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Biodrying of rejected materials from mechanical separation processes of municipal solid waste for utilization as refuse-derived fuel

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Abstract: During the municipal solid waste mechanical separation process, the wastes with sizes >50-100 mm, excluding magnetic items and dense materials, are transformed into refuse-derived fuel. The remainder of the two waste streams can be disposed of in landfills, including materials with a size of ≤50 mm (rejected material 1) and heavy materials with a size of >50-100 mm (rejected material 2). The use of rejected materials for refuse-derived fuel (RDF) production in Thailand has not been investigated. This research aimed to convert the rejected materials into RDF using a biodrying process. The results revealed that rejected material 1 contained both plastic and organic waste. It had low moisture content, high volatile solid content, and high heating values (about 2,074.20-2,680.30 kcal/kg) compared to the rejected material 2. It is indicated that the rejected material 1 was a more suitable raw material for RDF production. For studying the effect of continuous aeration rates on the biodrying process for rejected material 1, three experiments were performed using lysimeters and operated at three different aeration rates, 2.27, 2.77, and 3.02 L/min/kg, for 14 days. At the aeration rate of 2.27 L/min/kg, the biodrying process of rejected material 1 had the highest average temperature (45.9-50.76°C) during the thermophilic phase and the highest accumulated temperature integration value (241.05°C). As a result, the moisture, volatile solids, and ash contents could be reduced to 21.67%, 81.21%, and 18.95%, respectively, with a lower heating value of 3,558.12 kcal/kg. However, the ash content from these RDFs exceeded the quality criteria. Therefore, this produced RDF, which was classified as a low-grade RDF. At the three aeration rates, the biodrying process emitted greenhouse gases between 0. 0.0053-0.0295 kg CO_2e/kg waste, which was significantly less than the landfill of rejected material.

Keywords: Biodrying, Greenhouse gas emissions, MSW rejected materials, Aeration rate, Refuse-derived fuel.

1. Introduction

With the lifestyle shift from agriculture to urbanization, population growth, tourism promotion, and higher consumption, Thailand's municipal solid waste (MSW) has increased accordingly [1]. MSW typically consists of organic wastes such as food waste, yard waste, plastics, wood, textiles, and paper, and inorganic wastes such as glass and metals. The vast majority of MSW is disposed of in landfills [2]. However, waste disposal poses severe environmental threats, such as greenhouse gas (GHG) emissions, odors, and groundwater contamination. In addition, it has adverse effects on human health [3]. Therefore, waste to energy (WtE) is one of Thailand's most appealing MSW management solutions for meeting legal waste management requirements. Depending on the waste composition and GHG emissions, it can reduce the original waste volume by 75-90% [4-5]. In Thailand, WtE approaches such as incineration and refuse-derived fuel (RDF) have been identified as suitable methods for MSW treatment [6]. One ton of MSW is estimated to produce 0.43 tonnes of RDF, and one ton of RDF can generate more than 300 kWh of electricity [7]. Although the incineration of MSW is an appropriate method for the disposal treatment of combustible waste, it has a high initial investment cost. In addition, incineration of MSW, it produces lower calorific values (9.58-17.71 MJ/kg) than the combustion of RDF (16.34-20.70 MJ/kg) [8]. Hence, recovering energy and material from MSW through RDF production is attracting interest.

TPI Polene Power Public Company Limited in Thailand operates a power plant business focusing on generating electricity from waste. The fuel production process begins with the mechanical separation of MSW into separate waste sizes of less than 100 mm, dense fractions, and magnetic waste from the process. The rest of the waste stream is used as feedstock for the production of RDF. Currently, the company is using RDF to generate and sell electricity. Generally, one MSW separation process line can treat 400 tons of MSW feedstock daily. Waste with a size of less than 100 mm is screened out of the process at a rate of approximately 150 tons per day, or 37.5% of the MSW feedstock (information obtained from the interview with staff of the TPI Polene Power Public Company Limited, Rayong Province). The company's estimated capacity to receive MSW in Thailand in 2021 was around 5.25 million tons per year. The rejected materials, which are ≤50 mm waste (light fraction) and >50-100 mm dense waste (heavy fraction) generated during the separation process, are estimated to be 54,750 tons per year. In contrast, approximately 5.19 million tons of waste per year was used to produce 2.19 million tons of RDF. Those rejected materials, which include organic waste, plastic debris, textiles, etc., have high moisture content with a low heating value, have not been used, and are usually

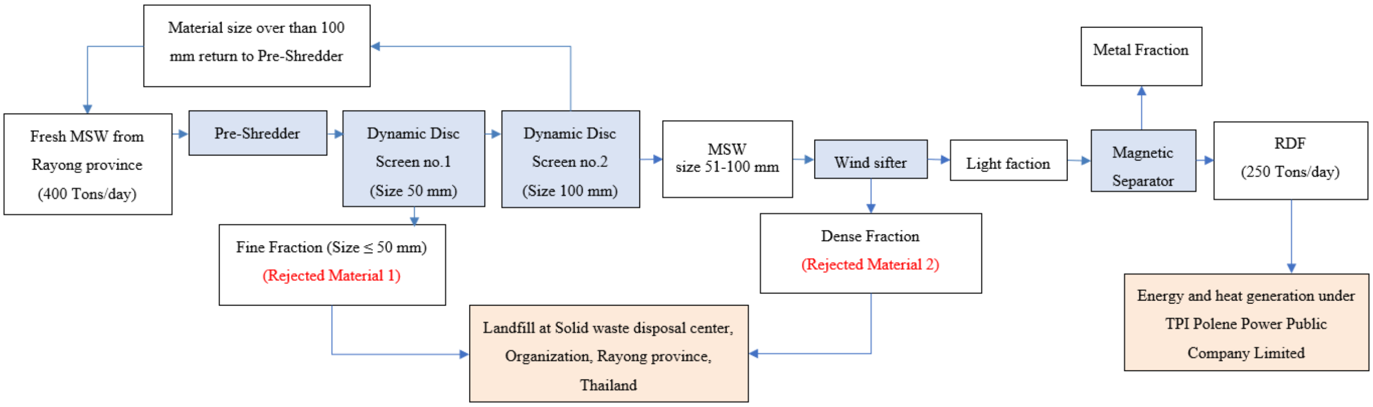

Figure 1. Schematic flow chart for the MSW separation process at the solid waste disposal center, Rayong province, Thailand (TPI Polene Power Public Company Limited and Thaipaiboon Rayong Company Limited, 2020).

disposed of in landfills. However, landfill without methane utilization results in high GHG emissions. One possible solution to reduce the waste treated via landfill is to convert a large portion of the MSW-rejected materials into RDF for energy recovery.

In practice, the admirable RDF is made up of MSW's most combustible components, such as non-recyclable plastics, paper, textiles, wood, and other organic matter, all of which can be burned and which have a high heating value. However, the issue with using MSW as a fuel is the inconsistencies in the heating value of the fuel produced due to variations in the physical composition and the high moisture content (MC) of the waste [5]. Therefore, the desirable RDF properties include a high heating value, low moisture content, and low ash content [9].

According to the literature, calorific value is closely related to the MC and is a significant parameter for assessing MSW's potential to produce RDF. However, the low quality of MSW as fuel is due to its high moisture content (40-70%), reducing the calorific values of the waste. Therefore, removing water from the waste with a high moisture content of 20-25% is essential for burning solid waste successfully. Biological drying (biodrying) is a convective evaporation process using biological heat resulting from the aerobic biodegradation of the organic waste and forced aeration [10]. The heat produced from the decomposition processes can reduce MC below the necessary threshold for biodegradation. This process increases the waste's heating values through minimal biodegradation [11]. A good biodrying process removes much of the water and has low volatile solid degradation and high calorific value [12]. So proper control of the operational parameters such as temperature and airflow rate during the aerobic stage can achieve high biodrying efficiency [13]. Optimizing the biodrying process is essential since high temperatures cause increased metabolic reactions in microbes [14]. Aeration rate is the primary variable used to control processes in biodrying, both in the laboratory and in commercial applications; the use of low aeration rates results in decomposition without significant moisture loss. When the aeration rate is too high, the waste dries only by physical phenomena because of the lack of microbial activities [15].

The potential of MSW in Thailand for producing RDF has been studied by several researchers [1,7,16-17]. However, research has yet to be conducted on the feasibility of using rejected materials from the MSW mechanical separation processes. Therefore, this study's objective was to assess the feasibility of using rejected materials from the MSW mechanical separation process for RDF production. In this study, the rejected materials were characterized to serve as feedstock for RDF production. Furthermore, the effect of the aeration rates for biodrying rejected materials from MSW mechanical separation processes on the physicochemical property changes during the biodrying process, and properties of the treated waste were investigated.

2. Materials and Methods

2.1 Materials

This study used the rejected materials as raw materials from the solid waste disposal center operated by TPI Polyene Power Public Company Limited and Thaipaiboon Rayong Company Limited in Rayong province, Thailand. The waste separation and treatment processes in this center are shown in Figure 1. The mechanical separation process includes shredding and separation processes. After waste shredding, the pre-shredded waste is sent to a dynamic disc screen, which separates the waste by size, over 50 mm and under 50 mm. Rejected material 1 is a fine fraction with a size of ≤50 mm. The remainder of the waste is then processed through a 100 mm dynamic disc screen and subjected to a wind sifter to separate the light fraction from the dense fraction. The rejected material 2 is a dense fraction that is >50-100 mm in size and was obtained by the wind sifter unit. Approximately 150 tons of rejected materials 1 and 2 per day are currently disposed of in landfills. The appearance of the rejected material 1 and 2 can be seen in Figure 2.

Figure 2. Rejected materials from the MSW separation plant: (A) rejected material 1 is a fine rejected fraction passing through a 50 mm dynamic disc screen, and (B) rejected material 2 refers to the dense rejected fraction passing through a 100 mm dynamic disc screen and subjected to a wind sifter.

2.2 Physical and chemical characteristics of the feedstock

The rejected materials 1 and 2 were collected to analyze the physical and chemical characteristics. Physical compositions of the rejected materials were identified by using the quartering method. The waste composition was classified according to the IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [18]. The potential of waste used for RDF production was identified based on combustible wastes such as food waste, garden and park waste, paper, wood, rubber, and plastic waste. The proximate analysis of the moisture, volatile solids, and ash content was analyzed according to the ASTM methods with ASTM E 949-88, ASTM E 830-87, and ASTM E 830-87, respectively [19-20]. The heating value was determined according to ASTM E 711-87 [21].

2.3 Experimental setup

Three laboratory-scale biodrying lysimeters (30 cm in diameter and 150 cm in height) were used in the experiments (Figure 3). The biodrying lysimeters were built with PVC pipe and wrapped in thermal insulation sheets. Temperature sensors were installed in the lysimeters to measure temperature variations. The lysimeters were outfitted with gas collection points at three different depths (50 cm, 100 cm, and 140 cm from the bottom) installed to collect the gases produced during the biodrying process. In addition, a blower was installed at the bottom of the lysimeter. This study used a continuous aeration system. Negative pressure is created in the lysimeter when the blower is turned on to draw in outside air and promote air movement. This helps to aerate the waste mixture, as the air is slowly forced into the lysimeter from the top due to atmospheric pressure. Finally, a PVC pipe was installed at the bottom of the lysimeter to collect the leachate.

The experiment included three treatments (T1 with 2.27 L/min/kg, T2 with 2.77 L/min/kg, and T3 with 3.02 L/min/kg) that were run for 14 days at different aeration rates [13]. The initial wet weights of the rejected materials in T1, T2, and T3 were 39.9, 41.7, and 44.8 kg, respectively. During the biodrying process, changes in the physical and chemical properties of the wastes, including temperature, moisture content, volatile solids content, and greenhouse gases (GHGs) were monitored.

The wastes were taken from the lysimeter on days 0, 7, 10, and 14 and analyzed for MC, volatile solids, ash content, and heating value. The temperature, GHG concentration, and weight reduction were all measured daily. Furthermore, the rejected material's GHG emissions from the biodrying process were calculated and contrasted with the rejected material's GHG emissions from the conventional landfill.

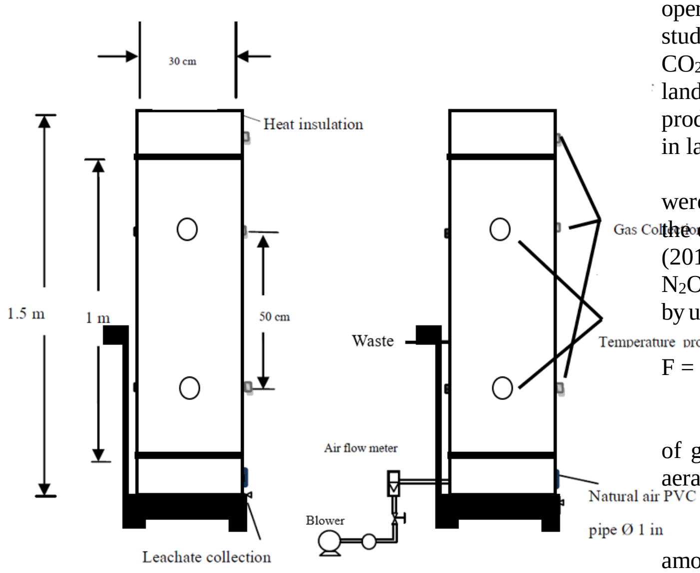

Figure 3. A laboratory-scale biodrying lysimeter.

2.4 Analysis

The sample MC was determined according to ASTM E 949-88 (reapproved 2004) by drying it at 107±3 °C for 1 hour [20]. The percentage weight reduction was calculated as [(initial weight- current weight) / initial weight]*100.

The ash content was determined following ASTM E 830-87 by gradually heating the sample to ignition at 575±25°C, cooling it, and weighing it until the ash weight was constant [19]. The percentage of volatile solid was calculated as %Ash = 100 - %Volatile solid. The weight reduction was determined by weighing each lysimeter. To measure the weight reduction, a weighing machine was placed at the bottom of each lysimeter. The High Heating Value (HHV) was determined using the sample ignited in a bomb calorimeter following ASTM E 711-87 [21]. The Low Heating Value (LHV) was calculated using Equation 1.

Low Heating Value (LHV) = High Heating Value (HHV) – 211.19H (kJ/kg) (1)

A thermocouple connected to a data logger (Graphtec GL220 Series, 10-Channels Data Logger from Japan) was used to determine the temperature. In addition, the temperature integration (TI) index was calculated using the following equation [22] to evaluate the biodrying process performance:

$$TI = \sum_{i=1}^{n}(Twi - Tai) \quad (2)$$

where t_{wt} is the average temperature of the rejected material in the lysimeter at time t (ºC), and t_{ai} is the average ambient temperature at time t (ºC).

GHGs were collected at the lysimeter's upper, middle, and bottom parts for 14 days of operation during the biodrying process. Three gas emission samples were collected and kept in Tedlar bags, and their average values were reported. Agilent 7890B gas chromatography (GC) was used to measure the concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In addition, a Flame Ionization Detector (FID-Methanizer) enabled CO_2 and CH_4 detection, and an Electron Capture Detector (ECD) measured N_2O.

The scope of the GHG emissions calculation for the rejected material biodrying process included only GHG emissions during the biodrying process, not electricity used for the biodrying operation, waste transportation, or RDF utilization. Therefore, the study's GHG emissions from the biodrying process, including CO_2, CH_4, and N_2O emissions, were calculated. Conventional landfill GHG emissions, on the other hand, comprised only CH_4 produced during the anaerobic decomposition of organic waste in landfills.

Since the gases collected during the biodrying process were collected in an open system rather than a closed system, the dynamic flux chamber method was described by Zhang et al. (2018) [23] was used to determine the fluxes of CO_2, CH_4, and N_2O in the lysimeters. The GHG flux calculation was determined by using Equation 3:

F = (Gas concentration (ppm)*MW/(V/mole)/1000) * Q (3)

where: F = flux of gas (g/hour), MW = molecular weight of gas (g/mole), V/mole = volume of gas (m^3/mole), and Q = aeration rate (m^3/hour).

The GHG equivalencies (CO_2eq), which are the equivalent amount of carbon dioxide (CO_2) emissions, were calculated using each pollutant's global warming potential (GWP). CO_2, CH_4, and N_2O have GWP values of 1, 28, and 265 [24].

The conventional landfill's GHG emissions were calculated using the methodology tools of the Thailand Greenhouse Gas Management Organization's "Thailand voluntary emission reduction program (T-VER)" (Public Organization). This method adapted the IPCC and CDM tools and methodologies to Thailand's situation. The First Order Decay (FOD) Equation 4 can be used to calculate the methane gas produced by waste landfills, which only included CH_4 produced by organic waste decomposition in landfills under specific anaerobic conditions [25].

$$BE_{CH4,SWDS,y} = \varphi_y x (1-f_y) x GWP_{CH4} x (1-OX) x 16/12 x F x DOC_{f,y} x MCF_y$$
$$x \sum_{x=1}^{y} \sum_j W_x x p_j x DOC_j x e^{-kj(y-x)} x (1-e^{-kj}) \quad (4)$$

Where: $BE_{CH4,SWDS,y}$ = methane (CH_4) emissions from municipal solid waste landfills in year y (tCO_2e), y = year, x = first year of landfill operation (x=1), j = number of MSW types, φ_y = model correction factor in year y (default 0.85), f_y = the proportion of methane forced to be collected from landfills and incineration in year y, GWP_{CH4} = 28, OX = oxidation factor (default 0.1), F = proportion of methane in the total gas generated from the landfill (quantitative proportion) (default 0.5), $DOC_{f,y}$ = biodegradable organic carbon in years y (default 0.5), MCF_y = Methane Correction Factor (default 0.4 - 1.0) W_x = total waste in year y (t, wet weight), P_j = proportion of j waste, DOC_j = biodegradable organic carbon of j waste (default 0.15-0.43), and k_j = degradation rate of j waste (default 0.035-0.400).

2.5 Statistical analysis

The data from the biodrying process was analyzed using SPSS for Windows version 11.5. Scheffe's method was used to determine whether the treatments had significant differences.

3. Results and Discussion

3.1 Physico-chemical characterization of feedstock

To assess the potential of the rejected fraction as a feedstock for RDF production, the two rejected materials generated during the MSW plant's mechanical separation process were collected for physical and chemical characterization. As shown in Table 1, it was found that rejected material 1 contained 91.41% combustible waste, which was greater than the combustible waste content in rejected material 2 (81.96%). Furthermore, the composition of the combustible waste of rejected material 1 contained 70.69% plastic waste which was substantially more than rejected material 2.

Table 1. Composition of the MSW rejected materials (weight percentages by mass).

Rejected material composition	Rejected material 1	Rejected material 2
	%	%
Combustible waste	91.41[a]	81.96[b]
1. Food waste	7.49 ± 2.72[a]	33.0± 0[b]
2. Yard and park waste	0± 0.00[a]	14.17± 0[b]
3. Paper and cardboard	1.02± 0.53[a]	0.60± 0[a]
4. Wood	2.71± 0.93[a]	9.60± 0[b]
5. Textiles	6.14± 1.23[a]	1.29± 0[b]
6. Nappies (disposable diapers)	0.01± 0.01[a]	5.36± 0[b]
7. Rubber and leather	3.35± 0.67[a]	2.62± 0[a]
8. Plastics	70.69± 4.41[a]	15.32± 0[b]
Non-combustible waste	8.59[a]	18.04[b]
9. Metal	0± 0.00[a]	0.85± 0[b]
10. Glass	0.01± 0.01[a]	5.56± 0[b]
11. Other (e.g., ash, dirt, dust, electronic waste)	8.58± 2.81[a]	11.63± 0[b]
Total (kg)	100	100

Note: Scheffe's test was used to compare pairwise means. At 95% confidence, values with the same letters are not statistically different.

In terms of physicochemical properties, the rejected material 1 had lower heating values (LHV) (2074.20-2680.30 kcal/kg), lower MC (46.63%), and lower volatile solid values than rejected material 2 (680.80-1252.80 kcal/kg, 57.6%, and 82.72%). Higher LHV in the rejected material 1 may form a lower MC and higher presence of plastics. Therefore, the higher the quantity of plastics, the higher the LHV. The findings agreed with those of Boonpa (2015), who discovered that plastic (LDPE) had the highest heating value, while food waste (organic waste) had lower heating levels. Since the satisfactory quality of the RDF requires a high heating value, low MC, and low ash, the waste characteristics used as feedstock for RDF production must correspond to the required RDF characteristics [22]. Therefore, the rejected material 1 was chosen as the feedstock for the biodrying process used to produce RDF.

Table 2. Physicochemical characteristics and calorific values of the two rejected materials obtained from the MSW plant.

Parameter	Unit	Rejected material 1	Rejected material 2
Moisture content	%	46.63 ± 0.02 [a]	57.60 ± 0.04 [b]
Volatile solids	%	82.72 ± 0.05 [a]	88.43 ± 0.05 [b]
Ash	%	17.28 ± 0.05 [a]	11.57 ± 0.05 [b]
Lower heating value (LHV)	kcal/kg MJ/kg	2074.20 [a] (8.68 MJ/kg)	680.80 [b] (2.85 MJ/kg)

Note: Scheffe's test was used to compare pairwise means. At 95% confidence, values with the same letters are not statistically different.

3.2 The effect of aeration rates on the bio-drying process

3.2.1 Temperature profile

The biodrying process at various aeration rates is shown in Figure 4. Temperature is a critical parameter in evaluating biodrying performance because the heat generated by microbial activity causes the temperature to rise during the biodrying process [26]. The average temperature range at the two depths (50 and 100 cm depth from the bottom) during the biodrying process for T1, T2, and T3 were 50.76-45.99°C, 47.38-47.39°C, and 45.93-38.68°C, respectively, which was significantly higher than the ambient temperature (32.3°C) (Figure 4 (A), (B), and (C)). Thus, the temperature conditions for the three treatments were in the range of the thermophilic phase between 40-65°C. Xu et al. (2019) [27] reported that the thermophilic phase (40-60°C) has the highest microorganism activity and, thus, the highest degree of biological material degradation.

As shown in Figure 4, the temperature evolved in three stages during the biodrying process: heating phase (ambient to mesophilic temperature (<40°C)), thermophilic phase (≥40°C), and cooling phase (≤40°C). However, the time it took to reach the maximum temperature and the maximum obtained temperature were both significantly affected by aeration rates. T1, T2, and T3 reached the thermophilic phase on days 3, 3, and 5, respectively, reaching their peak temperatures of 55, 60, and 50°C on days 8, 8, and 10, respectively. The results indicated that T1 and T2 had a shorter heating phase and achieved the thermophilic phase faster than T3. Furthermore, it was implied that T1 and T2 had a faster decomposition process than T3. The provision of too much air in T3 may affect the drying process because of the shortened thermophilic stage and reduced thermophilic temperature range. Physical phenomena, rather than heat generated by microbial activity, could be responsible for drying [28].

Temperature differences between waste layers were measured in this study to investigate the effect of the aeration rate on waste decomposition based on the temperature distribution within the lysimeter (Table 3). In T2, the average temperature at the middle and bottom of the lysimeter during the heating, thermophilic, and cooling phases, did not differ significantly (p>0.01). However, T3 had a lower average temperature at the lysimeter's middle (100 cm depth from the bottom) than at the bottom (50 cm depth from the bottom) during the thermophilic phase and cooling phase (p<0.01), as shown in Figure 4. Previous research (Zhang and Chen, 2016; Mohanraj and Varga, 2016; Nigam and Das, 2018) suggested that the aeration rate influences temperature distribution homogeneity in the biodrying process. Because of localized heat generation and limited heat dissipation, higher aeration rates can result in non-uniform temperature distribution, resulting in hot spots within the reactor. Furthermore, these studies suggest that several factors, including aeration rate, moisture content, and reactor design, influence temperature distribution homogeneity in the biodrying process.

3.2.2 Temperature integration

The accumulated TI index for the entire process (Figure 5) indicated that the TI values of T1 and T2 at day 14 were comparable and significantly higher than T3 (P<0.05). These TI values are significantly lower than those reported by Payomthip et al. (2022), where higher TI values could be attributed to the composition and quality of the MSW used as a feedstock. TI was related to the heat generated by microbial degradation, implying the waste materials' ability to self-heat, and was also related to the biodrying treatment time. The higher the heat evolution, the higher the daily TI values obtained. According to the findings, increasing the aeration rate did not improve the biodrying process. Aeration rates greater than 3.02 L/min/kg might cause faster drying by ventilating the air inside the lysimeters, leading to heat loss and lowering the system's daily TI and accumulated heat. Our findings agreed with those of Payomthip et al. (2022) who found that the TI value of the biodrying process of MSW decreased when the aeration rate supplied was excessive.

Figure 6 compares the temperature integration (TI) values of the three phases of the biodrying process. The TI values of T1 and T2 were clearly higher than T3 in the second phase (thermophilic phase days 3-11) and cooling phase. The result is consistent with the temperature evolution depicted in Figure 4. According to the findings, excessive aeration does not improve biodrying efficiency.

Table 3. Temperature layer significance values in three lysimeters operated at different aeration rates.

<table>
<tr><th rowspan="2">Treatments</th><th colspan="3">Duration</th></tr>
<tr><th>Heating phase day 0-3</th><th>Thermophilic phase day 3 -11</th><th>Cooling phase day 11-14</th></tr>
<tr><td colspan="4">T1 with 2.27 L/min/kg</td></tr>
<tr><td>100 cm depth from the bottom</td><td rowspan="2">>0.01</td><td rowspan="2"><0.01</td><td rowspan="2">>0.01</td></tr>
<tr><td>50 cm depth from the bottom</td></tr>
<tr><td colspan="4">T2 with 2.77 L/min/kg</td></tr>
<tr><td>100 cm depth from the bottom</td><td rowspan="2">>0.01</td><td rowspan="2">>0.01</td><td rowspan="2">>0.01</td></tr>
<tr><td>50 cm depth from the bottom</td></tr>
<tr><td colspan="4">T3 with 3.02 L/min/kg</td></tr>
<tr><td>100 cm depth from the bottom</td><td>>0.01</td><td><0.01</td><td><0.01</td></tr>
</table>

Note: Scheffe's test was used to compare pairwise means. At 99% confidence, values with the same letters are not statistically different.

Figure 4. Daily average temperature (at a depth of 50 and 100 cm from the bottom) during the bio-drying process of the MSW rejected material 1 at different aeration rates: (A) T1 (B) T2 and (C) T3.

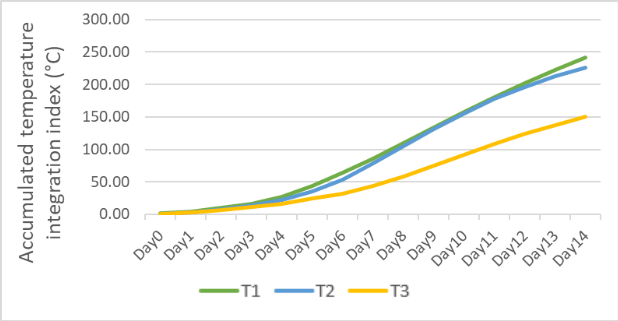

Figure 5. The time course of accumulated TI of the bio-drying process at different aeration rates.

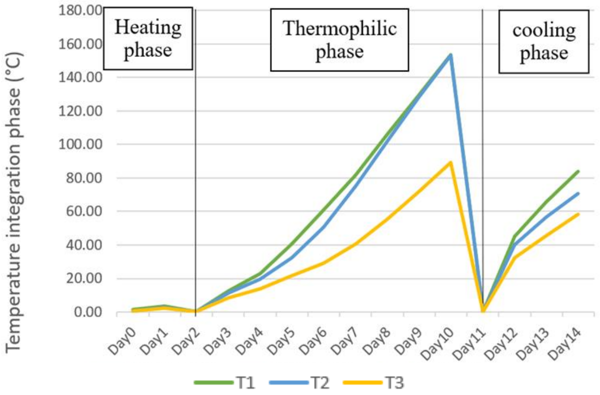

Figure 6. Temperature-integrated phase of the bio-drying process at different aeration rates.

3.2.3 Weight loss and moisture removal

The heat generated during the drying process by the metabolic activity of microorganisms and the mechanism of passive ventilation causes moisture removal from the biodried materials, reducing both their weight and MC. The total weight losses of T1, T2, and T3 were 14.89%, 14.26%, and 10.26%, respectively, on day 14 of the biodrying process. The total moisture reductions of T1, T2, and T3 were 44.94%, 44.70%, and 42.90%, respectively. Total weight loss and total moisture reduction did not differ between T1 and T2 ($p>0.05$), but T1 and T2 experienced significantly greater total weight loss and total moisture reduction than T3 ($p<0.05$).

The weight loss accumulation phase was identified to comprehend how the aeration rate impacts biodrying. Figure 7 shows that T1 and T2 had more significant weight loss during the heating, thermophilic, and cooling phases than T3. The highest weight loss was observed in T2 and T3 during the thermophilic and cooling phases. The results were consistent with the highest accumulated TI value during the 2 phases (Figure 6). The results demonstrated that the highest weight loss and moisture reduction occurred at airflow rates of 2.27 and 2.77 L/min/kg. The results were consistent with the two treatments' highest peak thermophilic temperatures and thermophilic range (Figure 1). Excessive forced air does not effectively remove moisture from waste material. According to the findings, an optimum aeration rate may provide favorable conditions for the microbial degradation of organic waste, which produces heat. The heat generated within the waste pile thus causes moisture to be drawn out of the waste, reducing the weight of the waste. Excessive aeration may result in heat loss from the lysimeter through passive ventilation, which would accumulate low-temperature integration indices (Figure 5 and Figure 6), reduce microbial activity, and ultimately result in less moisture removal and weight loss.

3.2.4 Volatile solids and ash contents

Generally, a proper air-supplied condition produces low degradation of volatile solids and does not cause fast drying due to evaporation [29]. Therefore, the volatile solid content in the waste should be reduced as far as possible to ensure less ash in the final RDF product. As reported in Table 4, T1 has the highest volatile solids content (81.05%) and Lower Heating Value (LHV) of 3558.12 (kcal/kg), with the lowest ash content (18.95%). However, the volatile solids, ash content, and LHV in the treatments with aeration rates of 2.27 and 2.77 L/min/kg were not significantly different ($p>0.05$). Therefore, considering energy saving, an aeration rate of 2.27 L/min/kg was promising.

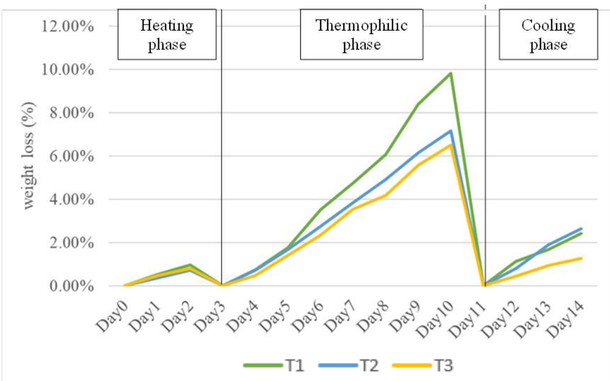

Figure 7. Weight loss accumulation phase of the biodrying process at different aeration rates.

Table 4. The chemical properties and calorific values of the bio-dried MSW rejected material 1.

Parameter	Time	T1	T2	T3	Cement kiln standards in Thailand	
					SCI Eco Services Company (2020) [30]	TPIPL Power Company (2015) [31]
% Moisture content	Day 0	64.57 ± 0.41			≤ 30 %	< 35 %
	Day 14	19.63 ± 0.81[a]	19.87 ± 0.32[a]	21.67 ± 0.11[b]		
% Volatile solids	Day 0	84.17 ± 0.09			-	-
	Day 14	81.05 ± 0.02[a]	80.13 ± 0.02[ab]	77.65 ± 0.03[b]		
% Ash content	Day 0	15.83 ± 0.09			-	< 15 %
	Day 14	18.95 ± 0.02[a]	19.87 ± 0.02[ab]	22.35 ± 0.03[b]		
Lower Heating Value (LHV, kcal/kg)	Day 0	2272.47 ± 1.24			2500 – 6001	> 3500
	Day 14	3558.12 ± 1.12[a]	3440.89 ± 0.94[a]	3318.01 ± 1.52[a]		

Note: At 95% confidence intervals, values with the same letters are not statistically different.

3.2.5 RDF quality

The desirable RDF properties include a high heating value, low MC, and low ash content; however, in Thailand, the satisfying property of RDF is determined by the customer as the producer in cement manufacturers. Table 4 compares the RDF quality obtained in this study to the Thailand standard of the TPIPL Power Company (2015) and SCI Eco Services Company (2020). The LHV and MC of RDFs obtained in the three treatments satisfied Thailand's RDF standards. During the process, the RDF produced by the biodrying process with the best aeration rate treatment 1 (T1) had the lowest MC and highest calorific value. However, the RDF produced in all treatments had high ash content, which exceeded the ash content level of the RDF required by Thailand's TPIPL Power Company. As a result, the RDF generated in this study was classified as a low-grade RDF.

3.3 Greenhouse gas emissions

In order to gain a better understanding of the overall environmental impact of the biodrying process under different aeration rates, we determined greenhouse gas (GHG) concentrations and emissions. As shown in Figure 8, the three treatments emitted carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are greenhouse gases that contribute to global warming. Additionally, the three treatments emitted more CO_2 and less CH_4 and N_2O from the decomposition of biodegradable organic matter in the rejected materials during the 14-day biodrying process. Levels of CO_2 were significantly higher than those of CH_4 and N_2O throughout the biodrying process. The results suggested that the drying process of waste under aeration promoted the activity of microorganisms to oxidize organic matter to CO_2, releasing energy for growth and reproduction. Methane production, on the other hand, is limited under aerobic conditions. Similarly, the production of N_2O is limited under aerobic conditions by promoting the activity of nitrifying bacteria over denitrifying bacteria.

Considering the effect of aeration rates on GHG concentrations, it was evident that T2 and T3 had the lower CO_2, CH_4, and N_2O concentrations during the drying process. On the other hand, T1, with lowest aeration rate, showed the high CO_2, CH_4, and N_2O concentrations during the drying process. The results supported those of Suthiprapa et al. (2020) [30], who found that the MSW biodrying process can result in high concentrations of CO_2, NO_2, and CH_4 at low aeration rates.

Total GHG emissions for T1, T2, and T3 were 0.0295, 0.0147, and 0.0053 kg CO_2e / kg waste, respectively (Table 5). Results showed that the total GHG emissions from the biodrying process increased with the aeration rate. Increasing the aeration rate during the biodrying process can help to reduce the production of methane and nitrous oxide (Figure 8), two potent greenhouse gases, and promote the production of carbon dioxide, which has a much lower global warming potential. This has the potential to significantly reduce GHG emissions from the biodrying process. T1 produced the most partial emissions of any treatment. Because the GWPs of CH_4 and N_2O are greater than those of CO_2, the highest levels of CH_4 and N_2O emissions in T1 (Figure 8) may contribute to high total GHG emissions. Our findings agreed with Zaman et al. (2018) [3], who discovered that increasing the aeration rate increased the aerobic biodegradation rate, decreasing CH_4 and CO_2 emissions.

To determine how the biodrying process of the rejected material can reduce global warming from gas emissions, the GHG emissions from the drying process with the rejected material 1 and the conventional landfill were compared. As shown in Table 5, the conventional landfill's GHG emission calculation results were approximately 0.3863 kg CO_2e/kg waste. In this study, the total value of total GHG emissions by the biodrying process was 0.0053 - 0.0295 kg CO_2e /kg waste, which was much lower than GHG emissions from landfills. The biodrying of rejected material can reduce GHG emissions by 13-74 times. The results were consistent with previous research, which found that biodrying can emit VOCs and other gases that may contribute to global warming, such as CO_2, CH_4, and N_2O [3]. The findings indicated that the biodrying process is critical in mitigating environmental issues.

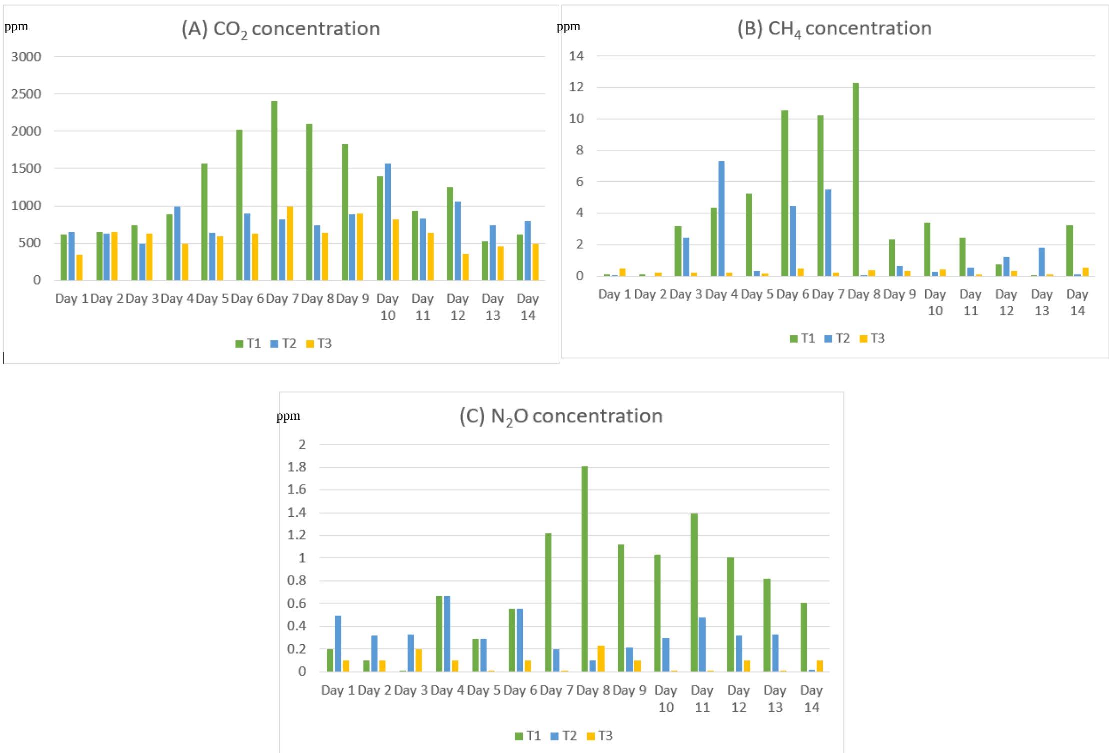

Figure 8. Greenhouse gas concentrations during 14 days of biodrying process for MSW-rejected material using different aeration rates. (A) CO_2, (B) CH_4, and (C) N_2O.

Table 5. Total GHG emissions (kg CO_2e / kg waste) from the biodrying process of the rejected materials under different aeration rates.

Total GHG emissions	
Treatment	kg CO_2e / kg waste
Conventional Landfill*	0.3864
Biodrying process (T1)	0.0295
Biodrying process (T2)	0.0147
Biodrying process (T3)	0.0053

***Total GHG emissions were calculated using the methodology tools of the Thailand Greenhouse Gas Management Organization's "Thailand voluntary emission reduction program (T-VER)" (Public Organization) [25].

4. Conclusion

The study demonstrated the feasibility of the biodrying of the MSW-rejected materials for producing RDF. As the feedstock for RDF production, the rejected materials are composed mostly of food waste and plastic fractions with low MC and high calorific value. The continuous aeration rate of 2.27 L/min/kg/kg for 10-14 days was suitable for biodrying. The biodrying process could reduce the MC to 21.7%, reaching 3558.12 kcal/kg of LHV (LHV as received), which is associated with the standard for high-quality RDF in Thailand. However, the ash content requirement for the produced RDF was higher than that standard. Therefore, the RDF obtained was classified as a low-grade RDF based on this condition. Transforming the rejected materials to RDF by the biodrying process emitted less GHG than landfill technology, thus mitigating total GHG emissions. A high heating value, with low moisture and ash content are requirements for Thailand's high-quality RDF. In addition, sulfur and chlorine are crucial RDF quality parameters in combustion processes. Chlorine and sulfur, however, were not measured in this study. Therefore, to ensure that the RDF in this study complies with the RDF standards of Thailand, it is necessary to determine further the chlorine and sulfur concentrations in the produced RDF.

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