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Research Article

# The effect of aeration rate and feedstock density on biodrying performance for wet refuse-derived fuel quality improvement

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**Abstract**. This study investigates the effect of aeration rate and feedstock density on the biodrying process to improve the quality of type 2 wet refuse-derived fuel. The aeration rate and feedstock density were varied to investigate these parameters' effect on the system's performance. The experiments used 0.3 $m^3$ lysimeters with continuous negative ventilation and five days of operation. In Experiment A, aeration rates of 0.4, 0.5, and 0.6 $m^3$/kg/day were tested with a feedstock bulk density of 232 kg/$m^3$. In Experiment B, the optimum aeration rates determined in Experiment A (0.5 and 0.6 $m^3$/kg/day) were used, and the feedstock density was varied (232 kg/$m^3$, 250 kg/$m^3$, and 270 kg/$m^3$). The results showed that an aeration rate of 0.5 $m^3$/kg/day was the most efficient for a feedstock density of 232 kg/$m^3$; when the aeration rate was increased to 0.6 $m^3$/kg/day, a feedstock density of 250 kg/$m^3$ was the most effective. However, a feedstock density of 270 kg/$m^3$ was not found to be practical for use in the quality improvement system. When the feedstock density is increased, the water in the feedstock and the water resulting from the biodegradation process cannot evaporate due to the feedstock layer's low porosity, and the system requires an increased aeration rate. Furthermore, the increase in density scaled with increased initial volatile solid content, initial organic content, and initial moisture content, which significantly impacted the final moisture content based on multivariate regression analysis.

**Keywords:** Waste to energy, Refuse-derived fuel, Biodrying index, Temperature integration, Alternative fuel


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## 1. Introduction

Nowadays, many essential problems are still existing throughout Thailand's municipal solid waste (MSW) supply chain. There is no law enforcing the waste generators to separate the waste before disposal. As a result, people have still disposed of their waste without sorting it (Itsarathorn *et al.* 2022). Moreover, the waste generation rate in 2030 is projected to be 84,070-95,728 ton/day, an approximately 10-25% increase compared to 2018 (Pudcha *et al.* 2022). Environmental concerns linked to rising emissions have been immensely discussed. It is no longer surprising that global warming is the most critical issue threatening our world today (Adebayo and Akinsola, 2021). The conversion of non-recyclable waste materials into electricity and heat represents a viable approach for waste management and generating renewable energy (Buyukkeskin *et al.* 2019). There are numerous social and industrial benefits from the waste-to-energy (WTE) conversion process; for example, this approach can help to increase waste management capacity, reduce health and environmental problems, and decrease the usage of imported fossil fuels, thus reducing energy costs for the industrial sector and helping to achieve energy security (Itsarathorn *et al.* 2022; Munir et al. 2023). In addition, this method can minimize methane generation from landfills, thereby reducing greenhouse gas (GHG) emissions (U.S. Environmental Protection Agency, 2016; Tippichai *et al.* 2023).

The cement production process uses fossil fuels as its primary fuel. Coal prices increased from US$178/ton in 2021 to US$400/ton in 2022 (Wulandari, 2022) directly affecting total cement production costs. In addition, cement plants also produce GHG emissions, especially carbon dioxide. These issues have led to a joint commitment by the global industrial sector to reduce GHG emissions. Thailand has set a target to reduce its GHG emissions by 20–25% by 2032 (TCMA, 2016). For the cement industry, the use of alternative fuels is key to solving fuel price problems and achieving GHG emission reduction goals.

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Refuse-derived fuel (RDF) is fuel created from certain types of waste, such as municipal solid waste and other combustible refuse (Kerdsuwan *et al.* 2016). RDF production is a technology for processing waste into an alternative fuel to replace coal (Hajinezhad *et al.* 2016). It can be classified into seven groups. RDF-1 is the minimum processing of MSW to remove large bulky material. The combustible fraction in RDF-1 is sorted and shredded to a coarse particle size of approximately six cubic inches or less, classified as RDF-2. RDF-3 is finer than RDF-2 as the material used in this fuel type is shredded to a particle size smaller than two inches. Powdered RDF which 95% of its weight can pass through a 0.035 in. square screen is RDF-4. When RDF is densified into pellets, slugs, briquettes, or other similar shapes, categorized as RDF-5. RDF-6,7 are processed into a liquid and gaseous fuel, respectively (Sommerlad *et al.* 1998). To be used as energy in the industrial sector, RDF is expected to have good quality, especially high heating value, low humidity value, and no contamination with incombustible material (Itsarathorn *et al.* 2022). Reject from the RDF production process, which mainly contains organic portion and food waste, can be managed by using bacteria for biogas generation and composting (Idris *et al.* 2021).

Although, the government has promoted the 3Rs (Reduce, Reuse and Recycle) concept and centralized facilities focusing on waste utilization and WTE technologies through the National Solid Waste Management Master Plan (2016–2021) (Chommontha *et al.* 2022). However, 52% of fresh MSW has still been disposed of by landfilling and only 12.63% is produced as RDF-2,3 and used in cement plants (Itsarathorn *et al.* 2022). Besides, the rate of alternative fuel usage including RDF in 2020 for cement plant in Thailand was only 17.38% (SCG, 2021). This figure is relatively low compared to cement plants in other countries, with RDF usage values of 83% and 47.8% in the Netherlands and Switzerland, respectively (Rahman *et al.* 2013). The primary reason for the limited alternative fuel usage in Thailand's cement plants is its potential to impact the quality of the clinker directly (Ngamket et al. 2021). Gendebien et al. 2003 reported that the effects of co-incinerating RDF compared with no use of RDF are confirmed for chlorine, lead, and copper, where concentrations in the clinker were generally 2 to 5 times higher. It is important to note that the RDF used in this study was sourced from two standardized production sources in Germany, which produced high-quality RDF. When low-quality RDF is employed, characterized by high moisture content and low heating value, it may adversely affect the production process and clinker quality. Therefore, a simple technology with low costs and short operating times must be developed and applied to improve the quality of RDF.

Various studies have also looked at the methodologies, effectiveness, and profitability of various drying techniques for improving the quality of solid wastes produced in the industrial, municipal, and agricultural sectors. The most common drying methods currently in use worldwide are biodrying, solar drying, biostabilization, and thermal drying. Thermal drying can make the highest drying temperature and provide faster drying efficiency in the shortest time. This method can achieve 100% moisture reduction, 87% weight reduction and 70% volume reduction within 6-10 hours. However, the cost of investment, operation, and energy are significantly high, so it impacts the economic value. Biostabilization process can reduce the weight of MSW by 85%, but takes the longest period up to 100 days. Solar drying can make a shorter drying time and a slightly higher drying temperature than biodrying. However, it is also most suitable for countries that have enough solar radiation and has higher operating cost. Consequently, biodrying is an intriguing drying method when various elements are considered. (Tun and Juchelková, 2019).

Biodrying is a natural, automatic heating process in which the drying process is enhanced by biological heat released from the decomposition of organic matter (Yang *et al.* 2017; Maia *et al.* 2023). Ngamket et al. (2021) concluded that pilot-scale solar greenhouse biodrying with positive ventilation at an aeration rate of 0.78 $m^3$/kg/day can improve the quality of MSW for RDF production within 7–10 days to meet the requirements of cement plants. Cai *et al.* (2013) investigated the effects of forced air volume on water evaporation from a sewage sludge biodrying pile. Their study revealed a significant positive correlation between air volume and water evaporation. In addition, forced aeration was found to control the pile temperature and improve evaporation, thus making it the key factor influencing water loss during sewage sludge biodrying. Payomthip *et al.* (2022) studied biodrying system performance using a pre-shredded MSW feedstock with a density of 300 kg/$m^3$. They supplied air to the system at rates of 0.5–1.0 $m^3$/kg/day and found that an aeration rate of 0.5 $m^3$/kg/day achieved the best efficiency when improving RDF quality to meet the required standards. Sen & Annachhatre (2015) reported that biodrying cassava peel mixed with sludge waste resulted in a final moisture content (MC) of 24.0% at an airflow rate of 0.72 $m^3$/kg/day. Colomer-Mendoza *et al.* (2013) found that the thermophilic phase was activated during garden waste biodrying at aeration rates below 2.88 $m^3$/kg dry matter/day. Xin *et al.* (2023) expedited the metabolic activity thermophiles stage by intermittent aeration to accelerate kitchen waste dehydration for recycling organic waste applications.

Most previous studies on biodrying systems for RDF quality improvement have used MSW as feedstock with an operating time of at least seven days. This is a relatively long timescale for commercial-scale implementations, and there is also a current lack of studies to date that have investigated feedstock density in biodrying systems. Therefore, an area of significant interest is the study of wet-RDF quality using a biodrying system with a shorter operating time (five days in the current study) and an investigation of the relationship between parameters, especially the feedstock's density and aeration rate. Although the efficiency of negative and positive ventilation in feedstock quality improvement is similar, however, negative ventilation also provides continuous aeration and approach achieves better performance in the biodrying process than positive ventilation, in which unsatisfactory outcomes such as condensation on the surface of the feedstock and odor problems have been reported in previous studies (Ngamket *et al.* 2021; Payomthip *et al.* 2022; Tom *et al.* 2016). Thus, to address these shortcomings, this study aims to investigate the effects of aeration rate and feedstock density under negative ventilation on the performance of the biodrying process for RDF quality improvement.

## 2. Materials and methods

### *2.1 Lysimeter description*

All of the experiments were performed in lysimeters constructed from stainless steel with a height of 2 m, a width of 0.5 m, and a length of 0.5 m. The lysimeters were covered by 2.5 cm-thick polyurethane foam to prevent heat loss. Some parts of the side of the equipment were constructed from hard, clear plastic to measure the feedstock's daily height change. An aeration system was set up at the base of each lysimeter to ensure continuous airflow during the operation. The ventilation pipes were 5.08 cm in diameter and 14 cm in length and were connected under the perforated metal plate to perform aeration, and a 1 cm diameter perforation was made at the center of the ventilation pipe to measure the airflow rate. A U-trap pipe was

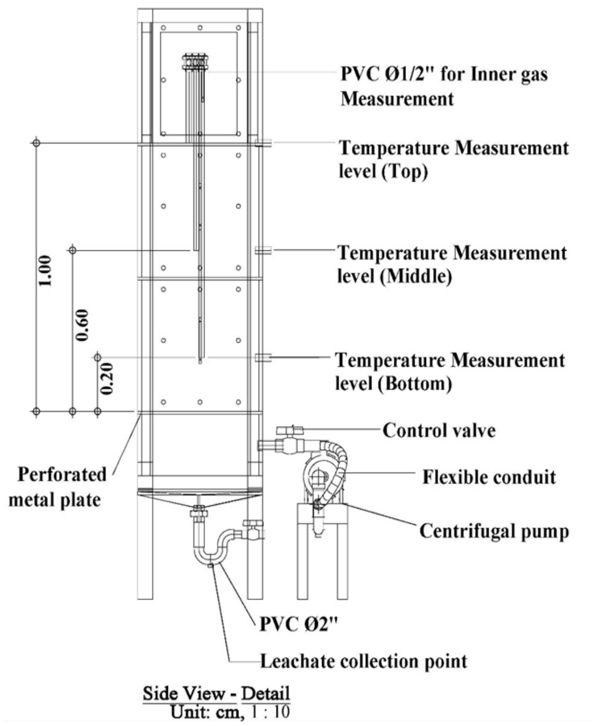



**Fig. 1** Biodrying lysimeter

connected to the ventilation pipe to collect the leachate and condensation water which accumulated at the bottom of the lysimeter. To measure the inner gases and temperature, which varied due to bioactivity during the experiment, 20 mm diameter PVC pipes were embedded at heights of 0.2 m (bottom level), 0.4 m (middle level), and 1 m (top level) above the base of the lysimeter. The design of the lysimeter is shown in Figure 1.

*2.2 Feedstock source and arrangement*

Fresh MSW from Bangkok metropolis about 1,500 tons/day has primarily sorted for the organic material to produce organic fertilizer. The remaining portion from the fertilizer production process was a combustible component of 400 tons/day, used as a raw material to produce RDF- 2. The production processes were both manual and mechanical sorting, which consists of a bag opener, air classifier, magnetic separator, and spinner. Each machine was designed to separate the individual components that are mixed in the raw material. The product volume of RDF-2 was about 170-200 tons/day, 50% yield. This material was used as the feedstock for this study in all experiments. This process is wildly used to sort MSW to produce RDF in Thailand, however the production capacity of each project is different depending on the amount of incoming MSW. About the chemical quality, average low heating value (LHV) was typically between 3,500 and 4,200 kcal/kg, while the MC was generally over 35%. The RDF, both as a feedstock and product, was sampled using the quartering method according to the ASTM D5231-92 standard and sorted manually to characterize its composition. Furthermore, samples of both feedstock and product were collected to determine their chemical properties. The MC was analyzed per the ASTM D7582 standard, the heating value was assessed per the ASTM D5865 standard, and the volatile solid content assessment followed the ASTM D7582 standard.

**Table 1**
The initial conditions of Experiment A.

| Condition | AR0.4 | AR0.5 | AR0.6 |
|---|---|---|---|
| Feedstock weight (kg) | 69.60 | 69.60 | 69.60 |
| Air flow rate (m/s) | 0.16 | 0.21 | 0.25 |

*2.3 Experimental design*

All the experiments were performed for five days. Air was continuously supplied to the system by negative ventilation. The experiments were separated into two main types based on the study's objectives, as described below.

Experiment A (Exp. A): In this experiment, the aeration rate was varied to assess the optimum aeration rate for wet RDF biodrying, which makes the biodrying system has the most efficient and feedstock quality is the most developed. The aeration characteristics were chosen based on the assumption that: 1) increased aeration can facilitate rapid drying of moisture from the feedstock, resulting in a drier product, 2) low aeration rates can evaporate the moisture from feedstock while allowing the system's temperature to reach the thermophilic phase, and 3) optimizing the system's aeration can ensure an acceptable final product while also minimizing energy consumption. Accordingly, the initial aeration rate was set as 0.5 $m^3/kg/day$ (AR0.5) based on the optimum aeration rate identified in a previous study by Payomthip *et al.* (2022) and varied to 0.4 $m^3/kg/day$ (AR0.4) and 0.6 $m^3/kg/day$ (AR0.6). The feedstock bulk density in this experiment was 232 $kg/m^3$. The initial conditions of Exp. A are presented in Table 1.

Experiment B (Exp. B): The material's porosity enables air to enter the feedstock layer, absorb moisture, and carry the internal water to the atmosphere; hence, the feedstock density is another essential factor in the biodrying process, directly affecting the system's performance and the feedstock quality improvement process. To investigate the effect of aeration rate and feedstock density on the system's performance, density values of 232 $kg/m^3$ (Density 232) as the bulk density, 250 $kg/m^3$ (Density 250) as the median density between the bulk density and the maximum density, and 270 $kg/m^3$ (Density 270) as the maximum density were chosen. The optimum aeration rate from Exp. A was chosen as the initial aeration rate, and the initial conditions are presented in Table 2.

*2.4 Experimental monitoring*

Type-K thermocouples were used to measure the temperature inside the feedstock layers. These were embedded at three elevations in the lysimeter (bottom, middle, and top). Another thermocouple was used to measure the external air temperature. All of the temperature measurement points were recorded hourly using a mini data logger (Graphtec GL220). The concentrations of carbon dioxide ($CO_2$) and oxygen ($O_2$) were determined using a Biogas 5000 instrument (Geotech, United Kingdom) once daily at the same levels as the temperature measurements. A digital crane scale was used to weigh the lysimeters containing the feedstock to determine the weight change, and the feedstock height was measured daily using the scale on the lysimeter.

*2.5 System efficiency indicators*

The system temperature and gas formation were examined to indicate the biodrying system's performance and quality improvement efficiency. The temperature integration (TI) was also calculated to assess the hourly temperature accumulation inside the feedstock layer, and the biodrying index (BI) was calculated to determine the organic content and water content loss during the process. The TI and BI values can be calculated using the equations below.

$$TI = \sum_{i=1}^{n}(T_{fi} - T_{ai}) \quad (1)$$

Where Tfi is the average temperature in the feedstock layer, and Tai is the ambient air temperature on day i (Ngamket *et al.* 2021).

$$BI = \frac{OL}{WL} \quad (2)$$

Where OL is the weight of organic loss; and WL is the weight of water loss (Bhatsada *et al.* 2023).

## 3. Results and discussion

### *3.1 Experiment A*

In Exp. A, the feedstock had an LHV of 2,936 kcal/kg and an MC of 45.68%. The combustible material constituted 71% of the feedstock, while the degradable organic portion and other materials comprised 20% and 9%, respectively.

#### *3.1.1 Temperature profile*

The biodrying processes inside the feedstock layer can be explained by studying the temperature profile, which indicates the degradation of organic matter in the system, resulting in heat and generation and water evaporation.

Figure 2 shows the trend of temperatures in the feedstock layer each day from the beginning (day 0) until the end of the experiment (day 5), in addition to the ambient air temperatures. Both temperature series rose during the day and fell at night, thus indicating that the outside air temperature directly affects the system's temperature. The daily temperature trends of all the experiments were a homogeneous, rapid rise from day 0 to day 1. Subsequently, the temperature increases in each experiment were heterogeneous. The maximum temperature range was reached during days 4 and 5. The highest system temperatures throughout the experiment were recorded in AR 0.6.

Polprasert (2007) described the temperature patterns based on temperature profiles. The latent phase involves the initial stage of acclimatization and colonization by microorganisms. This is followed by the growth phase, during which the temperature rises to mesophilic levels due to biological activity.

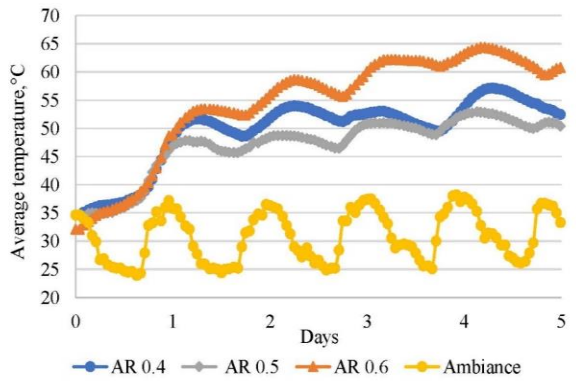



**Fig. 2** The temperature profile formation

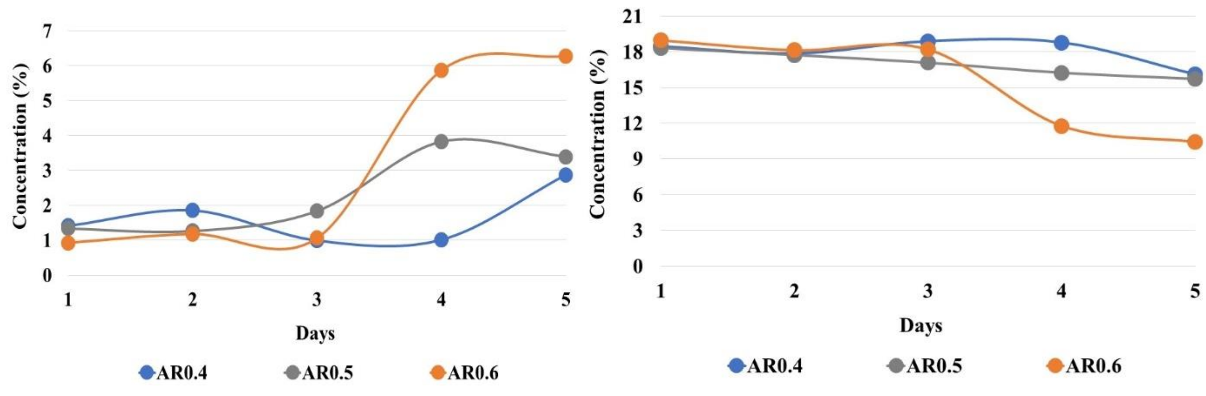
During the thermophilic phase, the system's temperature increases to its highest level. Finally, in the maturation phase, the temperature decreases to mesophilic and, subsequently, ambient levels. Li *et al.* (2022) investigated the consequences of a hot-air supply to the traditional biodrying process for kitchen waste. The first temperature rising developed after 24–42 hr. After this period, a small temperature decrease and fluctuation showed, which was driven by a shift in the microbial community from mesophilic to thermophilic bacteria. Then, the temperature began to increase until reaching its peak at 60-75 hr. The increases in temperature could be attributed to the dominance of thermophilic bacteria at that time. Comparing Polprasert and Li's temperature patterns with the temperature profiles recorded in the present study, the start of the experiment to day 0.5 was defined as the latent phase, the period from day 0.5 to day 1 was defined as the growth phase, and the period from day 1 until the end of the experiment was defined as the thermophilic phase. However, the present study ended on day 5 and the temperature had still increased to its maximum level; therefore, there was no indication that the maturation phase had been reached. Sutthasil *et al.* (2022) studied the biodrying process using MSW with high organic content, MC, and bulk density as a feedstock. In their study, the temperature phases were classified as follows: the rising phase occurred from day 0 to day 2, while the heat-constant phase was recorded from day 3 to day 6. In contrast to the present study, which involved the biodrying of wet RDF with low organic content and bulk density, the temperature phase was categorized in terms of latent and rising phases.

#### *3.1.2 Gas formation*

$CO_2$ is an essential parameter to detect microbial activity because it is a product of the aerobic digestion process. In addition, the $O_2$ concentration describes the level of air supply to the system and the microbial activity in the feedstock layer.

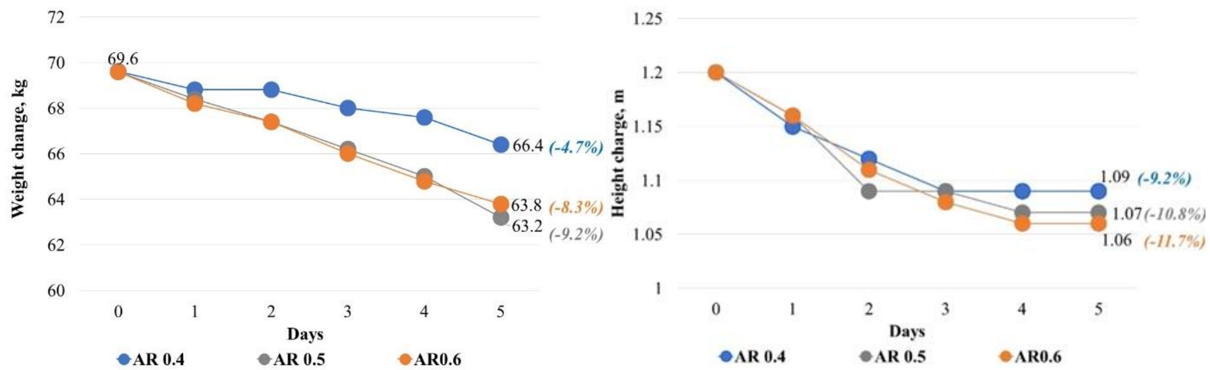
Figure 3 shows the average $CO_2$ and $O_2$ concentrations from the three studied levels of the feedstock layer. As shown, the $CO_2$ concentration began to increase on the first day of the experiment, indicating an ongoing biodegradation process; the concentration then increased significantly after day 3 in all conditions, especially in AR0.6. The O2 concentration decreased in the same period. Furthermore, changes in the $CO_2$ and $O_2$ concentrations were monitored throughout the operation, including the suspension period on day 5. The findings indicate that microbial activity occurred extensively on day 3 and had not finished on day 5. The highest $CO_2$ concentration and the lowest $O_2$ concentration were detected on day 5 in AR0.6, corresponding to values of 6.28% and 10.41%, respectively. The $CO_2$ concentrations also correspond to the temperature results, with the highest values recorded in AR0.6.

The results of this study were markedly different from those of previous studies such as Sutthasil *et al.* (2022), who recorded peak $CO_2$ generation from MSW biodrying between days 2 and 5 of their experiment, with a subsequent decrease recorded until the end of the process on day 18. According to their findings, the degradable material was rapidly fermented under intermittent aeration; however, in the present study, based on continuous aeration, the $CO_2$ generation peaked between days 4 and 5. This observation is because the lower organic content of the substrate and higher MC affect the rate of $CO_2$ generation. The study by Sutthasil *et al.* (2022) reported faster $CO_2$ generation in the presence of a substrate with high organic content and intermittent aeration to provide sufficient oxygen. Lawrance *et al.* (2022) investigated gas generation using a mathematical model of the MSW biodrying process. In




**(a)** **(b)**

**Fig. 3** Gas concentrations (a) Carbon dioxide (b) Oxygen




**(a)** **(b)**

**Fig. 4** The observed changes in (a) Weight (b) Height during the experiment

their study, the $CO_2$ concentration increased from day 1 to day 5 and then slightly decreased until the end of the process on day 15. Ham *et al.* (2020) performed biodrying using simulated waste (commercial dog food), with a similar gas formation trend reported to the study of Lawrance *et al.* (2022). However, these studies were simulated under the condition of positive aeration and the presence of sufficient organic content for digestion, whereas the present study had a high proportion of MC per organic substrate and slow-onset $CO_2$ generation.

*3.1.3 Changes in the feedstock's weight and height*

The weight loss rates were relatively consistent from day 0 to day 5. The final weights were 66.40 kg, 63.20 kg, and 63.80 kg for AR0.4, AR0.5, and AR0.6, respectively. The maximum weight decrease was recorded in AR0.5, accounting for 9.2% of the total. However, the observed height decreases were slightly different. The initial height of the feedstock was 1.20 m in all of the experiments. The final heights of AR0.4, AR0.5, and AR0.6 were 1.09 m, 1.07 m, and 1.06 m, respectively. The greatest height decrease was recorded in AR0.6, representing 11.7%. The height decrease was rapid in the first three days of the experiment and then relatively stable in the final two days. The changes in weight and height recorded in this study are shown in Figure 4.

The observed height change was related to the volume of the matrix, as the volume of the lysimeter was fixed. A significant increase in the final density was recorded in AR0.4, with a value of 243.69 kg/m$^3$, followed by AR0.5 and AR 0.6 with values of 240.75 kg/m$^3$ and 236.26 kg/m$^3$, respectively. This observation indicated that low aeration can effectively conserve the mass of recovered fuel, as represented by the bulk density. The results of this study were similar to those of Tom *et al.* (2016), who studied the bulk density during 33 days of MSW biodrying at an aeration rate of 0.528 kg/m$^3$/day. Their study reported a final bulk density of 263.69 kg/m$^3$, similar to the value reported in the present study. Therefore, the significant parameters determining the bulk density are the feedstock, degradable material content, MC, and aeration rate.

*3.1.4 The improvement of RDF quality*

The quality of the products was analyzed after the biodrying process and compared to the feedstock. The MC and LHV were evaluated as these parameters are the strict criteria for all RDF users in both power plant and cement plant applications (Itsarathorn *et al.* 2022)

The AR0.5 was the most efficient in terms of increasing the LHV of the wet RDF. The LHV of the feedstock increased by 24.5% from 2,936 kcal/kg to 3,656 kcal/kg. However, the conditions in AR0.6 decreased the MC the most, with a 14.0% decrease recorded from 45.68% to 39.28%. Figure 5 shows the analysis results of the RDF feedstock and products.

Park and Lee (2022) reported that a high aeration rate can achieve significant MC reductions in biodrying operations using mechanically sorted residue MSW as a feedstock. This was because high aeration rates can force moisture in the form of vapor from the biodrying system. Same as the study of Bhatsada

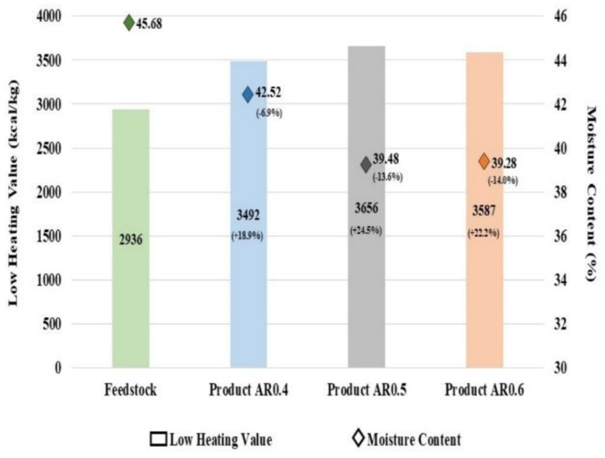



**Fig. 5** The analysis results of the RDF feedstock and products

*et al.* (2022), which examined the effect of the aeration rate on wet RDF biodrying process for quality improvement. Their results presented that higher aeration rates have greater potential to improve RDF quality.

The present study also observed that high aeration rates (AR0.5 and AR0.6) achieved the maximum MC reduction, consistent with the results of Park and Lee (2022) and Bhatsada *et al.* (2022). The feedstock used in Park and Lee's study was waste residue collected from the mechanical sorting process and water extracted from both organic and inorganic waste was thoroughly mixed into the feedstock, which was the same as the feedstock used in this study. The high initial MC values in both Park and Lee's study and the present study were minimized by high aeration rates in the biodrying process through a combination of evaporation and aeration force.

In Exp. B, the optimum aeration rate from Exp. A was chosen as the aeration rate for the system. From the results of Exp. A, AR0.6 achieved the most effective biodrying reaction based on the system's temperature and the $CO_2$ produced from the biodrying process; however, it was ambiguous whether AR0.5 or AR0.6 achieved better matrix changes and product characteristics. Accordingly, aeration rates of both 0.5 and 0.6 $m^3$/kg/day were chosen for study in Exp. B.

### *3.2 Experiment B*

Exp. B was divided into two experiments with different aeration rates: the rate of 0.5 $m^3$/kg/day (AR0.5) was denoted as Experiment B1 (Exp. B1), and the rate of 0.6 $m^3$/kg/day (AR0.6) was denoted as Experiment B2 (Exp. B2). The initial conditions of the experiments are presented in Table 2, and the initial feedstock composition and chemical properties are presented in Table 3.

#### *3.2.1 Temperature profile and gas formation*

The temperatures inside the feedstock layers were measured and averaged per the procedure used in Exp. A. Figure 6a and 6b show the average temperature trends for Exp. B1 and Exp. B2, respectively. The ambient air temperature directly affected the temperatures in the feedstock layers which rose during the day and fell at night in both experiments. The temperatures under all conditions increased rapidly from day 0 to day 2. The subsequent temperature changes varied between the different conditions; however, an upward trend was recorded in all cases until the final day of the operation. The configuration with the highest recorded system temperature for Exp. B1 was a feedstock density of 232 kg/$m^3$, with a maximum temperature of 61.5 °C recorded on day 4. However, in Exp. B2, the trends between feedstock densities of 250 kg/$m^3$ and 270 kg/$m^3$ were unclear. Initially, the system's temperature with a density of 270 kg/$m^3$ was notably higher than that recorded for the 250 kg/$m^3$ configuration. However, after three days, this trend reversed: the system temperature for the density of 250 kg/$m^3$ exceeded that of the 270 kg/$m^3$ configuration. The highest temperature recorded in Exp. B2 was 62.7 °C on day 4 for a density of 250 kg/$m^3$.

Figure 7a and 7b show the average $CO_2$ and $O_2$ concentrations. The trends for both gases followed the biodrying principle. In Exp. B1, the experiment with a density of 250 kg/$m^3$ had the highest $CO_2$ concentration and the lowest $O_2$

**Table 2**
The initial conditions for Experiments B1 and B2.

| Condition | Exp.B1: AR0.5 | | | Exp.B2: AR0.6 | | |
|---|---|---|---|---|---|---|
| | Density 232 | Density 250 | Density 270 | Density 232 | Density 250 | Density 270 |
| Feedstock weight (kg) | 69.60 | 75.00 | 81.00 | 69.60 | 75.00 | 81.00 |
| Air flow rate (m/s) | 0.20 | 0.22 | 0.24 | 0.24 | 0.27 | 0.29 |

**Table 3**
The chemical properties and composition of the feedstock.

| Parameter | Quality of feedstock | |
|---|---|---|
| | Exp.B1. | Exp.B2. |
| Low heating value (kcal/kg) | 3,399 | 4,494 |
| Moisture content (% by weight) | 36.10 | 33.50 |
| Combustible material (% by weight) | 62 | 70 |
| Organic portion (% by weight) | 24 | 19 |
| Other material (% by weight) | 14 | 11 |

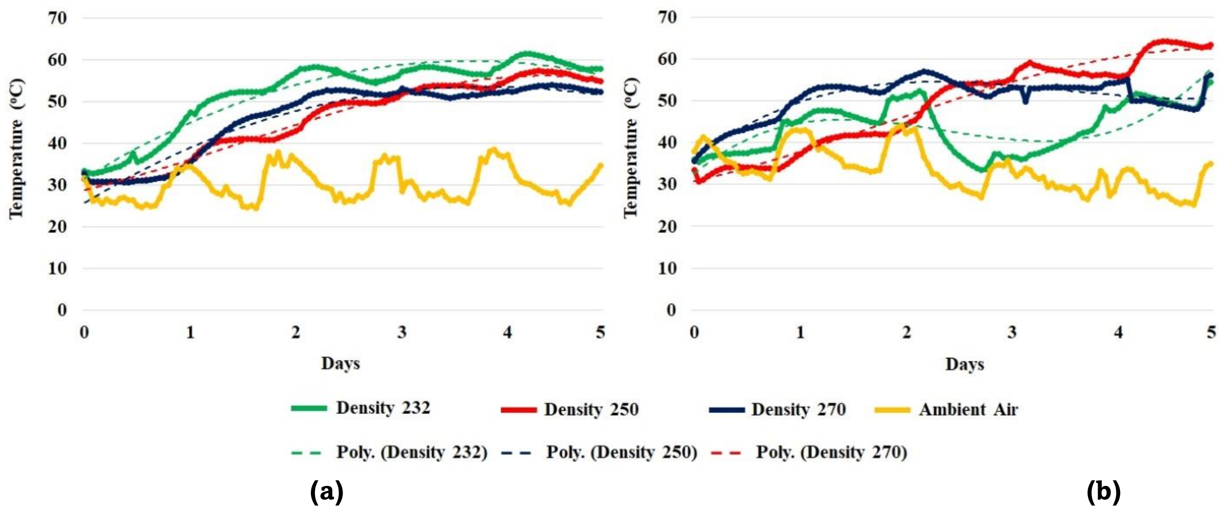



**Fig. 6** The temperature profiles recorded in (a) Exp. B1 (b) Exp. B2

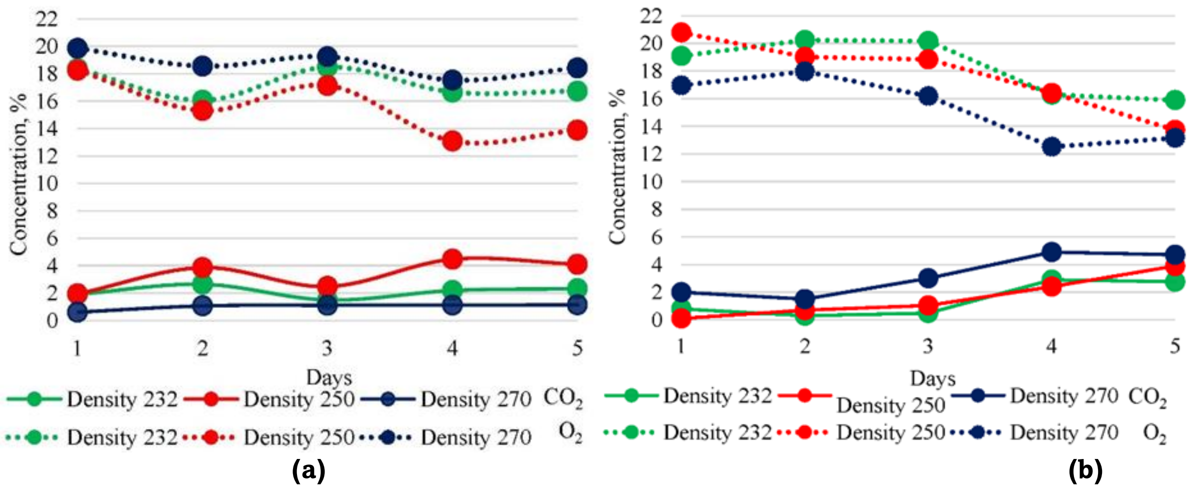


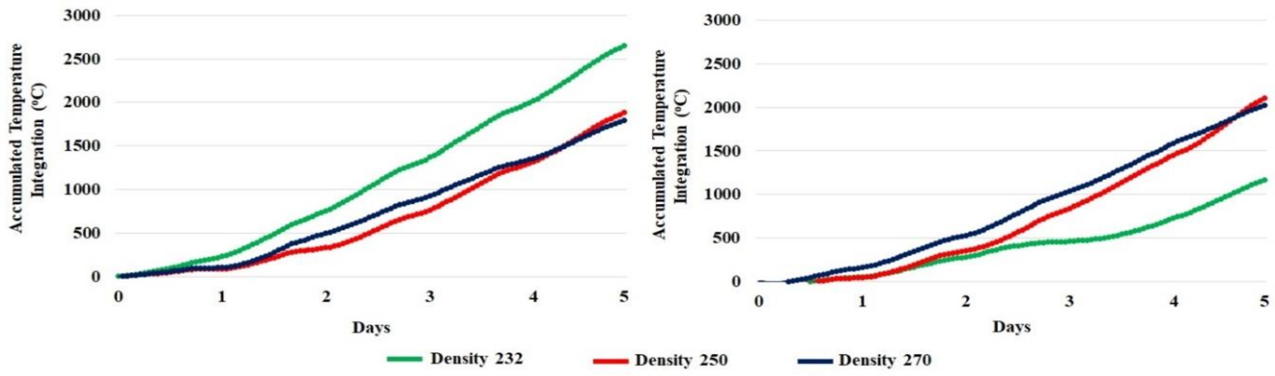

**Fig. 7** $CO_2$ and $O_2$ concentrations recorded in (a) Exp. B1 (b) Exp. B2

concentration. However, in Exp. B2, the density of 270 kg/m$^3$ showed the same results. In both experiments, the highest rate of $CO_2$ generation was recorded on day 4.

In terms of the relationship between the gas concentration and temperature, the density of 232 kg/m$^3$ had the highest system temperature but did not produce the highest $CO_2$ concentration in Exp. B1. However, in Exp. B2, the highest density of 270 kg/m$^3$ corresponded to the highest system temperature and CO2 concentration. The maximum system temperature and CO2 concentration occurred on day 4 in all configurations. Furthermore, the system temperature and the $CO_2$ concentration had still not decreased on the last day of the operation, consistent with the observations in the previous experiment. These findings highlight that the biodegradation process occurs rapidly at the onset of the experiment and takes more than five days for the microbial activity to finish.

The temperature profile fluctuations in the MSW layers were similar to those reported by Ngamket *et al.* (2021), who studied biodrying performance in solar greenhouses using MSW as a substrate; their study reported high temperatures in the daytime and low temperatures at nighttime. For the system temperature, his study found the highest value was 61.5–62.7 °C from day 4 to day 5 with the highest $CO_2$ concentration. However, these values are lower than those reported by Payomthip *et al.* (2022), who studied the optimization of aeration for MSW biodrying. They concluded that the highest temperature and $CO_2$ concentration values were achieved within the first two days of the operation, with a maximum temperature value of 71.2 °C. Same as the results presented by Zaman *et al.* (2018). They studied the temperature profile of the solid waste, which contained 61% organic portion in the process of biodrying. The temperature continued to increase from the beginning and peaked within the first 12 hours of operation. However, Bhatsada *et al.* (2023) conducted a biodrying process using wet RDF as a feedstock and presented similar results: the temperature increased rapidly during the first two days, and the peak temperature and $CO_2$ concentrations were recorded on day 3 to day 5 of the study. The maximum recorded temperature was around 60 °C.

A comparison between the present study's results and those of previous studies further confirms that the organic content and MC in feedstock influence the biodrying performance and reaction time. The biodrying experiments performed with MSW with high organic content and high MC undergo faster reactions, and the feedstock layers' temperatures increase faster than those that used RDF. Additionally, Tom *et al.* (2016) reported that temperature evolution affected the bulk density of material during biodrying.




(a) (b)

**Fig. 8** Temperature integration results for (a) Exp. B1 (b) Exp. B2

In their study, the bulk density was varied between 182.88 kg/m$^3$ and 220.2 kg/m$^3$, with a maximum temperature of 60 °C achieved for the lowest bulk density. This finding was similar to that of the present study, where a low density achieved high temperatures due to increased aeration force moving through the feedstock body. There was a correlation between the ability of air to adsorb into the feedstock and gas generation during the process, which varied according to the bulk density. Here, higher densities were found to be associated with lower gas generation.

*3.2.2 Temperature integration*

The efficiency of the heat-capture and drying process can be assessed by the hourly temperature difference between the ambient air temperature and the temperature in feedstock layers in terms of the temperature integration (TI) (Yuan *et al.* 2017).

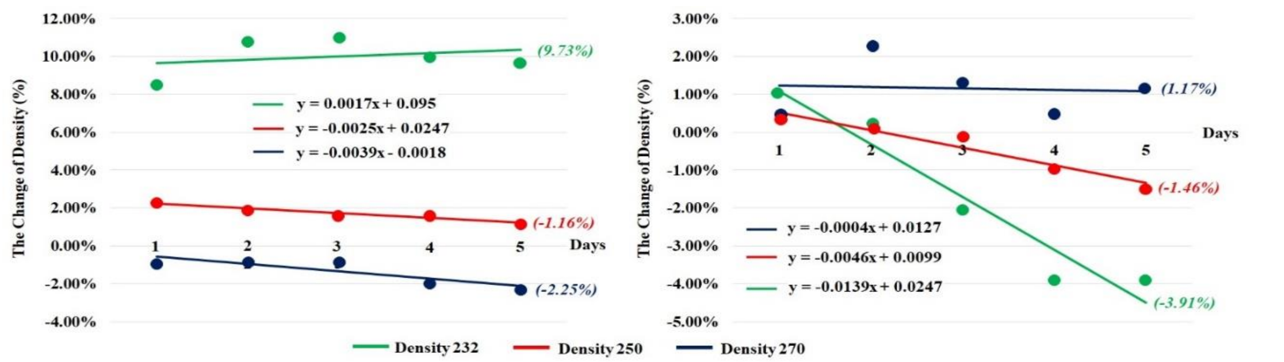
The TI values for both aeration conditions are presented in Figure 8. In Exp. B1, the TI value for a density of 232 kg/m$^3$ was the highest at 2,648.87 °C, while the density of 250 kg/m$^3$ achieved the highest TI value in Exp. B2 of 2,108.10 °C. The highest TI values in Exp. B1 were higher than those in Exp. B2. This observation was similar to the findings of the study of Ngamket *et al.* (2021); the TI values of the configuration with a low aeration rate were higher than those in the configuration with a high aeration rate. In the present study, the heat loss in the feedstock layer was more significant at a high aeration rate. Furthermore, the configuration with a density of 270 kg/m$^3$ in both experiments, in which the feedstock was tightly compacted, did not achieve the highest TI values because of the difficulties in achieving water evaporation. Therefore, the aeration rate and feedstock density both had a significant effect on the biodrying process, especially in terms of heat retention.

*3.2.3 Changes in the feedstock's density during the biodrying process*

The evaporation of water from the system, whether the water from wet RDF or water from the biodrying reaction, causes the experiment's weight and height to reduce over time. The density is represented by the change in the proportion of the experiment's weight and volume. If the density decreases, this indicates that the rate of weight loss exceeds the rate of height loss. In contrast, an increasing density indicates that the rate of weight loss is less than the height loss rate.

In Exp. B1, the density for the 232 kg/m$^3$ configuration increased by 9.73%; however, the density values for the 250 kg/m$^3$ and 270 kg/m$^3$ configurations decreased by 1.16% and 2.25%, respectively. Exp. B2's density increased by 1.17% in the initial 270 kg/m$^3$ configuration; however, the initial density values of 232 kg/m$^3$ and 250 kg/m$^3$ decreased by 3.91% and 1.46%, respectively. In each experiment, the average rate follows a second-order polynomial function. The feedstock's density trend decreased under all studied conditions. The daily changes in the feedstock's density in this experiment are shown in Figure 9 and can also be found in this article's supplementary material section

The daily density changes during biodrying operations were also described by Tom *et al.* (2016), who reported that low bulk density values allow improved aeration relative to high density values. This indicated active biological decomposition during biodrying. In the present study, the results showed that density increased throughout the operation in some conditions




(a) (b)

**Fig. 9** The changes in the feedstock's density (a) Exp.B1 (b) Exp.B2 due to temperature evolution and gas generation. Petrovic *et al.* (2022) reported a strong relationship between particle density and the volume of waste during the mechanical–biological treatment process. The rise in the solid particle density was controlled exclusively by the increase in the solid particle volume. The current study revealed that a daily density increases corresponded to a decrease in the density of the solid particles; this change was attributed to the evaporation of vapor that filled the void spaces and a mass decrease of the organic particles due to decomposition.

### *3.2.4 Biodrying index*

Ngamket *et al.* (2021) and Payomthip *et al.* (2022) notified that the principle of the biodrying process is to eliminate as much water as possible from the system while the organic carbon is minimally decomposed to obtain a product with a low MC and a high heating value. Moreover, Yuan *et al.* (2018) concluded that the key factor affecting biodrying performance was the aeration volume. Forced aeration controlled the pile temperature and improved evaporation, meaning it was the prominent factor controlling water loss. Thus, biodrying index (BI) describes the biodrying process efficiency, with small values expected in the case of higher efficiency.

In terms of the water weight loss in both experiments, the configuration with a density of 232 kg/m$^3$ underwent the greatest loss. The feedstock with low density encouraged the evaporation of water from the system. This trend was confirmed by the results for the configuration with a density of 270 kg/m$^3$; this configuration experienced the smallest water loss due to feedstock compaction which prevented water evaporation. The configurations with density values of 232 kg/m$^3$ and 250 kg/m$^3$ had the smallest BI values (0.20 and 0.27 for Exp. B1 and B2, respectively). Figure 10 shows the weight loss of organic content and water and the corresponding BI values.

The feedstock condition and biodrying operation indicate the mass of water and carbon loss. Various studies on these factors have been performed using a range of different conditions and experimental setups, including assessments using the BI. Bhatsada *et al.* (2023) performed a biodrying experiment using wet RDF as feedstock and reported BI values of 0.209–1.256, which are close to the values of the present study. Ngamket *et al.* (2021) found that the optimum rate between water loss and carbon loss in MSW biodrying affect the system's efficiency and quality of the product. In case of excessive water loss and carbon loss. It resulted in the MC of the product was low, but LHV was also low. Zhang *et al.* (2020) reported that higher aeration intensity may result in more water removal, with less biodegradation of organic substrate. Thus, low BI values, resulting from excessive water loss in the system, may result in physical drying. Accordingly, the BI value can indicate the performance of the biodrying process; however, its value depends on the organic content level and initial MC of the feedstock. Consequently, the operating conditions, aeration, initial MC, and organic content mass all significantly influence the BI.

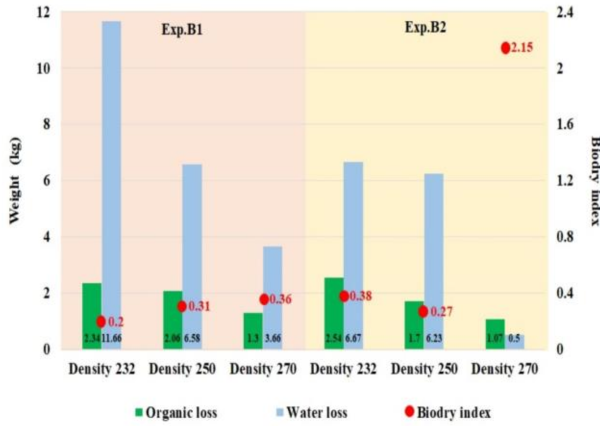



**Fig.10** Biodrying index values

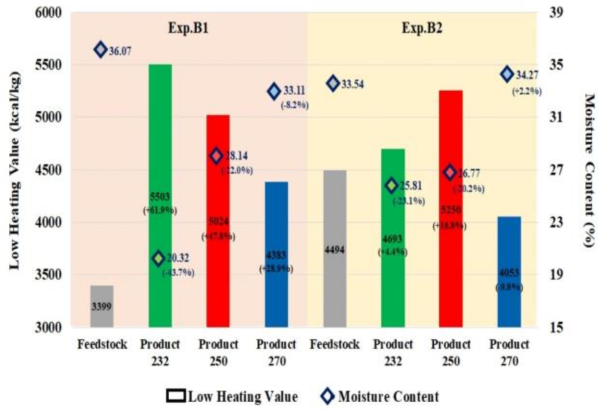



**Fig. 11** The product quality change

### *3.2.5 The improvement of RDF quality*

Based on the product quality from both experiments, the configuration with a feedstock density of 232 kg/m$^3$ in Exp. B1 achieved the greatest quality improvement. In this instance, the MC decreased by 43.7%, and the LHV increased by 61.9%. The configurations with density values of 250 kg/m$^3$ and 270 kg/m$^3$ showed respectively less improvement. In Exp. B2, the product quality of the configuration with a feedstock density of 250 kg/m$^3$ improved the most: the MC decreased by 20.2%, and the LHV increased by 16.8%. Notably, the products from the configuration with a density of 270 kg/m$^3$ degenerated, with an MC decrease of 2.2% and an LHV decrease of 9.8%. The configurations with a feedstock density of 270 kg/m$^3$ in both Exp. B1 and B2 had the lowest potential to improve RDF quality, especially in terms of MC reduction. The water loss weight described in the previous section corroborates the RDF quality findings. Specifically, excessive density of the feedstock resulted in the compression of material, which hindered the removal of water from the system. The product quality change for both experiments is shown in Figure 11.

Wright and Inglis (2002) described the initial performance of a biodrying process conducted on an 85-cow dairy farm. He concluded that reducing the MC from 70% to 60% and/or lowering the height of the compost piles from 2 m to 1.2 m will reduce the density and increase the airflow, making drying more likely. His results are consistent with the findings of the present study. As the density of the feedstock increased, the moisture reduction efficiency decreased, resulting in a high-humidity product.

### *3.3 Results summary*

Experiment A aimed to identify the ideal aeration rate for wet RDF with a feedstock density of 232 kg/m$^3$. AR0.6 had the highest biodrying efficiency; in addition, this configuration demonstrated the maximum feedstock height loss rate and decreased the MC of the feedstock the most. However, the AR0.5 configuration had the maximum feedstock weight loss rate, and the LHV of the RDF was maximized under these

**Table 4**
The coefficient of determination values.

| Parameter | $R^2$ | Parameter | $R^2$ |
|---|---|---|---|
| Aeration rate (m3/kg-substrate/day) | -0.080 | Initial MC of organic content (%) | -0.248 |
| Aeration rate (m3/kg-VS/day) | 0.452 | Initial VS of organic content (%) | 0.036 |
| Density (kg/m$^3$) | -0.298 | Initial LHV of organic content (%) | 0.747 |
| Feedstock mass (kg) | -0.297 | Initial volatile solid (%) | -0.528 |
| Initial organic content (%) | -0.628 | Final LHV (kcal/kg) | -0.981 |
| Initial LHV (%) | -0.307 | Final MC (%) | 1.000 |
| Initial MC of feedstock (%) | 0.719 | Final VS (%) | -0.984 |

experimental conditions. On this basis, aeration rates of 0.5 and 0.6 m$^3$/kg/day were chosen for further study in Experiment B.

Experiment B aimed to examine the effect of feedstock density on biodrying system performance by varying the feedstock density while using the optimum aeration rates determined in experiment A. The operation was separated into two experiments: Exp. B1, with an aeration rate of 0.5 m$^3$/kg/day (AR0.5), and Exp. B2, with an aeration rate of 0.6 m$^3$/kg/day (AR0.6). The results showed that at AR0.5, the quality improvement efficiency was greatest for a feedstock density of 232 kg/m$^3$, in which the highest system temperature, highest TI, and lowest BI were recorded. This configuration also achiev ed a highly effective feedstock MC decrease and LHV increase. However, when the aeration rate was increased to 0.6 m$^3$/kg/day, the most effective results were recorded for a feedstock density of 250 kg/m$^3$, with the highest system temperature and TI and the lowest BI; therefore, at the higher aeration rate, this configuration performed best in terms of improving the RDF quality by reducing the MC and increasing the feedstock's LHV the most.

### *3.4 Statistical analysis*

One of the key goals of the biodrying process is to eliminate water in the system to reduce the feedstock's MC. To determine the factors that significantly affect the MC, the initial parameters in this study were analyzed using Pearson's correlation coefficient. Table 4 represents the coefficient of determination values ($R^2$), describing the correlation between the initial parameters and the final MC. $R^2$ values with a magnitude greater than 0.5 indicate a moderate correlation between the parameters (Rumsey, 2015). Accordingly, the aeration rate, initial organic content, initial LHV, and initial volatile solid content in the feedstock directly affect the final MC. In addition, the final LHV and volatile solid content are strongly correlated with the final MC.

**Table 5**
Coefficient values and their significance levels.

| Parameter | Coefficients value | Significant level |
|---|---|---|
| Constant value | 59.310 | 0.003 |
| Density × Initial volatile solid | -0.002 | 0.032 |
| Initial organic content | -1.182 | 0.033 |
| Initial MC | 0.476 | 0.053 |

To predict the final MC as a dependent variable, the initial parameters were analyzed based on the biodrying process with five days of operation and continuous negative ventilation. The initial parameters in Table 5 were analyzed using SPSS software with a 95% confidence level. The p-value must be lower than 0.05 to be defined as significant. The feedstock density multiplied by the initial volatile solid content, organic content, and MC were identified as significant parameters to the final MC. Table 5 shows the coefficient values and their significance level.

Accordingly, the final MC can be predicted using the equation below;

Final MC = 59.310 – (0.002 × (Density × Initial volatile solid content)) – (1.182 × Initial organic content) + (0.476 × Initial MC)

Figure 12a, 12b, and 12c illustrate the relationship between the final MC and the multiplied density and initial volatile solid content, initial organic content, and initial MC, respectively. The relationship between the final MC and multiplied density and initial volatile solid was inverse and greater than 21% of the initial organic content. However, less than 21% of the initial organic content and initial MC were positively correlated with the final MC.

## 4. Conclusions

This study analyzed the impact of aeration rate and feedstock density on the efficiency of a biodrying system using wet RDF-2 and negative ventilation. The performance of the drying system was assessed in terms of various factors, such as temperature, $CO_2$ generation, weight loss, and height reduction rate. This study found that determining an appropriate aeration rate is crucial to achieving optimal system performance. An insufficient aeration rate results in low biodegradation, whereas excessive aeration can substantially reduce the MC, which harms the product's organic content. Additionally, the feedstock density affects the system's efficiency, with increased density values corresponding to lower porosities and reduced MC and heating values. Therefore, the aeration rate and feedstock density must be jointly considered to achieve maximum efficiency. This study also found that the density and initial volatile solid content, the organic content, and the moisture content significantly influence the final MC. Overall, this study highlights the importance of considering multiple factors to achieve optimal performance in biodrying systems. Since this study was performed on a lysimeter scale, the concepts and methods applied in this study should be extended to pilot and commercial scales in future research.

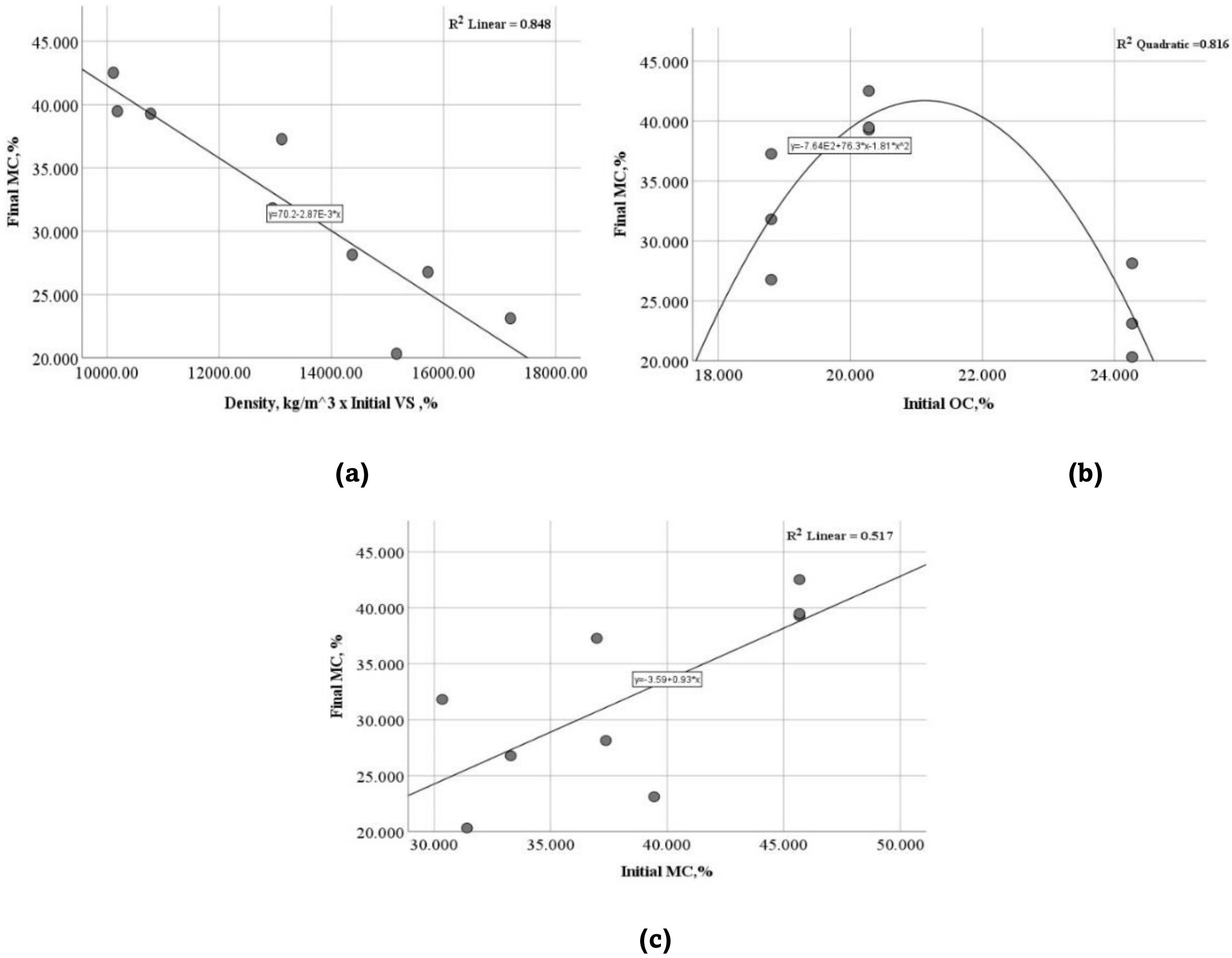



**Fig. 12** The relationship between (a) The final MC and multiplied of density and initial volatile solid content (b) The final MC and initial organic content (c) The final MC and initial moisture content.

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**Conflicts of Interest:** It has been declared that there are no personal or financial interests that may influence this study.

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