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Effect of Negative Aeration Rates on Water Balance in Biodrying of Wet-Refuse-Derived Fuel

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Abstract

Biodrying as a part of mechanic biological treatment (MBT) is a wide application method to reduce the excess moisture content in the substance and to improve the combustible materials as refuse-derived fuel (RDF) production process. The moisture content is reduced by evaporation and leachate generation during the biodrying process. To minimize the leachate generation due to it being more harmful to the environment, the optimization of the aeration rate should be assessed. Therefore, this study investigated the water balance under the variation of continuous negative aeration. The experiment set aeration rates of 0.4, 0.5, and 0.6 m^3/kg/day. The operation time of each experiment was set to five days. This study was performed with a lysimeter scale using wet-RDF as a feedstock. The initial weight of wet RDF was 70.0 kg. At the end of the operation, the comparison of moisture content change in the feedstock and biodried products from evaporation and leachate generation was analyzed. The study illustrated that the highest moisture content reduction by evaporation was obtained from 0.4 m^3/kg/day, followed by 0.5 m^3/kg/day and 0.6 m^3/kg/day, respectively. The highest water reduction by leachate generation was obtained at 0.6 m^3/kg/day, followed by 0.4 m^3/kg/day and 0.5 m^3/kg/day, respectively. The final moisture content in the biodried product was 20.27 kg, 23.03 kg, and 23.47 kg from the negative aeration rates of 0.4, 0.5, and 0.6 m^3/kg/day, respectively. Also, the moisture reduction of each experiment was 35%, 27%, and 26% that corresponding to weight reduction at 18%, 17%, and 15% of 0.4, 0.5, and 0.6 m^3/kg/day, respectively.

Keywords : Biodrying; Wet-RDF; Water balance; Moisture removal

Introduction

Waste generation is steadily increasing in developing countries, especially Thailand, due to the growth of industrialization and urbanization. However, mismanagement of municipal solid waste (MSW) not only severely impacts the environment but also puts the public's health at risk and raises several other socioeconomic issues that need to be addressed [1]. Thailand's Pollution Control Department estimates a nationwide total of 26.9 Mt of MSW, of which 16% was produced alone in Bangkok [2]. The composition of MSW in Thailand varies depending on urbanization, population density, and income in various regions, but it usually comprises roughly 51% organic waste, 22% plastic, 13% paper, and 3% glass. The whole MSW was appropriately managed by 47%, disposed of by 27%, and reused/ recycled by 20%; the rest was incinerated [2, 3].

Waste-to-energy conversion is now a kind of renewable energy that can benefit both the environment and the global economy. However, a waste-to-energy solution through thermal waste treatment, such as incineration, is inappropriate in Thailand due to the higher proportion of organic fractions in their MSW composition [4]. In Bangkok, Thailand, at On-Nut waste transfer station is receiving more than 45% of the whole MSW generated from Bangkok and the metropolitan area, mechanical biological treatment (MBT) is used to separate the MSW for converting into various applications, i.e., recycling, composting, refuse-derived fuel (RDF) production, incineration, and landfilling. After MSW passes through the MBT process, the remaining material can be transferred to the RDF production due to comprising more than 50% non-degradable material, less than 30% biodegradable material, and recycling material. The chemical composition was analyzed to characterize the RDF production potential. The chemical composition has been measured the moisture content and heating value for more than 40% and less than 3,000 kcal/kg, respectively. Therefore, this object has been named wet-RDF [5, 6].

The viability of MBT is a comprehensive application method related to MSW management. Biodrying is a part of the MBT operation that generally to be able to enhance the combustion quality of waste in terms of increased Heating Value and reduced moisture content [7, 8]. Heat is produced by the degradable material, which accelerates the evaporation of water. In the biodrying process, biological heat is incorporated to diminish the excessive moisture content, together with forced aeration, to almost totally accomplish the drying process. There are three types of water in mixed substances, i.e., water components in the feedstock, water vapor associated with the air input, and water generated during organic degradation [4]. In the biodrying process, the biodried product is influenced by two primary steps; 1) The evaporation process changes water-vapor molecules from liquid to gaseous and emits them into the surrounding air; 2) airflow moves the evaporated water-vapor through the matrix and removes it with the exhaust gases. The aeration rate influences the water removal activity produced by these two processes. Zhou et al. [9] executed the airflow rate at 0.088 $m^3/kg_{TS}/h$ and modified the air pump's on-off duration by supplying air for 6 minutes before turning it off for 34 minutes. They observed that water removal was highest removed for sewage sludge biodrying. Zhao et al. [10] found that a high airflow rate of 0.3 $m^3/kg_{TS}/h$ improved heat generation more than a low one of 0.15 $m^3/kg_{TS}/h$) and effect to the loss of moisture content in the sewage sludge biodrying. In light of the above, the study of the effect of aeration rate on the biodrying of wet-RDF in water removal performance has not been widespread. Therefore, this work investigates the aeration rate's interactive influence on water balance.

Materials and Methods

Feedstock analysis

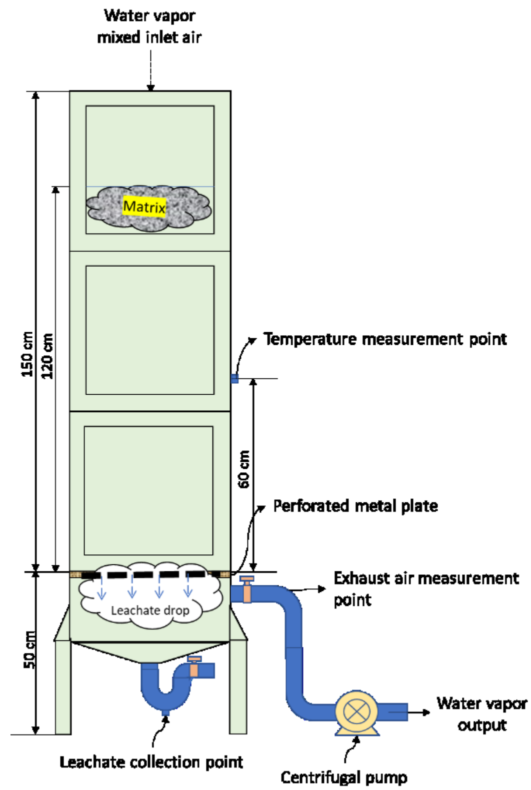
First, the MBT plant in the On-Nut waste transfer station produces the wet-RDF, referred to as feedstock. It is then transported to waste-to-energy plant in Thailand's Saraburi province. Wet-RDF samples for 20 kg were randomly collected from different locations in stockpiles in the waste-to-energy plant for composition analysis. Another 20 kg was also collected and quartered to remain 1.5 kg for measuring their chemical properties before biodrying process. The wet-RDF is depicted as having an observed values composition made up of 8.72% packaging and plastic tube, 13.08% cloth and napkins, 46.33% plastic bags, 22.98% degradable materials (food, garden, and paper trash), 1.43% rubber, and 5.09% other/separated waste. Second, the wet-RDF stockpile was randomly sampled for this study before being put into the biodrying lysimeters. The content of the wet-RDF feedstock and bio-dried product was examined using the quartering method following ASTM D5231-92. Finally, the degradable material was separated to measure the moisture content from the feedstock and biodried product. The average weight of the feedstock in the lysimeters was 70.0 kg with 232 kg/m^3 of bulk density, and it was equally loaded to a height of 1.2 m. By ASTM D7582, a thermogravimetric analyzer was used to measure the moisture content accumulation in the feedstock and biodried product. The initial moisture content of the wet-RDF was 46%.

Investigation of biodrying system

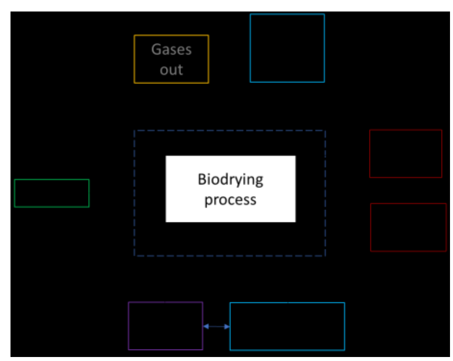
The feedstock material was loaded into a square lysimeter made of stainless with 2 m of height and 0.5 width. The outer wall was covered in 2.5-cm-thick polyurethane foam for thermal insulation. The perforated metal plate was positioned at the lysimeter's bottom to support the waste material and air ventilation. A ventilation pipe, condensation pipe, and blower are parts of the ventilation component system established at the bottom of the lysimeter to provide airflow. The U-trap pipe, which has a 5.08 cm diameter, was connected to the ventilation pipe to collect condensation. Leachate was collected using the 5.08 cm diameter U-trap pipe that was placed at the lysimeter's bottom. A process flow diagram of the investigated biodrying of the wet-RDF system is shown in Figure 1A.

The biodrying is the purpose of utilizing the exothermal bacterial oxidation of organic matter to evaporate the excess moisture contained in the waste. A process flow diagram of the investigated biodrying system showing the thermodynamic system boundary and primary process inputs and outputs is shown in Figure 1b. The thermodynamic system represents the energy transformed due to biological activity within released heat to the surroundings. Major input is the feedstock, aeration feeds, and its associated water vapor. The biodried product, dry exhaust gases, and exited water vapor are major outputs. The heat input and output represent ambient air and exhaust temperature, respectively.

The wet-RDF is usually desirable to evaporate water and generate leachate during biodrying for producing a relatively biodried product.



(A)



(B)

Figure 1 Description of the wet-RDF biodrying system; a) schematic diagram of process layout and b) process flow boundary of this study

The overall airflow through the lysimeter is the mixture of fresh air (dry air mixed water vapor) used to provide the oxygen consumption of the microorganism activity and evacuate evaporated moisture. This study operated three experiments in different conditions based on aeration rate, i.e., 0.4, 0.5, and 0.6 m^3/kg/day. Therefore, the negative ventilation can be distributed down-flow from the top to the bottom of the lysimeter. The following aeration rate set in this study was base on the 1) stoichiometric air demand for the compositing process [11], the stoichiometric air demand for biodrying process [6, 8], and the literature review of the appropriate aeration rate for biodrying process [9, 12-19]. The appropriate aeration rate was assumed the oxygen consumption while minimize the energy consumption for aeration supplied in the biodrying process.

The main mechanisms for moisture movement in the matrix are air convection and molecular diffusion. Removal of water content from the wet-RDF matrix during the biodrying process by convective evaporation is determined by the thermodynamic equilibrium between the solid and gas phases. The water balance was contained for two terms; 1) two-stream for gas (water vapor) and solid (wet-RDF) for the inlet, and 2) two-stream for gas (water vapor) and solid (biodried product) for the outlet. There is a general equation (1) to describe the water balance as follows;

$$W_{inlet} - W_{outlet} + W_{matabolic} = W_{accumulation} \quad (1)$$

$$W_{inlet}\,(g) = W_{feedstock} + W_{vapor\ inlet} \quad (2)$$

$$W_{outlet}\,(g) = L_{generation} + W_{vapor\ outlet} \quad (3)$$

$$W_{vapor\ inlet/outlet}\,(g/h) = F\,(m^3/h) * [\frac{217 * p_v}{237.15 * p_{vs}}] \quad (4)$$

$$p_v\,(Pa) = RH\,(\%) * p_{vs} \quad (5)$$

$$p_{vs}\,(Pa) = 6.1078 * 10^{[\frac{7.5 * Temperature\,(°C)}{Temperature\,(°C) * 237.3}]} \quad (6)$$

$$W_{vapor\ air\ flow}\,(g/h) = W_{vapor\ outlet} - W_{vapor\ inlet} \quad (7)$$

$$W_{matabolic}\,(kg/h) = \frac{16.3}{21} * \Delta C_{gen} * \frac{18\,kg}{1kmol} \quad (8)$$

$$\Delta C_{gen}(kmol/h) = [(F * CO_2)_{out}] * \frac{1\,mol\,CO_2}{100 * 22.4 m^3} \quad (9)$$

$$W_{vapor\ evaporation} = W_{outlet} - (W_{inlet} + W_{matabolic}) \quad (10)$$

when; W_{inlet} is water inlet, W_{outlet} is water outlet, $W_{accumulation}$ is water accumulation, $W_{feedstock}$ is water in feedstock, $L_{generation}$ is leachate generation, $W_{vapor\ inlet/outlet}$ is water-vapor inlet or outlet, RH is relative humidity, p_v is water vapor pressure, p_{vs} is saturated water vapor pressure, $W_{vapor\ air\ flow}$ is water-vapor mixed airflow, ΔC_{gen} is CO_2 generation rate, F is airfow rate, and $W_{vapor\ evaporation}$ is water-vapor evaporation.

The water inlet (2) represents the water mixed in feedstock and water vapor mixed inlet air (4). The water outlet (3) represents the leachate and water vapor in the outlet air (4). The metabolic water generation (8) is water mass produced from bioactivity organic digestion. The water accumulation represents the moisture in the biodrired product (1). Finally, water vapor evaporation (10) is represented the whole water vapor in the biodrying system that is evaporated into the surrounding [20, 21].

In addition, this study focused on water balance, the unit of gases and leachate output corresponding to the production of microorganism digestion, i.e., carbon dioxide and methane, and other organic fractions, was not accounted for in this study.

Experimental monitoring

The temperature was measured using thermocouples type K, which have a temperature range of -270 °C to 1,327 °C. These sensors were positioned in the center and exhaust air measurement point of lysimeters, while a third sensor for monitoring ambient temperature was positioned outside the lysimeter. The midi Logger recorded all temperature measurements hourly (Graphtec GL220). Daily measurements of the CO_2 concentration in percent by volume during the biodrying process were conducted with Biogas 5000 (Geotech, UK) at the lysimeter's exhaust air sampling location. Daily weight measurements of the feedstock in the lysimeter were performed using a push gantry hoist and digital crane scales. The relative humidity was measured for the ambient and exhaust air measurement point.

Results and Discussion

Water balance before and after the biodrying process

Table 1 summarizes the results of the three experiments on water balances between input and output of the biodrying process of wet-RDF. It was observed that the aeration rate influenced water removal and water generation. The AR 0.4 showed the highest water removal by evaporation (9.98 kg), followed by AR 0.5 and AR 0.6 at 8.26 kg and 6.72 kg, respectively. The water vapor air flow was water removal due to air force without considering the metabolic water generation. The highest water vapor air flow was AR 0.4 at 24.04 kg, followed by AR 0.5 and AR 0.6 at 21.70 and 18.71 kg, respectively. The highest leachate generation was obtained from AR 0.6 at 1.6 kg, followed by AR 0.4 and AR 0.5 at 1.04 kg and 0.5 kg, respectively. Finally, metabolic water generation is the production of organic digestion by bioactivity. The highest generation was from AR 0.4 at 14.05 kg, followed by AR 0.5 and AR 0.6 at 13.44 kg and 11.99 kg, respectively.

Table 1 Balance of water during the biodrying process

Condition	AR 0.4	AR 0.5	AR 0.6
Water vapor evaporation (kg)	9.98	8.26	6.72
Water vapor air flow (kg)	24.04	21.70	18.71
Water in feedstock (kg)	31.79	31.79	31.79
Leachate generation (kg)	1.04	0.50	1.60
Metabolic water generation (kg)	14.05	13.44	11.99
Water accumulation (kg)	20.27	23.03	23.47

The overall water balance during the biodrying process of wet-RDF is shown in Figure 2. The proportion of water in feedstock was the highest in the system, followed by the difference between the water outlet and water inlet due to vapor carried in the air flow without considering the water generation by metabolic activity (water vapor airflow). The lower water vapor air flow is represented by the lower remaining water in the system. On the other hand, the air force represents the higher removal. The lowest water vapor air flow was AR 0.6 at 26.42%, followed by AR 0.5 and AR 0.4 at 28.67% and 29.71%. This is because a high aeration rate drives the water vapors out of the system more than a low aeration rate. This was confirmed by Yang et al. [22], who summarized the relationship between aerations and water vapor removal. They reported that the inlet air increase could transport the vapor out from the system due to the increase in water holding capacity. The metabolic water generation is the third proportion of water in the system; AR 0.5 was the highest, accounting for 17.75%, and the lowest was AR 0.6, accounting for 16.93%. This can be summarized that; AR 0.5 was the optimum aeration rate for bioactivity due to the appropriate oxygen consumption.

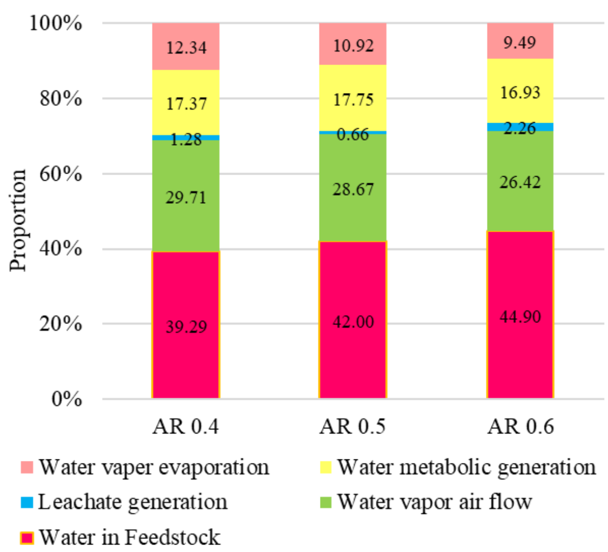


Figure 2 The proportion of water balance during the biodrying process

On the other hand, AR 0.6 was the higher aeration for the biodrying system of wet-RDF. Water vapor evaporation is related to water removal within bioactivity because it accounts for the removal from metabolic water generation. The leachate generation was the nominal proportion of the water balance system because of less removal. Although, this study was performed under a negative ventilation system that allows for a higher excretion of leachate than positive ventilation. However, the amount of leachate removal was still low. Tom et al. [23] operate the MSW biodrying under a positive ventilation system. They observed no leachate production during the entire reaction period, although the feedstock condition reported the potential for leachate generation, i.e., % organic substance and moisture content. The leachate reduction mechanism of the biodrying system is an effective waste management operation in reducing environmental pollution.

Daily metabolic water generation

The water produced from organic digestion by microorganisms is presented by metabolic water generation, as shown in Figure 3. This result was obtained from the balancing process using equation 8. The daily carbon dioxide concentration is the bioproduction converted into a mass of water under aerobic digestion [24].

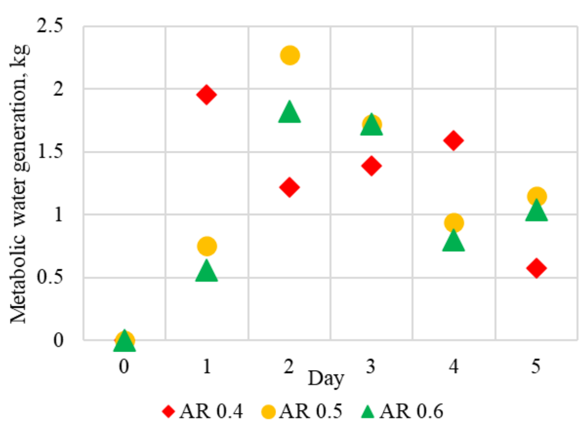


Figure 3 Daily metabolic water generation of each experiment

The highest metabolic water generation was obtained from AR 0.5 for 2.27 kg on day 2, followed by AR 0.4 for 1.90 kg on day 1, while AR 0.6 had the maximum for 1.82 kg on day 2. The metabolic water generation trend of AR 0.4 rapidly increased to its peak on day 2 and then decreased to its minimum on day 5. Notably, AR 0.5 and AR 0.6 were slightly increased to their peak on day 2, then slightly decreased to their minimum on day 4. Ham et al. [21] reported that the effect of metabolic water generation on the variation of airflow rates was not changed throughout the time for the biodrying process. In contrast, this study showed a different generation rate trend because of the difference in feedstock and operations.

Effect of aeration rate on total water removal

Referring to equation (1), the balancing process, the difference between water input and water output, the water accumulation is the remaining water in the biodried product compared to the feedstock. Figure 4 shows the comparison of water accumulation in each experiment's balance process and measurement.

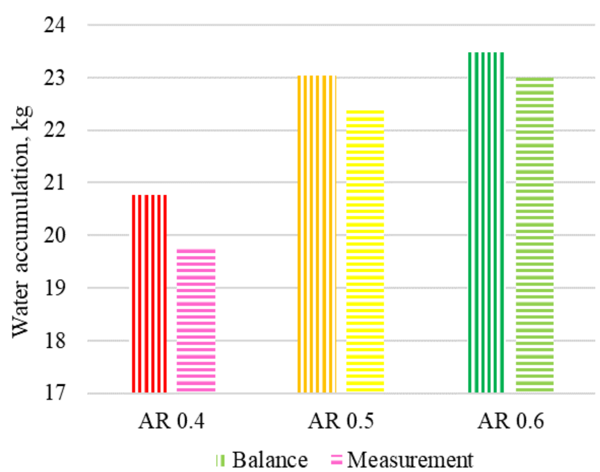


Figure 4 Water accumulation of each experiment

The lowest water accumulation from the balancing process was AR 0.4 at 20.77 kg, followed by AR 0.5 and AR 0.6 at 23.03 kg and 23.47 kg, respectively. The lowest water accumulation from measurement in the laboratory was AR 0.4 at 19.97 kg, followed by AR 0.5 and AR 0.6 at 22.42 kg and 23.23 kg, respectively. Therefore, the average water accumulation of AR 0.4, AR 0.5, and AR 0.6 at 20.37 kg, 22.72 kg, and 23.35 kg, respectively.

The lowest aeration rate at 0.4 m^3/kg/day can drive water removal by evaporation for the biodrying of wet-RDF operation. This aeration rate was better for producing gases, water, and heat, allowing the evaporation of water vapor to the surrounding.

Furthermore, this study more effectively removes water by transforming it into vapor than by disposing of leachate. According to the findings, a high aeration rate produced less water vapor and more leachate than low aeration rates, with a higher elimination of water vapor. Wang et al. [16] and Zhou et al. [9] provided similar explanations, confirming that a lesser amount of water is transferred by air because of a higher aeration rate.

Daily water accumulation and temperature profile

The daily amount of water accumulated in the matrix of each experiment is shown in Figure 5.

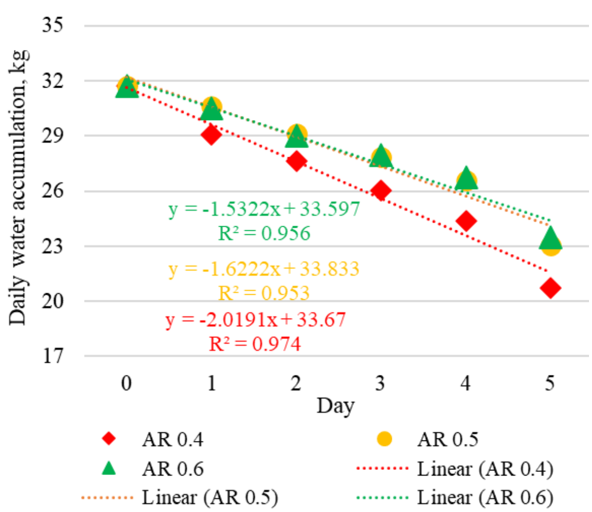


Figure 5 Decrease of daily water accumulation in each experiment

The initial water content of all experiments was 46%, measured at 31.74 kg. However, the water accumulation was slightly decreased from the beginning until the end of the process. AR 0.4 was the highest reduction rate of water accumulation at 2.01 kg/day, followed by AR 0.5 and AR 0.6 at 1.66 kg/day, and 1.53 kg/day, respectively.

The matrix water accumulation change was related to matrix temperature and aeration rate. The matrix temperature of each experiment is shown in Figure 6. In this study, the biodrying of wet-RDF was rapidly increased in matrix temperature from the beginning to day 1, then slightly increased to the end of the process. The highest temperature was obtained from AR 0.4, which reached the peak on day 4 at 64.4 °C, followed by the maximum temperature of AR 0.6 and AR 0.5, which peaked on day 4 at 57.1 °C and 52.4 °C, respectively.

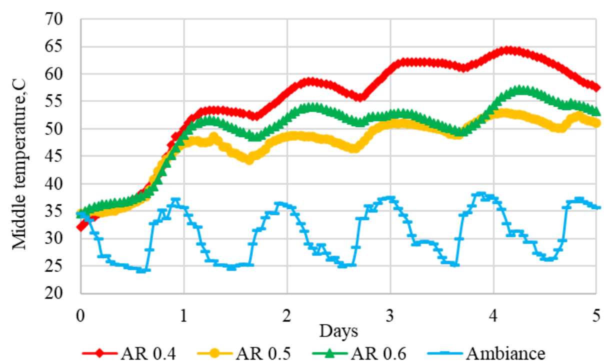


Figure 6 Daily temperature in the matrix of each experiment

The matrix temperature of this study was higher than in the previous study. However, the feedstock condition was unfavorable for reaching the higher temperature generation compared to those studies, i.e., the amount of degradable material and moisture content [21, 23, 25]. According to Ham et al. [21], when the aeration rate increased from 0.60 to 2.50 m^3/kg/day, the highest matrix temperature reduced from 58 to 49.9 °C, while the moisture reduction increased by 2.3 times. Compared to the results of the experiment by Tom et. al. [23], this study provided the maximum water reduction only 1.5 times, but it was found that the maximum temperature was higher.

Conclusions

To investigate water balance, this study performed a biodrying of wet-RDF on the lysimeter scale. The water balance was estimated within the variation of the aeration rate. The water inlet was from water in feedstock and water vapor mixed inlet air. The water outlet was from evaporation and leachate generation. The remained water was the water accumulation in the biodrired product. This study reported that minimizing leachate generation and water accumulation was the optimum water balance influenced aeration rate. Less leachate generation and water accumulation were obtained from the biodrying operation of wet-RDF with 0.4 m^3/kg/day because it maximizes water evaporation. Moreover, the phenomenon findings in this study are the low aeration rate (0.4 m^3/kg/day) resulted in maintaining the system temperature to enhance the water evaporation. In comparison, the high aeration rate (0.5 m^3/kg/day) resulted in a force of leachate dropdown in the negative ventilation system.

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