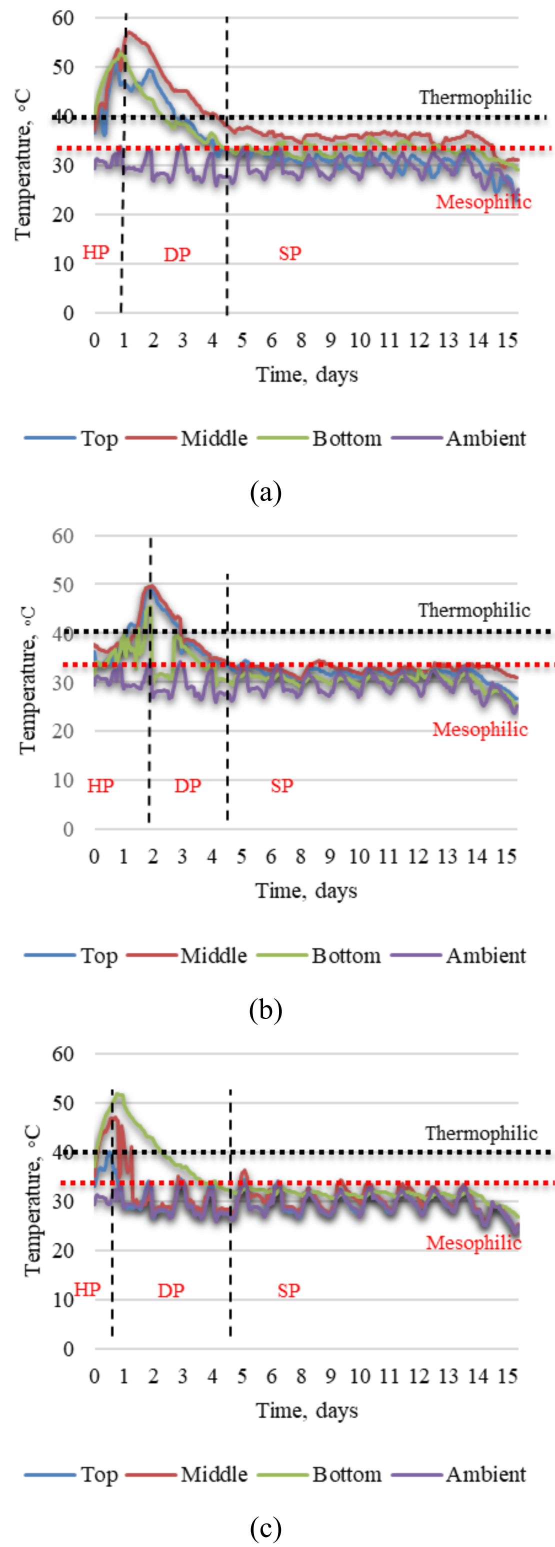


Figure 3 Temperature evolution during the biodrying process for (a) lysimeter 1, (b) lysimeter 2, and (c) lysimeter 3 (HP, Heating Phase, DP, Declining Phase, SP, Stable Phase)

indicates substantial variations in mean temperatures among the layers. For Lysimeter 1, the temperature differences between the top and bottom layers ($p < 0.05$) were found to be statistically significant in the heating phase. At the same time, there were no differences in the top-middle and middle-bottom layers, showing homogeneity. During the declining phase, the top and bottom layers showed similar temperature distributions ($p = 0.349$). In Lysimeter 2, the temperature between the top and middle layers showed similar temperatures in the heating and declining phases, while statistically significant temperature differences were observed in other layers. However, in Lysimeter 3, there were similar temperatures only in the middle and bottom layers for the heating phase and the top and bottom layers for the stable phase. Regarding the overall phase, the three layers in all lysimeters had p-values lower than 0.05, showing significant temperature differences.

Payomthip P. et al. (2022) found that excessive aeration increases heat dispersion in waste materials' top and middle layers. Meanwhile, continuous aeration achieves effective heat dispersion, resulting in high-temperature uniformity during biodrying. The same scenario can be seen in Lysimeter 3, indicating excessive aeration, while the other lysimeters had uniform temperature distribution.

Temperature integration index

The TI indicates heat accumulation values during the biodrying process were estimated and shown separated in recirculation and non-recirculation periods based on temperatures at the bottom layer because of minimal displacement due to volume reduction. Figure 4 (a) shows the TI value in the recirculation period that Lysimeter 1 had the greatest TI value (2,063 °C), followed by Lysimeters 3 and 2, which had 1,580 °C and 797 °C values, respectively. The TI values were significantly lower than those reported in previous research, with higher TI values associated with longer biodrying periods. Payomthip P. et al. (2022) obtained TI values of 365.6 °C, 346.2 °C, and 318.0 °C after seven days of biodrying, but Shao et al. (2012) reported TI values ranging from 432.0 to 542.0 °C after 14 days of processing [28]. Waste materials can self-heat due to microorganisms and biodrying treatment duration, resulting in lower non-recirculation periods and lower daily temperature evolution.

The TI phase of the three biodrying phases is compared in Figure 4(b). The study revealed that Lysimeter 1 had higher TI values during the heating phase, while Lysimeter 1 and 3 had similar values during the heating and declining phases. The findings of the study associated with the work of Bhatsada et al. (2023) when the highest TI values were found in the declining phase and a lower aeration rate having a higher TI due to the airflow rate conducive to heat accumulation [42]. The higher airflow rate increased heat loss to the exhaust air through ventilation.

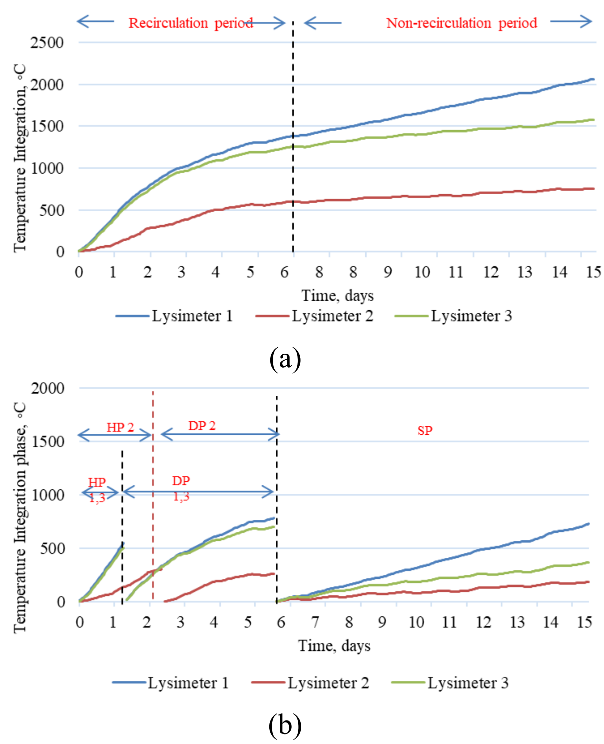


Figure 4 (a)Temperature integration index (b) temperature integration index by phase during the biodrying process (HP, Heating Phase, DP, Declining Phase, SP, Stable Phase, 1= Lysimeter 1, 2= Lysimeter 2, 3= Lysimeter 3)

Gas generation and concentration

Various factors, including waste properties and operating parameters, cause this variation in gas generation. CH_4 and CO_2 are the significant gases produced during anaerobic breakdown. In contrast, aerobic decomposition, which

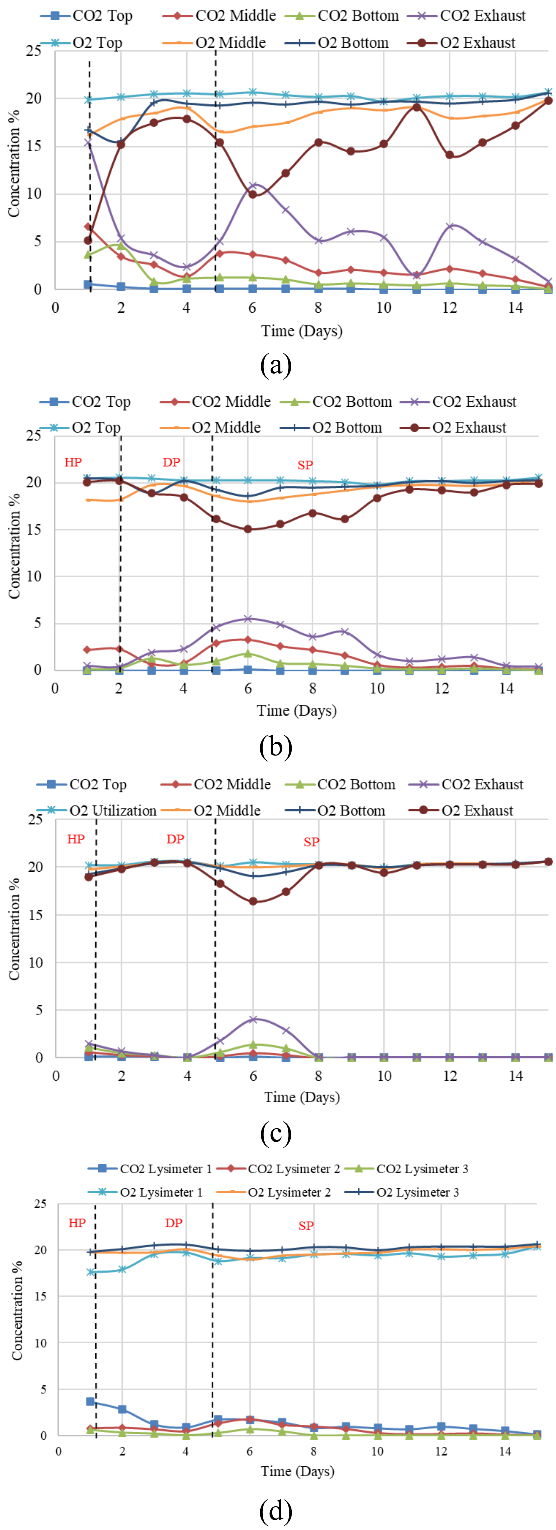
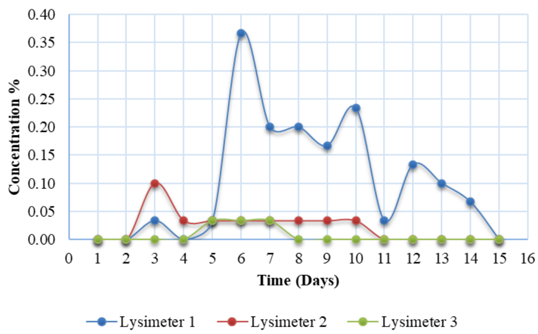


Figure 5 CO_2 and O_2 concentration during the biodrying process for (a) Lysimeter 1, (b) Lysimeter 2, (c) Lysimeter 3, and (d) their average concentration (HP, Heating Phase, DP, Declining Phase, SP, Stable Phase)

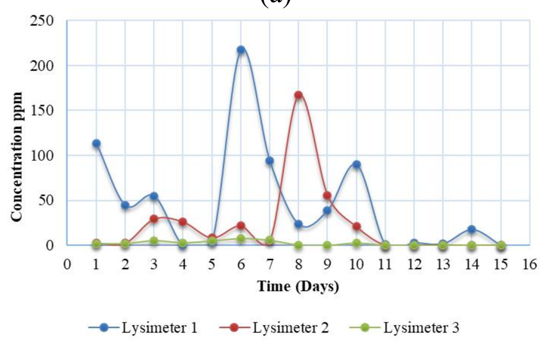
requires O_2, produces primarily CO_2 [57]. The optimum O_2 concentration for aerobic breakdown is between 15% and 20% [51]. Lower O_2 concentrations would result in inefficient, anaerobic conditions; however, the quantities utilized in this study guaranteed that microorganisms had a steady O_2 supply to continue metabolic activity. Figure 5 shows the gas generation and concentration at all lysimeters' top, middle, and bottom levels.

The 15-day experiment in Lysimeter 1 revealed unique CO_2 concentration patterns across vertical layers. The top and middle layers had comparable CO_2 levels, but the lower layer showed a diverging pattern, starting higher on day 1 and decreasing until the end. This scenario is similarly similar to the work by Sutthasil et al., (2022), in which facultative biodegradation was developed at the start of the operation with a sudden increase in CO_2 from day 2-5 during the biodrying process with water addition [45]. The experiment showed low CO_2 levels in Lysimeters 2 and 3, significantly increasing the lower layer. Lysimeter 3 had the lowest CO_2 levels, indicating lesser microbial activity. The overall CO_2 concentration trend showed high levels in the bottom layer for the first two days, but activity remained low when leachate was returned. The recirculation of leachate led to a jump in CO_2 concentrations, progressively falling until the experiment ended. The content of exhaust CO_2 was significantly higher than the ambient CO_2, which is only about 400 ppm. This significant difference indicates that ambient CO_2 has no substantial impact on the results of this study.

Anaerobic breakdown of organic materials produces CO_2, H_2S, and CH_4 gases. Lysimeters show fluctuating CH_4 levels, with Lysimeter 1 having the highest levels, as shown in Figure 6. Low aeration and leachate recirculation increase CH_4 levels. Leachate recirculation resulted in higher degradation of the original C content in the solid waste and increased C emissions in the form of CH_4 [58]. The study confirms Francois et al. (2007) 's findings, revealing increased CH_4 and CO_2 production in columns undergoing leachate recirculation, suggesting accelerating degradation processes [59]. Top et al. (2019) found that leachate recirculation and aeration in



(a)



(b)

Figure 6 (a) CH_4 and (b) H_2S concentrations during the biodrying process

landfill cells improve gas generation, reduce volume, enhance waste breakdown, and enhance leachate quality [60]. Tran et al. (2014) studied MBT techniques. Recycling of leachates and extra aeration are known to reduce emissions to standard levels in a reasonable amount of time [61]. Anaerobic digestion leachate recycling techniques were investigated by Kusch et al. (2012). The results indicate that intermittent return was not superior to continuous flow, implying that if methanogenesis is the rate-limiting phase, continuous leachate recirculation at start-up may be detrimental [62].

Elevation change and weight loss

The experiment measured waste matrix elevation daily, showing a significant decrease in waste height from days 1-5. Reduced waste height during heating and declining phases led to uniform temperature distribution, enhancing heat penetration and microbial activity, thus optimizing biodrying efficiency. Figure 7 shows the relationship between elevation change and leachate accumulation during biodrying. The maximum waste height reduction was observed on days 1-3 in all lysimeters, with Lysimeter 1 showing the highest reduction of 50.83%. Factors contributing to this decrease include residual heat from earlier stages, leachate recirculation, and compaction due to gravitational force and water filling in waste pores.

The weight of the matrix was only measured on the first and last days of the experiment. The highest weight reduction was seen in Lysimeter 2 (72.39%), followed by Lysimeters 3 and 1 (69.94% and 58.56%). However, the output of leachate was rigorously monitored throughout the period.

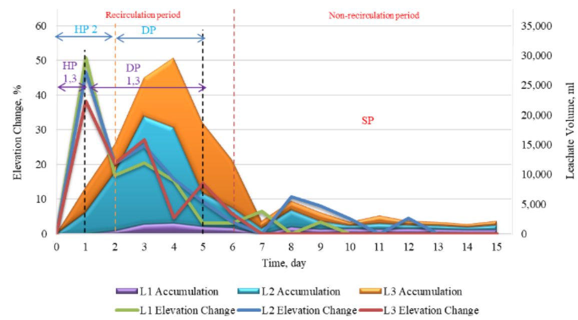


Figure 7 Relationship between elevation change and leachate accumulation during the biodrying process (HP, Heating Phase, DP, Declining Phase, SP, Stable Phase)

Product characteristics

Biodrying involves microorganisms breaking down organic substrate to produce water, gasses, and heat, causing mass loss through biodegradation, moisture removal, and leachate leakage due to waste's higher MC [63]. Furthermore, the gravimetric outflow of water in leachate should be regarded as a parameter influencing wastewater reduction [45].

After the procedure was completed, the final MC and LHV were measured to determine the efficiency of the biodrying process. The initial MC of all lysimeters was around 90.19% by weight. However, following the process, the ultimate MC varied, with decreases of 5.97%, 7.97%, and 2.47% for Lysimeters 1, 2, and 3, respectively, indicating that Lysimeter 2 produced the highest reduction. According to Ngamket et al. (2021), the feedstock should be dried as much as possible with a higher MC reduction to retain the energy content [64]. The LHV of the product for Lysimeters 1, 2, and 3 were 198 kcal/kg, 169.5 kcal/kg, and

134 kcal/kg, respectively. Regarding heating value increases, Lysimeter 1 had the highest increase with 317%, followed by Lysimeters 2 and 3 (257% and 182%). Sutthasil et al. (2022) found that LHV could not be significantly enhanced due to the remaining MC in the waste. The heating value of waste after biodrying for 15 days was lower than its original value in the experiment with water addition during the entire period. As a result, biodrying during water addition was not possible [45]. According to Zhang et al. (2009), organic waste with a high water content and heat from biodegradation is insufficient to evaporate water, making it difficult to lower the water content sufficiently [37].

The biodrying experiments on market waste used three lysimeters with different aeration rates. A comprehensive comparison involving CO_2 concentration, weight loss, leachate volume, and temperature profiles across the lysimeters was conducted. Although biodrying aims to treat market waste using the heat generated from microbial activities under aerobic conditions, excessive moisture addition and returning leachate for six consecutive days hindered the drying mechanism. This leads to sudden heat loss and leachate drainage. Feng et al. (2017) investigated the combination of spray and vertical well (VW) recirculation systems. VW recirculation may not be a viable solution since recycled leachates run directly down to the landfill's leachate collecting system, squandering the recycled leachate. One method for reducing leachate misapplication is to combine a spray VW system with a horizontal leachate flow to allow more MSW to pass through [57].

Lysimeter 1 consistently outperformed in these analyses, indicating its efficiency in the biodrying process. Lysimeter 1 achieved a substantial reduction in MC (5.97%) compared to Lysimeter 2 (7.97%) and Lysimeter 3 (2.47%). The lower aeration rate in Lysimeter 1 appears to have effectively contributed to a more efficient moisture reduction process. The results suggest that the controlled aeration rate in Lysimeter 1 contributed to a more favorable organic content transformation, enhancing the final product's heating value with an LHV increase of 317%. In conclusion, Lysimeter 1, employing the lowest aeration rate, stands out as the most favorable configuration for biodrying market waste based on superior moisture reduction and heating value increase.

Conclusion

This investigation elucidates the efficacy of biodrying in enhancing the LHV and reducing the MC of market waste, focusing on the pivotal role of the aeration rate. Our findings demonstrate that waste abundant in degradable material benefits from biodrying under continuous negative ventilation, where aeration rate optimization is crucial for maximizing biodegradation and thermal efficiency. Initial results showed promising temperature increases due to high organic loads, yet leachate recirculation emerged as a significant impediment to microbial activity, warranting future exclusion from the biodrying process. Significantly, while diminished aeration rates were advantageous for heat preservation, they required careful management to prevent detrimental shifts in moisture and organic material levels. Despite Lysimeter 2 achieving the highest reduction in MC, it fell short of meeting the heating value standards for RDF, highlighting the necessity for further refinement of operational practices. Therefore, future research should refine aeration strategies to comply with industry standards and improve the sustainability of waste management practices. This involves fine-tuning aeration rates and possibly incorporating alternative practices that do not hinder microbial activity. Exploring innovative aeration techniques and their integration with zero-discharge systems could further improve the efficiency of biodrying processes. This study's insights into the interplay between aeration rate and biodrying efficiency pave the way for more effective waste treatment solutions, with implications for environmental sustainability and resource recovery.

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