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SPECIAL FEATURE: ORIGINAL ARTICLE

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Improvement of energy recovery potential of wet-refuse-derived fuel through bio-drying process

Abhisit Bhatsada[1,5] · Suthum Patumsawad[2] · Tanik Itsarathorn[1,3] · Sirintornthep Towprayoon[1,5] · Chart Chiemchaisri[4] · Awassada Phongphiphat[1,5] · Komsilp Wangyao[1,5]

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Abstract

This paper proposes novel wet-refuse-derived fuel (Wet-RDF) bio-drying process with the variation of initial organic substrate and moisture content. The bio-drying was carried out using 0.3 m^3 lysimeter aerated continuously at different rates. Two conditions of Wet-RDF feedstock tested included: Experiment A − 37% organic substrate and 58% moisture content with an initial heating value of 2,889 kcal/kg; and Experiment B − 28% organic substrate and 35% moisture content with an initial heating value of 4,174 kcal/kg. The bio-drying was performed in both experiments under negative ventilation mode and non-ventilation mode, the ventilation mode was set at the aeration rates of 0.2 m^3/kg/day and 0.4 m^3/kg/day. The results suggest that the optimum aeration rate was 0.4 m^3/kg/day, achieving a 30% moisture reduction and a 60% heating value increase from their initial values. As a result, the improved wet-RDF qualified for the local cement industry's standard in terms of heating value.

Keywords Municipal solid waste · Mechanical biological treatment · Bio-drying · RDF

Introduction

Current municipal solid waste (MSW) generation worldwide, including Thailand, is caused by accelerated urbanization, increasing consumption of goods and services [1, 2]. Furthermore, the COVID-19 pandemic made working from home impermissible and also increased online food ordering services. Consequently, much single-use plastic packaging is mixed with MSW, especially in cities. The Pollution Control Department of Thailand reported a 15% average increase in single-use plastic from the usual situation of 5,500 tons/day to 6,800 tons/day [3–5]. In this regard, daily generated MSW becomes a concerning situation for the management of public and private agencies. Presently, 33% of generated MSW is recycled under several activities — waste banks, informal waste collectors, and junk shops. In addition, 36% of generated MSW is treated and disposed of with appropriate technologies — composting, landfilling, RDF production, thermal treatment, and control dumping. The remaining MSW (31.1%) is treated by improper disposals, including open dumpsite and open burning. The MSW in Thailand has heterogeneous properties being the mixture of degradable materials, recyclable materials, and non-degradable materials with their contribution of around 50%, 30%, and 17%, respectively. Its chemical characteristics of high moisture content and low calorific value affect RDF production; however, it is suitable for conversion into fertilizer and biogas production through biological processes [6, 7].

Many countries are prioritizing their MSW management through converting them into waste-derived fuel. Currently,

✉ Komsilp Wangyao
komsilp.wan@kmutt.ac.th

1 The Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi, Bangkok, Thailand

2 Department of Mechanical and Aerospace Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

3 SCI Eco Services Co., Ltd., Bangkok, Thailand

4 Department of Environmental Engineering, Faculty of Engineering, Kasetsart University, Bangkok, Thailand

5 Center of Excellence On Energy Technology and Environment (CEE), Ministry of Higher Education, Science, Research and Innovation (MHESI), Bangkok, Thailand

RDF production for energy recovery from solid waste is already well established. RDF production removes non-combustible materials and moisture content simultaneously, remaining waste portion with a higher calorific value. In Poland, approximately 30% of the material used in cement plants is RDF or solid recovered fuel (SRF) [8]. Furthermore, the overall energy recovery from MSW in South Korea showed that the RDF production for heat and power (CHP) plants is increased by 22%. Moreover, many counties under laws and operations for waste-to-energy intend environmentally friendly utilization of MSW [9].

The MSW generated in Bangkok Metropolitan Area (BMA), the capital city of Thailand, accounted for more than 20% of the whole county. The collected MSW is delivered to three transfer stations: On-Nuch, Nong Khaem, and Tha Raeng stations for handling and pre-treatment of the MSW before landfilling. In the On-Nuch transfer station, which receives more than 50% of the generated MSW, a part of MSW is managed by a mechanical biological treatment (MBT) process with a maximum capacity of 1,200 tons/day. About 42% is biodegradable waste, and the remaining is a recyclable material. The MBT process separates organic matter to produce fertilizers and inorganic materials to produce RDF. The RDF is utilized as a fuel in cement production. In addition, its composition that collected between the years 2020 and 2022 holds more than 41% of plastics, 27% of woody biomass, 9.48% of food waste, 9.41% of paper, 6.23% of stone and ceramic, 4.21% of cloth, and others. The moisture content, ash content, and lower heating value (LHV) are 60%, 11.8%, and 4,634 kcal/kg, respectively [4, 6, 7]. Therefore, the RDF can be considered for the cement production process. However, the moisture content of the produced RDF is also high, which in this study named Wet-RDF. The LHV is also low, which is not acceptable to the requirements for utilization in cement production.

Various alternative technologies have been suggested to reduce the moisture content of MSW, e.g., thermal drying, mechanical separation, composting, bio-stabilization, and bio-drying. Thermal treatment is a strategy for minimizing pathogens and toxic while obtaining solid fuel products quickly but, in most cases, not cost-effective for operation [10]. Mechanical separation is most straightforward in the mechanical screening of MSW designed to maintain the low water content in the MSW [11]. Composting and stabilization of MSW can reduce high moisture content, while organic as the high carbon content is lost during the long-time consuming process [12].

Bio-drying is a moisture removal process by activated microbial activities. By-products of the decomposition include heat, carbon dioxide (CO_2), and water. The heat produced from the decomposition process can diminish the moisture 4 content of waste, which results in increased heating values of the final product. Researchers have developed bio-drying systems in several feedstocks, e.g., mostly MSW [13, 14] and sludge [10]. However, there are currently no studies reported on drying the Wet-RDF. Compared to MSW and sludge, there are some problems in moisture removal for the Wet-RDF, for example, less bio-activity due to less organic content and less oxygen transferring due to high moisture content blocking. However, due to its cost-effectiveness in operation, it is necessary to determine optimal bio-drying operating conditions to allow bio-generated energy to be effectively and economically used for Wet-RDF as a feedstock.

Parameters affecting the bio-drying process, such as aeration rate, have proven to be the most significant for operation, simultaneously exerting bio-heat generation and evaporation. Extensive research and operation on the airflow rate available for MSW bio-drying have been published. Colomer-Mendoza et al. (2013) used garden waste to perform bio-drying with 0.88 to 6.42 L/kg$_{-TS}$/min [15]. Tambone et al. (2011) reviewed the airflow rate for 0.1–0.4 L/kg$_{-TS}$/min in the MSW bio-drying [16]. Ham et al. (2020) studied the airflow in the range of 0.4–1.1 L/kg$_{-VS}$/min operated to simulate waste biodrying [17]. However, appropriate aeration rate in biodrying system applied to Wet-RDF has not been reported. Therefore, this research aims to study the effect of the aeration rate on the Wet-RDF biodrying process.

Materials and methods

Experimental setup

Each experiment was operated in the lysimeter under different conditions. The aeration was supplied continuously using a negative ventilation system at three aeration rates for both experiments. The set aeration rate was 0.2 m^3/kg/day (AR0.2) and 0.4 m^3/kg/day. All experiments were operated for five days. The feedstock and final product were analyzed at the beginning and the end of the biodrying process. Table 1 shows the experimental setup under different conditions, including aeration rate, feedstock condition, and characteristics. The density of Wet-RDF in Experiment A varied between 198.7 and 248.0 kg/m^3, and in Experiment B was fixed at 232 kg/m^3. Each experiment's chemical characteristic, heating value, and moisture content was analyzed differently according to different experiments. The initial heating value, moisture content, and degradable material in Experiment A were 2,889 kcal/kg, 58%, and 37%, respectively. Experiment B's initial heating value, moisture content, and degradable material were 4,172 kcal/kg, 35%, and 28%, respectively.

Table 1 Experimental condition of the research

Condition	Experiment A			Experiment B		
Code	AR 0	AR 0.2	AR 0.4	BR 0	BR 0.2	BR 0.4
Aeration rate (m^3/kg/day)	0	0.2	0.4	0	0.2	0.4
Initial density (kg/m^3)	198.7	232.7	248.0	232.2	232.0	232.0
Initial weight (kg)	59.6	69.8	74.4	69.7	69.6	69.6
Initial heating value (LHV), kcal/kg	2,889	2,889	2,889	4,172	4,172	4,172
Initial moister content, %	58	58	58	35	35	35
Initial organic, %	37	37	37	28	28	28

Lysimeter configuration

The experiments were performed in the square-stainless steel lysimeters with a width of 0.5 m and a height of 2 m performing as biodrying reactors. Each lysimeter had a 2.5 cm thick cover of polyurethane foam. The perforated metal plate had been placed at the bottom of the lysimeter to support the air ventilation and waste material. The aeration component system was installed at the bottom of the lysimeter to supply airflow, including a ventilation pipe, condensation pipe, and blower. The 5.08 cm diameter and 14 cm length of ventilation pipe were connected under the perforated metal plate for ventilating the aeration, and 1 cm of the holding diameter was perforated at the central ventilation pipe for measuring the airflow rate. The 5.08 cm in diameter of the U-trap pipe was connected to the ventilation pipe to collect the condensation. The leachate was collected in the 5.08 cm in diameter U-trap pipe installed at the bottom of the lysimeter. Inside the lysimeter, the perforated pipe of 20 mm in diameter was placed at 0.6 m (middle) to measure the inner gasses (CH_4, O_2 and CO_2). The configuration of the lysimeter is shown in Fig. 1.

Feedstock preparation

The feedstock taken for this study was the Wet-RDF collected from the MBT process in On-Nuch waste transfer station in Bangkok, Thailand. It has a bulk density of 232 kg/m^3 (w/w). The feedstock was sampled to analyze the composition and characteristics and then fed into the lysimeters. The quantity of feedstock in each lysimeter varied between 59.6 and 74.4 kg, and feedstock elevation was 1.2 m. The moisture content was analyzed by oven-drying method at 105 °C following the ASTM D-3173 1997. A bomb calorimeter was used to measure the heating value according to the ASTM D-2015 1997. The ultimate analyses consisting of Carbon (C), Hydrogen (H), Oxygen (O), and Nitrogen (N) were performed on a CHN instrument by referring to the ASTM D-5373–14 1997. The feedstock composition was categorized as degradable material, non-degradable material, and other/unclassified. The degradable materials included food waste, yard waste, paper, and wood. Non-degradable materials included plastic, rubber, foam, fabric, etc. Other/unclassified was inseparable material due to coagulating. Figure 2 illustrates the waste composition in Experiment A and Experiment B. The feedstock in both experiments was mainly non-degradable materials comprising 40.1% and 39.6% plastic bags by mass for Experiment A and Experiment B, respectively. The degradable material mainly comprised yard waste and food waste, accounting for 36.8% and 25.2% by mass for Experiment A and Experiment B, respectively.

Monitoring parameters

Three type K thermocouples with a detectable temperature range of −270 °C to 1,327 °C were placed at the top, middle and bottom of the lysimeters to monitor the temperatures. Another thermocouple was placed outside of the lysimeters to measure the ambient temperature. The temperature data were recorded hourly with the midi Logger (Graphtec GL220). The O_2 and CO_2 concentrations as % by volume were monitored using Biogas 5000 (Geotech, UK) at the middle point of the lysimeter. The weight of feedstock in the lysimeter was daily measured using a push gantry hoist and digital crane scales.

Performance indicators

In the biodrying process, water and degradable material in the initials substrate were reduced. Therefore, in the operation and performance of Wet-RDF biodrying, analyzing the temperature, biodrying index, and biodrying-air ratio was taken into account. Those corresponding indicators were shown in the analysis described below.

To indicate the accumulated daily difference between the matrix and ambient temperatures, temperature integration (TI) index can be calculated as:

$$\mathrm{TI} = \sum_{i=1}^{n} \left(T_m - T_a\right) \cdot \Delta t \tag{1}$$

where T_{m} and T_{a} are the matrix and ambient temperatures at day I, respectively; Δt is the time element [18, 19].

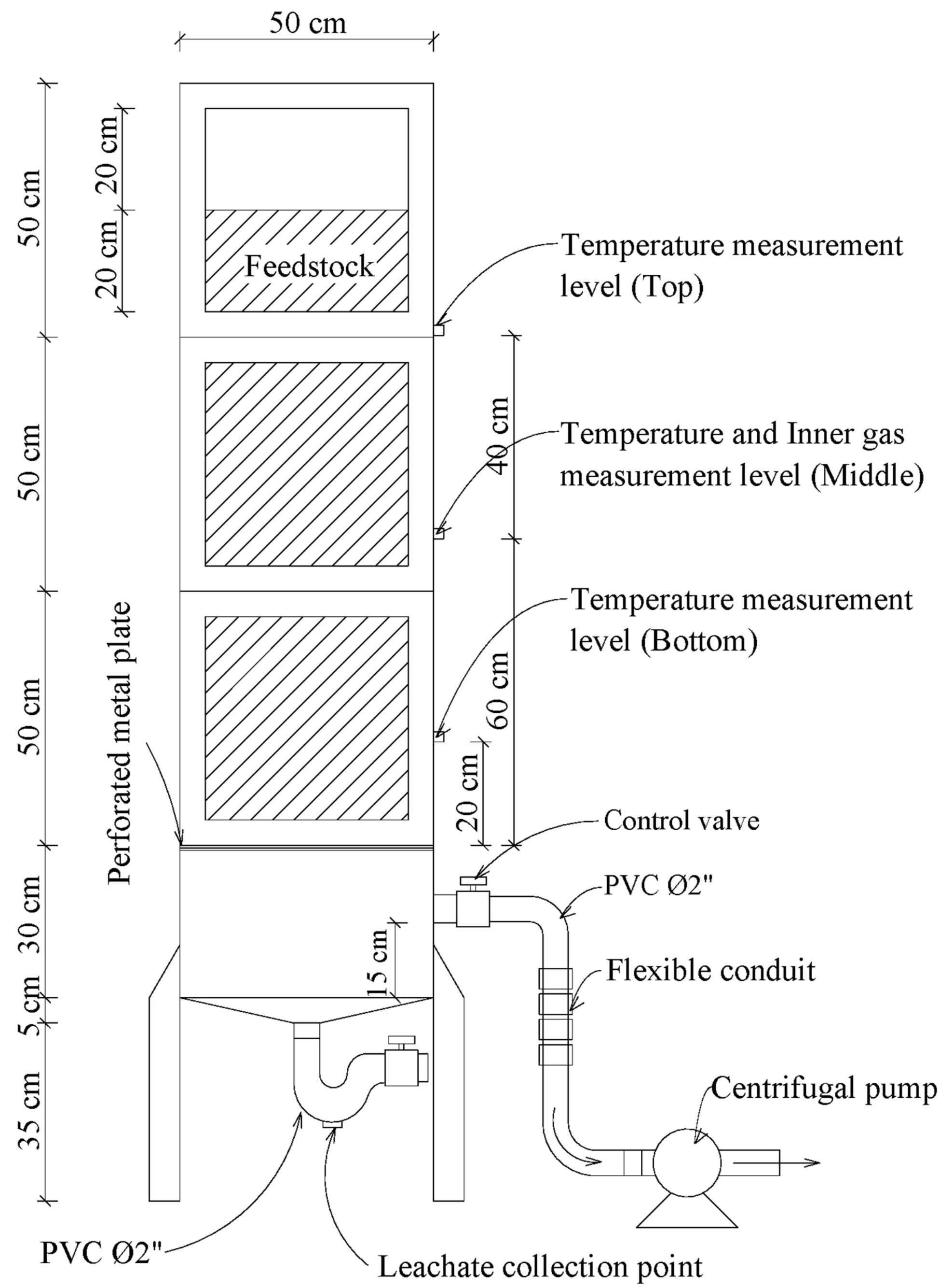

Fig. 1 Lysimeter configuration

To provide *I* biodrying performance, the biodrying index is defined as the ratio of water lost to degradable lost by the following equation:

$$I = \frac{OL}{WL} \tag{2}$$

where *I* is biodrying index at the final process; OL (kg) the organics loss; and WL (kg) the water loss [18, 19].

To observe the relation between the composting and biodrying processes, the biodrying-air ratio is calculated using aeration rate feed to the biodrying process per stoichiometric air demand of the composting. The equation shown below was proposed by Payomthip et al.

$$\text{B.A.} = \frac{\text{AR}_{\text{air}}}{\text{ST}_{\text{air}}} \tag{3}$$

where B.A. ratio is the biodry-air ratio; AR_{air} and ST_{air} are the aeration rate feed to the biodrying process (m^3/kg/day) and stoichiometric aeration rate demand of the composting process ($m^3/kg_{-organic}$/day), respectively [20].

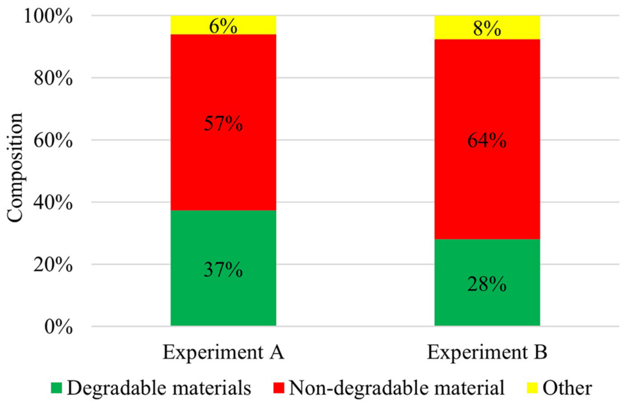

Fig.2 Feedstock composition of experiments

Statistical analysis

The average and standard deviation for temperature data in each experiment were analyzed. Least-significant difference tests were calculated to determine the significant difference between averages. To determine the differences in temperature between matrix and ambient environment, the significant difference in various trials of each experiment was performed using one-factor variance analysis (ANOVA) with 95% confidence using Excel 2010.

Results and discussion

Temperature evolution during the biodrying process

The temperature in the feedstock during the biodrying process presents the self-heating. It was a crucial factor affecting water evaporation and organic degradation. The daily evolution of the average temperature obtained top, middle, and bottom of lysimeters is shown in Fig. 3. The evolutions of daily temperature for both experiments can be divided into three phases: the rising phase, stable phase, and declining phase, respectively. The rising phase is the duration of temperature increases precipitously to the maximum level. The stable phase is the duration of the temperature value peak and relatively constant, which is another defined as the heat-constant phase. The declining phase is the duration of temperature value slightly decreases [10, 21–23].

In Fig. 3, the trend of daily temperatures from day zero to day 5 is quite not similar compared in each experiment. To classify the daily temperature's trend of both experiments based on the effect of aeration rate on temperature evolution, the daily temperatures of the followed experiment: AR 0.2 and BR 0.2, AR 0.4 and BR 0.4, and AR 0 and BR 0 were illustrated in Fig. 3a–c, respectively. The daily temperature

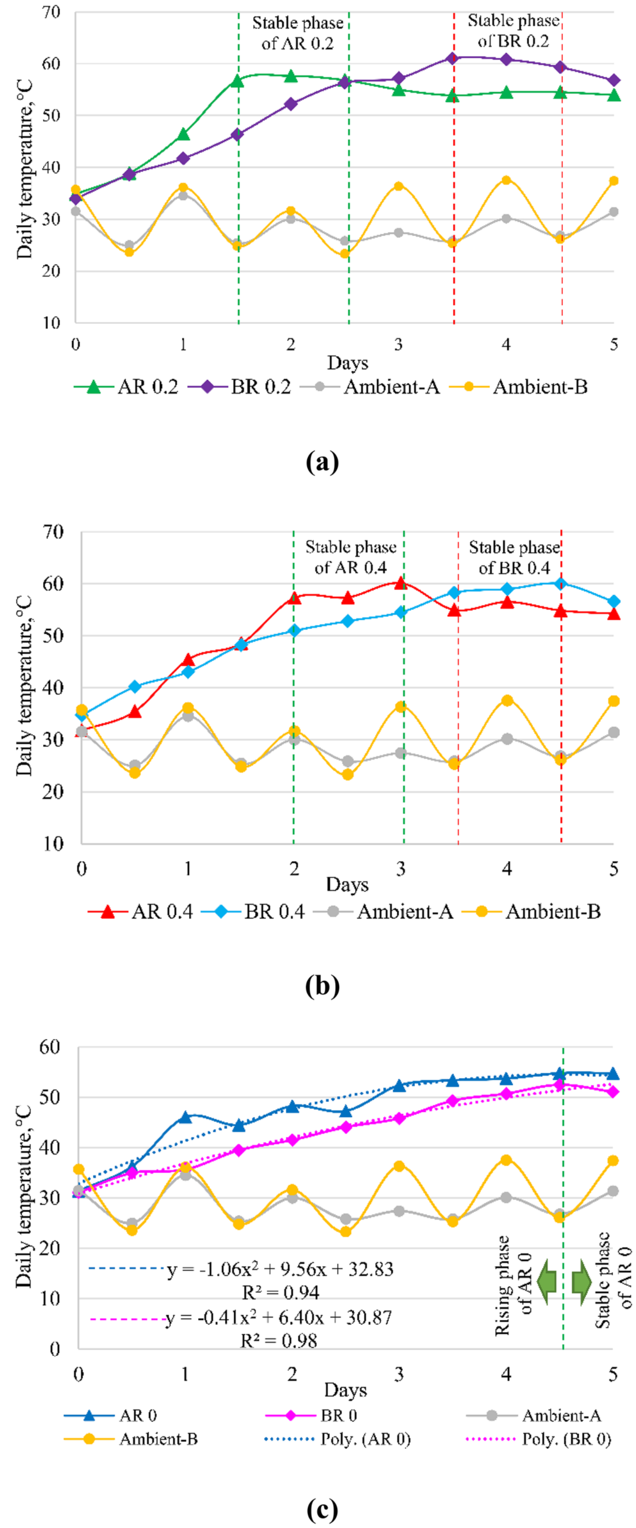

Fig. 3 The daily temperature evolution during the biodrying process of experiments for **a** AR 0.2 and BR 0.2, **b** AR 0.4 and BR 0.4, and **c** AR 0 and BR 0

of AR 0.2 stayed at the rising phase from the beginning until day 1.5, then entered the stable phase during day 1.5–2.5. While AR 0.4 stayed at rising phased from beginning to day 2, and entered the stable phase during days 3–4. The daily temperature of BR 0.2 and BR 0.4 was entered the rising phase from day zero to day 3.5, and entered the stable phase from day 3.5 to day 4.5.

There was an increasing trend of temperatures in AR 0 and BR 0 from the beginning until the end of the operation. When analyzing the trends of the daily temperature of AR 0 and BR 0 by polynomial curve, the equation of the polynomial curve was minus at the constant of the higher degrees. The polynomial curve was used to predict the peak of temperature in the context of 5 days' operation. It shows that the daily temperature has risen and then slightly decreased in the manner of a bell-shaped curve. The maximum point of the bell-shaped curve represents the end of the rising phase of the daily temperature. Therefore, Experiment A has a daily temperature rising from day 0 until day 4.51, and Experiment B has a daily temperature rising from day 0 until the end of process which was predicted at day 7.62. A homogeneous temperature of each trial in Experiment A was calculated. There were significant differences between AR 0 and AR 0.2 ($P<0.05$), AR 0 and AR 0.4 ($P<0.05$), and AR 0.2 and AR 0.4 ($P<0.05$). In contrast, there was no significant difference in temperature between AR 0 and ambient ($P=0.91$), AR 0.2 and ambient ($P=0.45$), and AR 0.4 and ambient ($P=0.65$). For Experiment B, there was a significant temperature difference between BR 0 and BR 0.2 ($P<0.05$), BR 0 and BR 0.4 ($P<0.05$), and BR 0.2 and BR 0.4 ($P<0.05$). On the other hand, there were no significant differences in temperature between BR 0 and ambient, BR 0.2 and ambient, and BR 0.4 and ambient accounted for $P=0.92$, $P=0.96$, and $P=0.94$, respectively.

The differences in daily temperatures of three trials in each experiment were assessed using temperature integration (TI), defined as based on Eq. (1).

The different TI for the experiments had separated into three-phase, followed by the daily temperature trends mentioned above, shown in Fig. 4. The highest TI values were in the declining phase, gaining the AR 0.2, while AR 0.4 gained the maximum TI in the declining phase. TI value in the declining phase of AR 0.2 was 1,564 °C, and AR 0.4 was 1,302 °C, respectively. The maximum TI value in

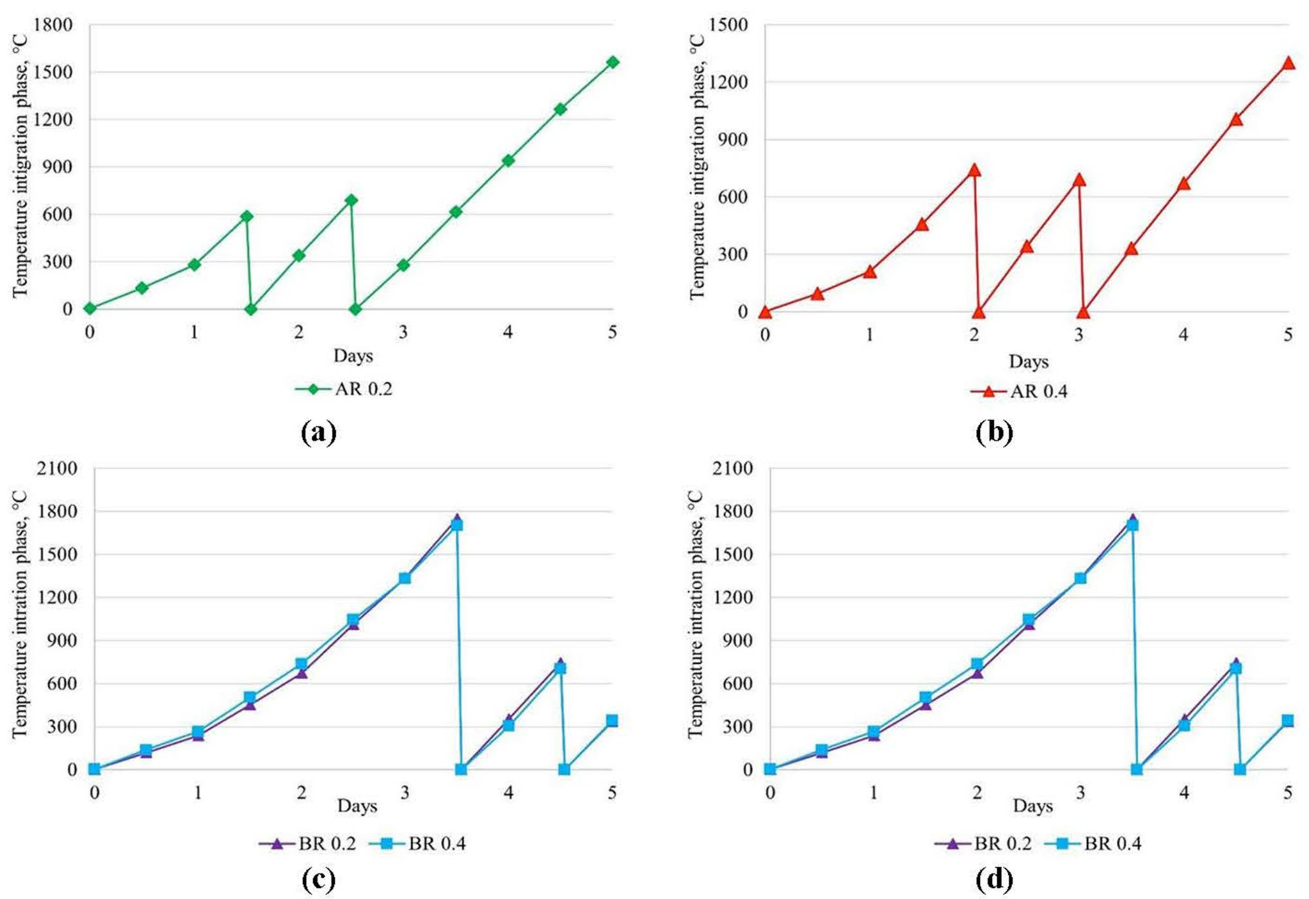

Fig. 4 Temperature integration **a** AR 0.2, **b** AR 0.4, **c** BR0.2 and BR 0.4, and **d** AR 0 and BR 0

the stable phase of AR 0.2 was 689 °C, while AR 0.4 was 693 °C. The maximum TI value in the rising phase of the AR 0.2 was 600 °C, while AR 0.4 was 718 °C. Overall, AR 0.2 had a higher TI value than AR 0.4; this phenomenon is due to the airflow rate conducive to heat accumulation. The higher airflow rate increased heat loss by ventilation to the exhaust air. The lower aeration rate as AR 0.2 would have caused more heat accumulation in the matrix and prevented heat ventilated to the exhaust than AR 0.4. Although AR 0.4 was a higher feedstock density than AR 0.2, the degree of density was not significant to the TI value.

In Experiment B, the highest TI values in the rising phase were 1,700 °C for BR 0.2 and 1,750 °C for BR 0.4, respectively. On the other hand, the TI value in the stable phase was 701 °C for BR 0.2 and 745 °C for BR 0.4. A similar trend entered the heat phases was explained due to the preparation of feedstock. In Experiment B, for all trials where the fixed density of feedstock was quite the same, the density related to free air space in the lysimeter. Similarly, the free air space in the matrix allowed for heat accumulation and ventilation. Therefore, this phenomenon in Experiment B was the same as entering the TI value's heat phases.

The highest TI values of AR 0 during day 0–5 of Experiment A and Experiment B were 2,386 °C and 1,880 °C, respectively. The AR 0 is a non-aeration feed to the system, but it is an open-air operation. Therefore, decomposition has occurred in the degradable material. Experiment A has a higher initial degradable material than Experiment B; therefore, the TI value of Experiment A was higher than Experiment B.

Factors that affect the entering of temperature's phases in each experiment are moisture content, initial degradable materials, and airflow rate. Sutthasil et al. (2022) presented daily temperature trends under domestic waste biodrying with the different additional water to the feedstock. This study provides a similar trend of daily temperature entered into the temperature phases in all trials [21]. Yuan et al. (2017) studied the different additional materials (cornstalk and wood peat) with mixed MSW performed in the biodrying process. They reported similar trends of daily temperature that entered three typical phases of degradation [22]. However, Experiment A resulted in higher moisture content and initial degradable material than Experiment B, making it faster to enter the stable phase. In addition, both experiments had the same duration in the stable phase, only 24 h, and TI values were between 600 and 700 °C.

Gasses generation and concentration in the bio-drying process

This study measured the temporal evolution of CO_2 generation and O_2 concentration during the bio-drying process. The CO_2 generation represents the production of microorganism activity to digest the degradable materials. The O_2 concentration describes the aeration level and bioactivity in the free space within the lysimeter. The gas generation and its concentration were determined at the inner lysimeter for the middle level. Figure 5 shows the highest CO_2 generation on day 3, about 12.27% in AR 0.2 and 9.97% in BR 0.2. However, AR 0.2 rapidly increased from day 1 and reached its maximum on day 3, while BR 0.2 gradually increased and reached its maximum from day 2 to day 3. AR 0.4 and BR 0.4 provided a lower CO_2 generation than AR 0.2 and BR 0.2. The maximum CO_2 generation of AR 0.4 was obtained on day 3 (3.4%), and the maximum generation of BR 0.4 was obtained on day 4 (5.13%). However, AR 0.4 gradually increased from day 1 to its maximum on day 3, then gradually decreased, while BR 0.4 gradually increased from

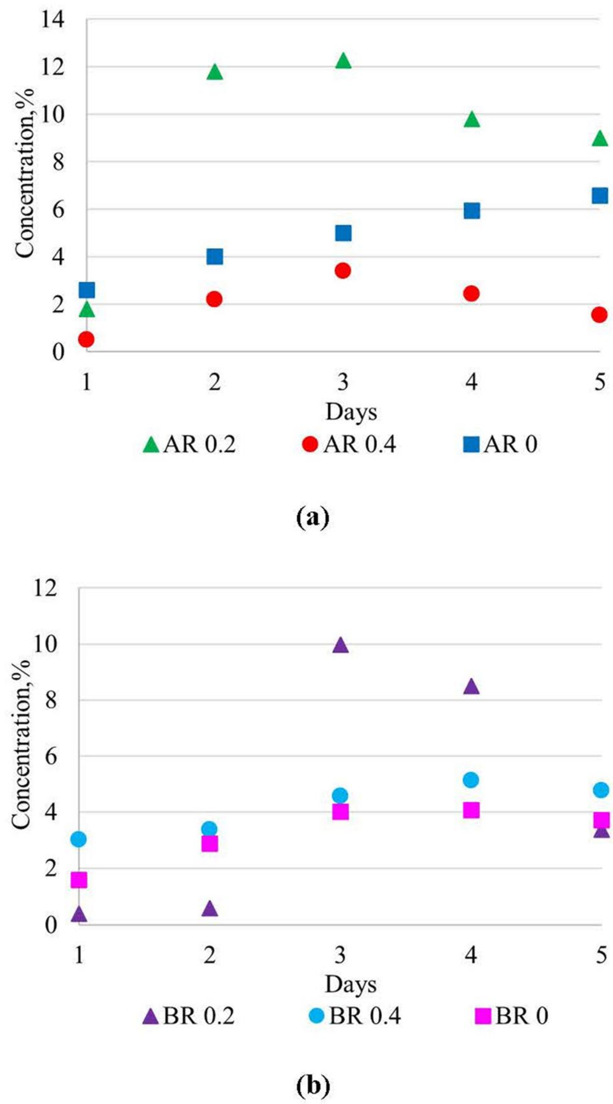

Fig. 5 CO_2 generation during the biodrying process of **a** Experiment A and **b** Experiment B

day 1 to its maximum on day 4, then slightly decreased. AR 0 continuously increased until the end of the process (maximum 6.57% on day 5), BR 0 gradually increased until day 3 (maximum 4.07%), then slightly decreased (at final = 3.70%). Similar results were reported by Ham et al. (2020), which operated simulated waste biodrying. Their CO_2 generation rate reached the peak on day 3, then continuously decreased [17].

Figure 6 shows O_2 concentrations; the lowest concentration was obtained in AR 0.2 on day 3, which was detected at 2.4%, followed by BR 0.2 detected at 4.97%. AR 0.4 had a minimum concentration on day 3 detected at 15%, while BR 0.4 had a minimum concentration on day 5, accounting for 12.6%. AR 0 was continuously decreased from the beginning until the end of the process, detected at 10.4% on day 5; however, BR 0 was slightly decreased until day 4 (14.77%) and then instantly increased on day 5 (15.63%). Zhou et al. (2014) simulated O_2 concentration during the sewage sludge composting process under the ventilation system. From their simulation, the trend of O_2 concentration was lowest in the first four days and then increased [23]. Hereupon, all trials in Experiment A and Experiment B can be forecasted that the low O_2 concentrations persisted over five days because the microbial activity did not reach the O_2 level in the ambient condition (20.8% O_2 in ambient air measured by Biogas 5000).

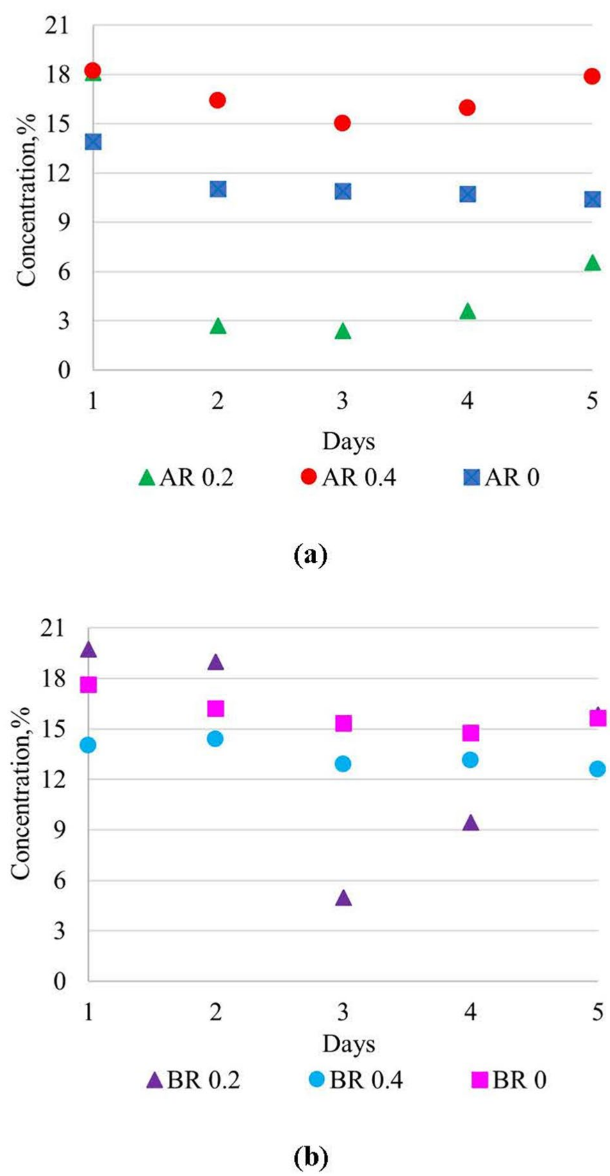

Fig. 6 O_2 concentration during the biodrying process of **a** Experiment A and **b** Experiment B

This phenomenon is explained by the relationship of essential parameters on bioactivities, e.g., CO_2 emission, temperature, and aeration rate. Similar to the work of Ngamket et al. (2021), the CO_2 concentration was raised when the temperature increases under the application of low aeration rate for MSW biodrying in the solar greenhouse bunker [24]. As a result, the bioactivity rises throughout the CO_2 and O_2 concentrations. This study showed the same results as Ngamket et al. research in the context of low aeration rate conditions (AR 0.2 and BR 0.2) resulted in the highest bioactivity corresponded to CO_2 generation and O_2 concentration. Experiment A had the highest spoilage rate presented by gas generation and concentration compared to Experiment B. This was due to better reaction conditions, i.e., moisture and initial organic contents. The O_2 concentration level was used to measure the consumption in bioactivity. The results suggested that the O_2 concentrations are inversely related to the CO_2 concentrations.

Weight loss during the bio-drying process

Weight loss in the experiments is shown in Fig. 7. The initial weight of Experiment A was 59.6 kg, 69.8 kg, and 74.4 kg of AR0, AR0.2, and AR0.4, respectively. The highest weight reduction was shown in the AR 0.4 at 14%, followed by AR 0.2 and AR 0 at 8% and 7%, respectively. The initial weight of Experiment B was 56.6 kg for all BRs. Maximum weight reduction was obtained in the BR 0.2 and BR 0.4 at 6%, while BR 0 was reduced by 5%.

In both experiments, it was found that Experiment A had the greatest weight loss compared to Experiment B. Furthermore, the minimum weight loss of Experiment A was higher than the maximum weight loss of Experiment B. Each experiment also presents the weight average-reduction rate through the linear equation. In Experiment A, AR 0.4 resulted in 3.15% reduction per day ($r^2 = 0.99$), AR 0.2 resulted in 1.81% reduction per day ($r^2 = 0.98$), and AR 0 resulted in 1.44% reduction per day ($r^2 = 0.99$). In Experiment B, BR 0.4 resulted in 1.37% reduction per day ($r^2 = 0.95$), BR 0.2 resulted in 1.17% reduction per day

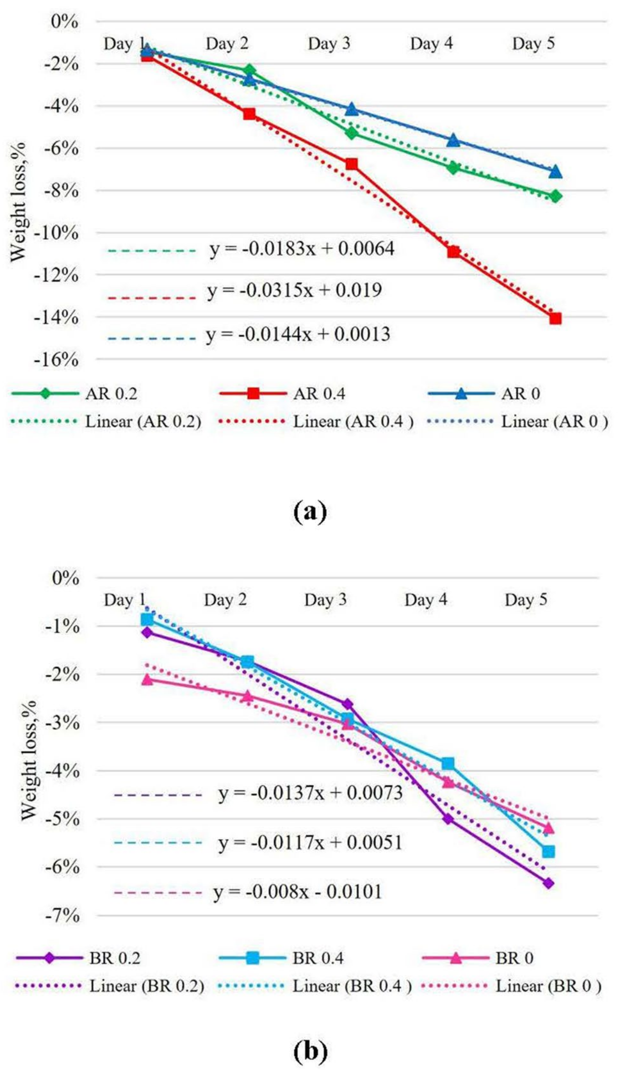

Fig. 7 Evolution of weight loss during the biodrying process of **a** Experiment A and **b** Experiment B

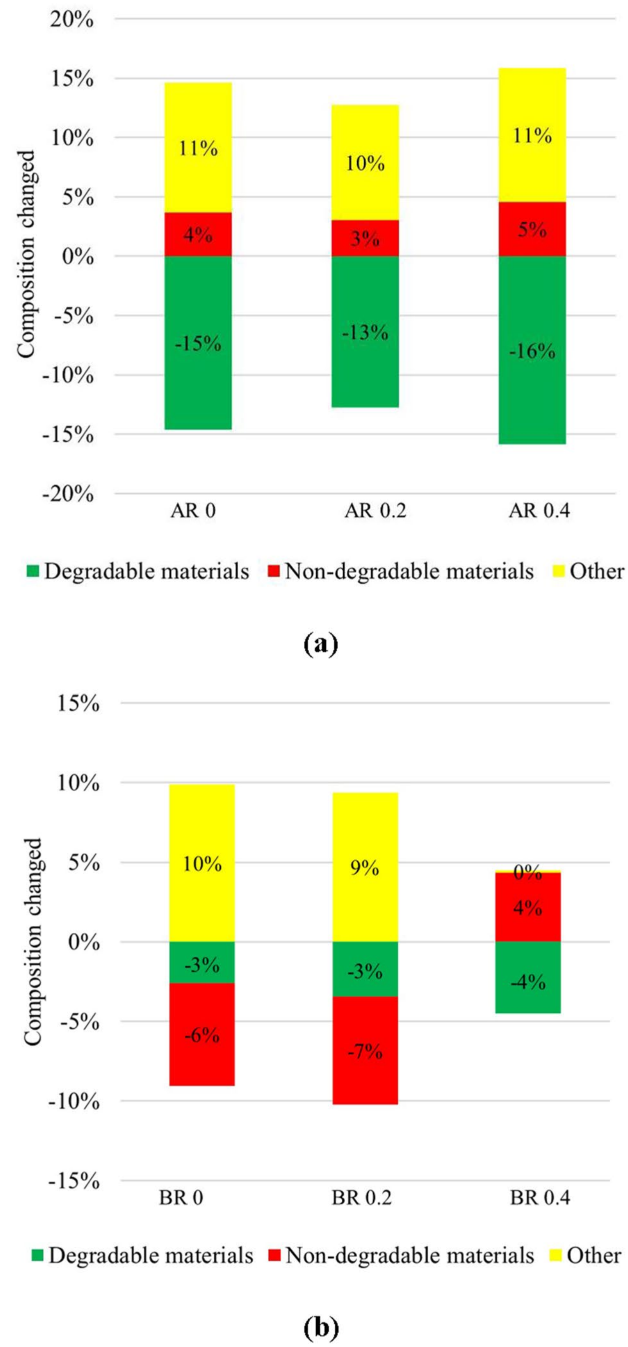

Fig. 8 Composition changed of the biodried product compared to feedstock

($r^2 = 0.98$), and BR 0 resulted in 0.8% reduction per day ($r^2 = 0.96$). Although BR 0.2 and BR 0.4 had the same 6% weight reduction when considering the weight average-reduction rate, BR 0.2 had a greater reduction than BR 0.4, which accounted for a 1.37% reduction per day, and 1.17% reduction per day in BR 0.2 and BR 0.4, respectively.

Composition change

The degradation of degradable material mixed with non-degradable material was changed during the biodrying process. The composition changes due to changes in degradable material, microorganisms break down organic substrate and provide the products, e.g., water, gasses, and heat. The remaining composition is non-degradable material, implying that the proportion of the compositions could be determined.

Figure 8 shows the changes in bio-dried products compared to initial waste. The proportion of degradable materials decreased, indicating biodegradation activity. In Experiment A, the highest percentage of degradable materials could be reduced up to 16% in AR 0.4, followed by AR 0 and AR 0.2 at 15% and 13%, respectively. On the other hand, the percentage of non-biodegradable materials was increased in all AR, which accounted for 5%, 4%, and 3% for AR 0.4, AR 0, and AR 0.2, respectively. Also, other compositions similarly increased by 10% for AR 0.2 and 11% for AR 0 and AR 0.4. In Experiment B, the proportion of change was different from Experiment A. The maximum degradable material decrease was 4% from BR 0.4, followed by 3% of BR 0.2 and BR 0. The percentage of non-biodegradable materials decreased by 7% from BR 0.2, followed by 6% from BR 0, but the percentage of non-biodegradable materials of BR 0.4 increased by 4%. Also, the percentage of other materials was increased by 10% and 9% of BR 0.2 and BR 0, respectively. However, the other material of BR 0.4 was not changed.

In comparison between the two experiments, it was found that Experiment A had a higher composition decrease of degradable material than Experiment B, and the composition increase in the other was also high. This is because degradable materials produce residues that mix with small non-degradable materials that cannot be separated, so the proportion of others has a higher amount. However, non-degradable material had a smaller percentage increase than Experiment B.

Biodrying index

The biodrying process was expected to remove more water and consume fewer organics, i.e., its performance could be indicated as the quantity of removed water per kg of organics consumed. Therefore, the biodrying index (I), defined as the ratio of water loss to organics loss, could evaluate the bio-drying performance, I was calculated by Eq. (2). The smallest value indicates the performance to remove water while retaining organic matter (which remains the fuel carbon), and the organic was defined as a degradable material. Table 2 shows the amount of the degradable material loss and water loss at the end of the biodrying process.

AR 0.4 had the highest degradable material loss of 3.525 kg and the highest water loss of 16.874 kg. AR 0 and AR 0.2 had degradable material loss of 2.186 kg and 2.864 kg, while the amount of water loss for 7.622 kg and 11.209 kg, respectively. Therefore, Experiment A gave the I from AR 0.4 at 0.209 as the lowest value, followed by AR 0.2 and AR 0 at 0.256 and 0.287, respectively.

Table 2 Biodrying index resulted from the proportion of organic loss and water loss

EXPs	Organic weight loss (OL), kg	Water weight loss (WL), kg	Index OL/WL
AR 0	2.186	7.622	0.287
AR 0.2	2.864	11.209	0.256
AR 0.4	3.525	16.874	0.209
BR 0	1.855	1.478	1.256
BR 0.2	1.875	2.121	0.884
BR 0.4	2.087	2.647	0.788

In the case of Experiment B, BR 0.4 had the maximum degradable material loss of 2.087 kg and water loss of 2.647 kg. Degradable material loss in BR 0 and BR 0.4 was 1.855 kg and 1.875 kg, while water loss was 1.478 kg and 2.121 kg, respectively. Therefore, Experiment B gave the I from BR 0.4 at 0.788 as the lowest value, followed by BR 0.2 and BR 0 at 0.884 and 1.256, respectively.

Under the experimental setup in this study, higher air rate effects lower the I value. Moreover, the I values in all trials in Experiment A were lower than in all trials in Experiment B. This indication shows compliance with all of the parameters mentioned above, the initial moisture content and degradable material affect the level degradation reaction. I values have been provided in other research studies. Zhang et al. (2008) studied the biodrying of MSW under the variations of aeration rate in the biodrying reactor; this research calculated I index from the ratio of moisture content loss to organic loss and reported the range of 2.49–6.00 [19]. Mohammed et al. (2017) found the maximum I index at 10.13 obtained from the high degradation of organic waste in the MSW per water loss [25]. In addition, the I index has been reported for various conditions of the feedstock, e.g., initial moisture content, organic content, and bulking agent. The variation of operations depends on reactor configurations, e.g., biodrying reactor, lysimeter, and solar greenhouse biodrying. These might have had an effect on the variations as reported in the literature. However, this study provided the I index using degradable material loss (kg) and water loss (kg) under Wet-RDF as a feedstock performed biodrying. Furthermore, this study proposes I index with the lower organic substrate and high moisture content condition.

Biodrying-air ratio

The biodrying process under aerobic conditions could be measured by aeration fed into the process. This is to ensure that the amount of air is sufficient for decomposition. Due to biodrying being a primary stage in the composting process, this definition describes the relationship between these processes. Biodrying-air ratio (B.A. ratio) is the proportion of the air-feed to the process and stoichiometric air demand for the compositing process [20]; the B.A. ratio is given by Eq. (3).

The feedstock of this study was separated only from the degradable material and then analyzed in the ultimate analysis, e.g., Carbon (C), Hydrogen (H), Oxygen (O), and Nitrogen (N). These elements represent the elemental composition of the degradable substrate, which is shown in the elemental composition in Table 3. The elemental composition was used to calculate the stoichiometric aeration rate demand for the composition process. The

Table 3 Elemental composition of degradable material in the feedstocks each experiment

Particulars	Experiment A (%)	Experiment B (%)
Carbon, (C)	16.50	20.85
Hydrogen, (H)	9.70	9.79
Oxygen, (O)	73.45	69.05
Nitrogen, (N)	0.37	0.31

Table 4 The biodrying-air ratio for each experiment

EXP	Aeration rate input, m^3/kg/day	Stoichiometric aeration rate demand, $m^3/kg_{-organic}$/day	B.A. ratio
AR 0.2	0.2	0.342	0.584
AR 0.4	0.4	0.342	1.168
BR 0.2	0.2	0.460	0.435
BR 0.4	0.4	0.460	0.869

stoichiometric aeration rate demand shows the quantity of O_2 used to digest organic material by microorganisms. The stoichiometric aeration rate demand calculation was under the chemical reaction between organic substrate and O_2. In addition, the O_2 demand for nitrification is not considered for aeration in the biodrying process due to more minor requirements for organic oxidation.

Using the elemental composition transformed into a molecular formula of each feedstocks, it was estimated to be $C_{52}H_{366}O_{173}N$ and $C_{78}H_{440}O_{194}N$ of Experiment A and Experiment B, respectively. In Experiment A, the carbonaceous oxygen demand can be determined as 13,136 gO_2, which can be estimated air volume requirement for 47.3 m^3 at standard temperature and pressure (STP). The aeration rate was estimated as 0.342 $m^3/kg_{-organic}$/day to give five days of operation. On the other hand, Experiment B changed the carbonaceous oxygen demand, air volume requirement at STP, and aeration rate to be 12,524 gO_2, 44.8 m^3, and 0.460 $m^3/kg_{-organic}$/day, respectively. The values of the stoichiometric aeration rate demand and B.A. ratios are shown in Table 4.

The B.A. ratio was determined except that of AR 0 because no aeration was fed into the experimental system. In Experiment A, the highest B.A. ratio was obtained from AR 0.4, calculated for 1.168. On the other hand, Experiment B was given the BR 0.4 as a maximum B.A. ratio accounted for 0.869. The biodrying-air ratio is the crucial parameter for biodrying operation. The physical drying may occur due to the higher B.A. ratio, while the insufficient moisture removal by aeration supplied may occur due to the lower B.A. ratio. Payomthip et al. (2021) reported the suitable B.A. value for biodrying operation and defined the physical drying occurs if the B.A. value was higher than 1.55. They also recommended the B.A. value should be less than 1.55 of that composting requirement [20]. This study found that B.A. value in all trials was less than 1.55. However, B.A. values of AR 0.2, BR 0.4, and BR 0.2 could be defined as inefficient aeration feed because the B.A. ratio was less than 1.

Biodried product

After the process was completed, to provide the efficiency of the biodrying process, the final moisture content (MC) and low heating values (LHV) were analyzed as shown in Table 5. In Experiment A, the moisture content was reduced by 30%, 22%, and 16% for AR 0.4, AR 0.2, and AR 0, respectively. Final moisture content of AR 0.4 was 41%. On the other hand, Experiment B reduced moisture content for 6%, 5%, and 1% of BR 0.4, BR 0.2, and BR 0, respectively. The final moisture content of BR 0.4 was 33%. Although the moisture content reduction of Experiment A was higher than Experiment B, its final moisture content was lower than Experiment B. Since the local cement industry determines RDF properties from LHV and moisture, the obtained moisture content within this study was unaccepted by the local RDF criteria (MC < 30%).

AR 0.4 yielded highest increase of LHV at 60%, resulting in its final value of 4,619.5 kcal/kg. AR 0.2 and AR 0 provided bio-dried products with LHV of 3,686.5 kcal/kg and 3,233.5 kcal/kg, accounted for 22% and 16% increase,

Table 5 Comparison of feedstock and biodried product

Condition	Experiment A			Experiment B		
Code	AR 0	AR 0.2	AR 0.4	BR 0	BR 0.2	BR 0.4
Aeration rate (m^3/kg/day)	0	0.2	0.4	0	0.2	0.4
Initial moister content, %	58	58	58	35	35	35
Final moister content, %	49.1	45.9	41	34.6	33.5	33
Moister content reduction, %	16	22	30	1	5	6
Initial heating value (LHV), kcal/kg	2,889	2,889	2,889	4,172	4,172	4,172
Final heating value (LHV), kcal/kg	3,233.5	3,686.5	4,619.5	4,250.6	4,527.6	4,933.0
Heating value increase, %	12	28	60	2	9	18

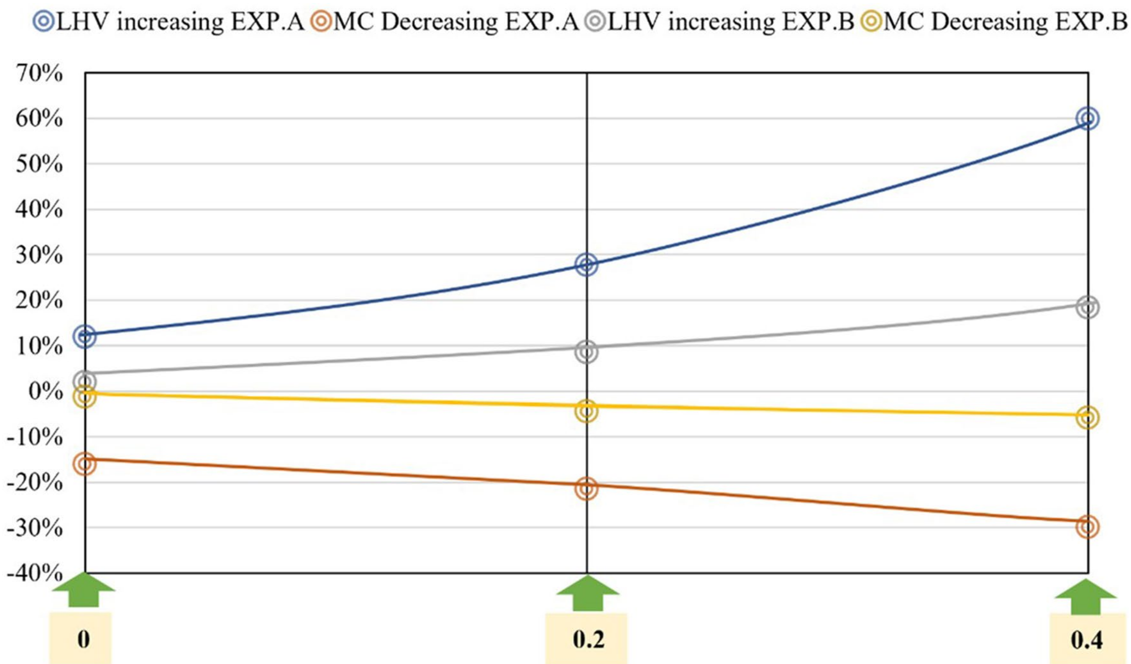

Fig. 9 The change in the final product consisting of LHV and MC values

respectively. In Experiment B, BR 0.4 gave bio-dried product with highest LHV of 4,933 kcal/kg (18% increase), while those of BR 0.2 and BR 0 were 4,527.66 and 4,250.66 kcal/kg, respectively. Referring to the RDF criteria for local cement production, the product of AR 0, AR 0.2, and BR 0 could not meet the required LHV of 4,500 kcal/kg or more.

The comparison of feedstock and bio-dried product suggests different results of moisture decrease and LHV increase corresponding to aeration rates (ARs and BRs) as shown in Fig. 9. Experiment A gave better results compared to Experiment B, i.e., higher moisture decrease and higher LHV increase. This was due to the initial moisture content and degradable material in the feedstock of Experiment A were larger than those in Experiment B. Thus, the decomposition of solid waste in Experiment A was faster than that in Experiment B. The aeration rate also affect the qualities of biodried product, i.e., higher aeration rate yielded higher LHV and lower moisture content of biodried product. High aeration rate provided greater oxygen supply for decomposition of degradable material, while reduce the moisture content at a greater extent.

Conclusion

This study provides information to perform bio-drying for reducing moisture content and increasing heating value in the Wet-RDF by the variation of aeration rate. The Wet-RDF with low degradable materials and high moisture content could be treated with the bioactivity maintained under continuous negative ventilation mode. The provision of sufficient aeration to Wet-RDF bio-drying process was necessary in developing biological reaction demonstrated in terms of daily and accumulated temperatures, inner gasses generation and concentration, bio-drying index, and qualities of final product.

Aeration rate affected temperature accumulation during biodrying. A lower aeration rate reduced heat loss during ventilation, but the accumulation of temperature was achieved under optimal feedstock density. Higher feedstock's initial moisture and organic content also yield higher degradable material and moisture losses when higher feedstock density was used. At a high value of initial moisture content (35%), the bioactivity increases, but a lower value of biodrying index was detected. To maximize water loss and minimize organic content loss, aeration supplied into the biodrying was found at about 5.8% above that was theoretically required for the composting process.

The Wet-RDF biodrying could be performed at an optimum aeration rate of 0.4 m^3 per kg per day. The final product met the RDF standard for the local cement industry in terms of LHV (4,619.5 kcal/kg).

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Author contributions AB and TI (Ph.D. student) performed the experiment. KW and SP suggested the experimental design and the numerical calculations in this study. AB also draft and interpreted data and analysis. All the Co-authors read, check grammar and language, approved the final manuscript, and agreed for this submission.

Data availability The data that support the findings of this study are available from the corresponding author, [KW], upon reasonable request.

References

1. UN (2015) World urbanization prospects: the 2014 revision, vol 41. United Nations Department of Economics and Social Affairs Population Division, New York
2. Intharathirat R, Salam PA, Kumar S, Untong A (2015) Forecasting of municipal solid waste quantity in a developing country using multivariate grey models. Waste Manag 39:3–14
3. Kulkarni BN, Anantharama V (2020) Repercussions of COVID-19 pandemic on municipal solid waste management: challenges and opportunities. Sci Total Environ 743:140693
4. PCD (2020) Thailand state of pollution report 2020. 2020 website https://www.pcd.go.th/wp-content/uploads/2021/08/pcdnew-2021-08-04_06-58-34_275626.pdf.
5. PCD (2020) Report on pollution situation in Thailand, the year 2020, in ministry of natural resources and environment. Ministry of Natural Resources and Environment, Thailand
6. Nithikul J, Karthikeyan OP, Visvanathan C (2011) Reject management from a mechanical biological treatment plant in Bangkok. Thailand Resour Conserv Recycl 55(4):417–422
7. Babel S, Ta AT, Liyanage TU (2020) Current situation and challenges of waste management in Thailand. In: Sustainable waste management challenges in developing countries. IGI Global, p 409–440.
8. Bień J (2021) Production and use of waste-derived fuels in Poland: current status and perspectives. Prod Eng Arch 27:36–41
9. Ryu C, Shin D (2021) Combined heat and power from municipal solid waste: current status and issues in South Korea. Energies 6(1):45–57
10. Zhao L, Gu WM, He PJ, Shao LM (2010) Effect of airflow rate and turning frequency on bio-drying of dewatered sludge. Water Res 44(20):6144–6152
11. Velis CA, Longhurst PJ, Drew GH, Smith R, Pollard SJ (2009) Biodrying for mechanical–biological treatment of wastes: a review of process science and engineering. Bioresour Technol 100(11):2747–2761
12. Punin W, Maneewan S, Punlek C (2014) The feasibility of converting solid waste into refuse-derived fuel 5 via mechanical biological treatment process. J Mater Cycles Waste Manag 16(4):753–762
13. Yuan J, Zhang D, Li Y, Li J, Luo W, Zhang H, Wang G, Li G (2018) Effects of the aeration pattern, aeration rate, and turning frequency on municipal solid waste biodrying performance. J Environ Manag 218:416–424
14. Tom AP, Pawels R, Haridas A (2016) Biodrying process: a sustainable technology for treatment of municipal solid waste with high moisture content. Waste Manag 49:64–72
15. Colomer-Mendoza FJ, Herrera-Prats L, Robles-Martinez F, Gallardo-Izquierdo A, Piña-Guzman AB (2013) Effect of airflow on biodrying of gardening wastes in reactors. J Environ Sci 25(5):865–872
16. Tambone F, Scaglia B, Scotti S, Adani F (2011) Effects of biodrying process on municipal solid waste properties. Bioresour Technol 102(16):7443–7450
17. Ham GY, Lee DH, Matsuto T, Tojo Y, Park JR (2020) Simultaneous effects of airflow and temperature increase on water removal in bio-drying. J Mater Cyclesd Waste Manag 22:1056–1066
18. Zhang D, Pinjing HE, Liming SH, Taifeng JI, Jingyao HA (2008) Biodrying of municipal solid waste with high water content by combined hydrolytic-aerobic technology. J Environ Sci 20(12):1534–1540
19. Zhang DQ, He PJ, Jin TF, Shao LM (2008) Bio-drying of municipal solid waste with high water content by aeration procedures regulation and inoculation. Bioresour Technol 99(18):8796–8802
20. Payomthip P (2021) Biodrying of municipal solid waste by combined air suction and mixing technology. Ph.D thesis, The Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi (KMUTT)
21. Sutthasil N, Ishigaki T, Ochiai S, Yamada M, Chiemchaisri C (2022) Carbon conversion during biodrying of municipal solid waste generated under tropical Asian conditions. Biomass Conv Biorefin. https://doi.org/10.1007/s13399-021-02284-1
22. Yuan J, Zhang D, Li Y, Chadwick D, Li G, Li Y, Du L (2017) Effects of adding bulking agents on biostabilization and drying of municipal solid waste. Waste Manag 62:52–60
23. Zhou HB, Chen TB, Gao D, Zheng GD, Chen J, Pan TH, Liu HT, Gu RY (2014) Simulation of water removal process and optimization of aeration strategy in sewage sludge composting. Bioresour Technol 171:452–460
24. Ngamket K, Wangyao K, Patumsawad S, Chaiwiwatworakul P, Towprayoon S (2021) Quality improvement of mixed MSW drying using a pilot-scale solar greenhouse biodrying system. J Mater Cycles Waste Manag 23(2):436–448
25. Mohammed M, Ozbay I, Karademir A, Isleyen M (2017) Pretreatment and utilization of food waste as energy source by biodrying process. Energy Procedia 28:100–107