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eISSN: 2255-8837

First Published: 26 Mar 2010

Publication timeframe: 2 times per year

Languages: English

Journal Subjects: Life Sciences, other

Journal Metrics

Cite Score: 2.3

SJR: 0.330

SNIP: 0.770

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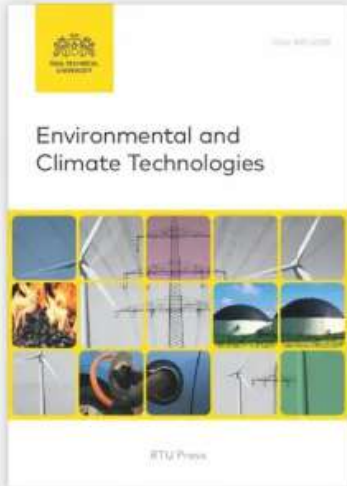
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Journal Details

Format: Journal
eISSN: 2255-8837
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Waste to Energy: Calorific Improvement of Municipal Solid Waste through Biodrying

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Abstract – Municipal solid waste (MSW) is an energy resource with sufficient energy/calorific value, making it a suitable substitute for fuel. This study investigated the effect of air flow rate on the MSW calorific value, the hemicellulose content, and the MSW degradation rate in a biodrying process. Four biodrying reactors equipped with flowrate and temperature recorders were used in the study. The air flow rate was varied as follows: 0 L/min/kg, 2 L/min/kg, 4 L/min/kg, and 6 L/min/kg, corresponding to reactors R1, R2, R3, and R4, respectively. The calorific value, water content, hemicellulose content, organic C content, and total N were measured on day 1, day 15, and day 30. The results showed that the biodrying process could increase the calorific value by 55.3 %, whereas the control reactor could increase the calorific value by only 4.7 %. The highest calorific value was 17.63 MJ/kg, at an air flow rate of 4 L/min/kg. The air flow rate had a significant effect on increasing the calorific value (sig.<0.05). The highest temperature in the biodrying process was 41 °C. The final MSW moisture content was 27.28 %, resulting from R4. According to the statistical test results, the air flow rate had a significant influence on the water content parameters. Hemicellulose degradation due to air flow rate reached 80–85 %. The air flow rate did not significantly influence the hemicellulose degradation (sig.>0.05). The biodrying process is the suitable method to increase the calorific value of MSW while reducing its water content; thus, the process promotes the realization of waste to energy as refuse-derived fuel.

Keywords – Biodrying; Calorific; Energy; Municipal solid waste; Refuse-derived fuel

Nomenclature

<i>HHV</i>	Higher heating value	MJ/kg
<i>MSW</i>	Municipal solid waste	–
<i>RDF</i>	Refuse-derived fuel	–

1. INTRODUCTION

Solid waste production is one of the greatest challenges of recently [1]. Municipal solid waste (MSW) is an energy resource with sufficient energy/calorific value, making it a suitable substitute for fuel [2]. Municipal solid waste comprises all the wastes arising from human and animal activities such as food waste, construction debris, polyethylene, cloth, garden

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trimmings, leaves and branches, hospital waste, metal, glass, shredded skins and leather, animal waste, industrial waste, and old appliances. The pretreatment of solid waste through biodrying technology can produce refuse-derived fuel (RDF), which can be applied in several industries, including the cement industry. This technology is one of the best methods to maximize the amount of energy recovered into a fuel product [2]–[4]. Globally, RDF have been produced from municipal solid waste [5]. From an energy perspective, MSW is the same as fossil fuels because they contain oxidisable materials (mainly carbon and hydrogen) that can free up energy quantified as heat. This energy can be utilized for heat production, electricity generation, and heat generation [2]. Physically, RDF can be made pellets with sizes and shapes as needed, such as non-loose granular shape [6]. Pellets are made using pressures ranging from 8.5 MPa to 76.2 MPa [7].

Calorific value is an important parameter to determine the RDF quality of municipal solid waste. Lokahita *et al.* [6] mentioned that in the conversion of MSW from the Jatibarang Landfill to RDF, the MSW calorific value needs to be considered, because as long as the MSW heating value the Jatibarang Landfill is still low. Currently, the higher heating value (HHV) from Jatibarang is approximately 3930.46 kcal/kg, which does not meet the minimum standard. Knowing the calorific value is vital to the proper application of the RDF; therefore, improving the MSW calorific value is important, especially MSW from the Jatibarang Landfill.

High-quality RDF can be obtained from ingredients with high calorific value and low humidity. The calorific value can be increased by drying solid waste through mechanical–biological treatment and biological–mechanical treatment [8]. These two processes are known as biodrying (biological drying), where the waste will undergo mechanical–biological bioconversion [7], [8]. Biodrying integrates mechanical processes (air circulation and enumeration of waste) and bioconversion (biological drying). In practice, the biodrying reactor processes high-water-content waste that has been chopped and produces an output of dry waste (biodried), which will undergo further mechanical processing. The heat generated from the aerobic decomposition process of organic compounds combined with excess air functions to dry the waste [10]. In the biodrying process, the water content will turn into steam as a result of high temperatures and adequate ventilation. Adani *et al.* [11] and Sugni *et al.* [12] showed that appropriate air flow rate settings (for example, air flow rate and flow direction) and temperature can efficiently reduce water content (66.7 % of initial water content). In principle, aerobic biodrying technology facilitates evaporation using energy produced from organic matter degradation. The presence of air flow increases the partial disintegration and hydrolysis of macromolecular organic compounds (such as organic C, cellulose, hemicellulose, lignin, and total nitrogen).

Research on MSW from Jatibarang landfill was conducted by Sesotyo *et al.* [13] used plasma gasification modeling to analyze its performance parameters for energy potential of Jatibarang landfill, which is focused on gas emission and H₂ gas production. Oktawan *et al.* [14] studied MSW from the Jatibarang Landfill (located at the west side of Semarang City, Indonesia) using a bioreactor. The research was conducted on a laboratory scale and focused on the pH value and nitrogen composition of MSW. Anaerobic bioreactors achieved a higher final pH value than aerobic bioreactors, whereas the accumulated nitrogen content of aerobic bioreactors was two times that of anaerobic bioreactors. Sesotyo *et al.* [13] used plasma gasification modeling to analyze the performance parameters of MSW from the Jatibarang Landfill and determined the energy potential of the MSW, focusing on gas emission and H₂ gas production.

The calorific value is an indicator of the energy content of a substance, including waste. Based on preliminary research, the calorific value of urban waste in Semarang, Indonesia, ranges from 4507.46 to 4534.51 cal/g [15]. Waste processing via biodrying increases the energy content by drying the waste to produce RDF products [16]. The existence of microorganism activities and the large consumption of nutrients by microorganisms affect the calorific value produced. According to Rahman [17], reducing the amount of wastewater can significantly increase the calorific value. The increase in heat value is also caused by a decrease in microorganism activity, which is characterized by a decrease in temperature so that nutrient consumption is low [18].

Hemicellulose is one of the macromolecular organic compounds in waste. Hemicellulose has a high resistance during the anaerobic degradation process [16], [19]. Moreover, products of hemicellulose hydrolysis are available as carbon and energy sources for cellulolytic microorganisms or other microbes living where hemicellulose is degraded [20]. The hydrolysis process of hemicellulose can increase the calorific value of the waste generated from the biodrying process.

Based on this background, in this research, the biodrying process with a suitable air flow rate was applied to improve the calorific value of MSW from the Jatibarang Landfill. The changes in temperature, water content, hemicellulose, organic C, and total nitrogen were evaluated, and their relationship with the calorific value was studied.

2. METHODS

2.1. Reactor design

The study was conducted at the Greenhouse Department of Environmental Engineering, Faculty of Engineering, Diponegoro University. Four cylindrical reactors were used for the research. The biodrying reactor design is shown in Fig. 1. The 45 L acrylic reactor was equipped with gas emission holes, MSW sampling holes, and temperature-monitoring holes for high-accuracy digital measurement (0.5 °C). The reactor was equipped with a blower to supply air, and the air flow rate measured using a flow meter.

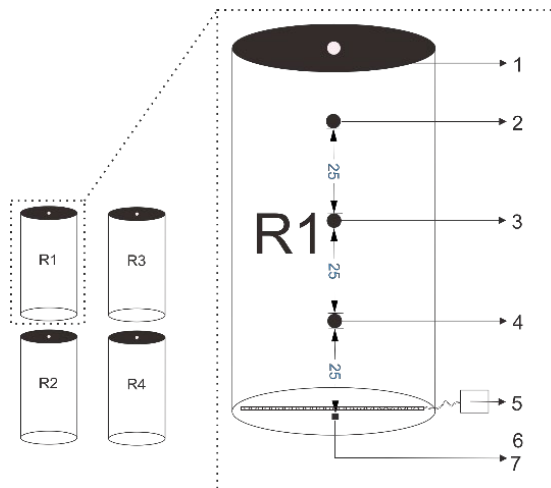


Fig. 1. Biodrying reactor design: (1) gas emission hole, (2) bottom sampling hole, (3) center sampling hole, (4) upper sampling hole, (5) air flow rate pump, (6) leachate outlets.

2.2. Sample preparation

MSW was obtained from the Jatibarang landfill, Semarang, Central Java, Indonesia. The solid waste consisted of organic, inorganic, and metal waste. This solid waste was sorted to determine the percentage of each component (%). The MSW composition used was 64 % (v/v) leaf litter, 2 % (v/v) food waste, 15 % (v/v) paper waste, and 19 % (v/v) plastic waste. The MSW was then mixed with mature compost (as a bulking agent) in the following proportion: 70 % (v/v) compost and 30 % (v/v) MSW matrix. The automatic height of the garbage was as high as three-quarters of the total reactor height (31.4 L). The height of each type of waste was as follows: 27 cm leaf litter, 1 cm food waste, 6 cm paper waste, and 8 cm plastic waste from the bottom.

2.3. Experimental setup

The designed biodrying reactor comprised four reactors. The air flow rate was measured at the end of the outlet hose using a flow meter (Dyer, USA). The air flow rates of the reactors were as follows: 0 L/min/kg (control), 2 L/min/kg, 4 L/min/kg, and 6 L/min/kg. The air flow rate was selected based on a previous study on MSW outside Indonesia. In that study, the optimum air flow was obtained as 4 L/min/kg [18]. In the current study, discharges of 0 L/min/kg, 2 L/min/kg, and 6 L/min/kg were used to determine the effect of air flow rate discharge in smaller and larger ranges. The MSW water content was adjusted to ± 60 % by homogeneously adding water and MSW into the biodrying reactor. The temperature was monitored using a digital temperature sensor probe (DS 18B12), which could record temperature data every 15 min and store them in a 2 GB SD card. The calorific value, water content, hemicellulose content, organic C content, and total N were measured on day 1, day 15, and day 30. This research was conducted for 30 days.

2.4. Sampling and analysis

During the biodrying process, about 300 g samples were collected from three depths (top, middle, and bottom) and mixed for the analysis of organic C, total N, hemicellulose, water content, and calorific value. All parameters were analysed in duplicate. The standard deviation was set as <10 %. Organic C was measured using a UV-vis spectrophotometer (Genesys 10s, Thermo Fisher Scientific, USA). The water content was measured by heating the sample at 70 °C for 48 h. The degradation of organic matter such as hemicellulose was determined based on the measurement of neutral detergent fibre and acid detergent fibre [21]. The calorific value is a measure of heat or energy produced and is measured as the gross calorific value or net calorific value. The calorific value was measured using a bomb calorimeter.

3. RESULTS AND DISCUSSION

3.1. Initial characteristics of MSW

The initial temperatures of each reactor were relatively the same, ranging from 31 °C to 32 °C. The reactor temperature was higher than the ambient temperature of 28 °C. The initial temperature in the study shows that the reactor had mesophilic-phase active bacteria at temperatures between 10 °C and 45 °C [22]–[24]. The initial water content in each reactor ranged from 65 % to 69 %; reactor R1 had the highest water content (69 %), while reactor R3 had the lowest (65 %). This finding accords with previous research [25], which states the

aerobic process will effectively run at 60–70 % water content. The organic C ranged between 80.42 % and 86.73 %, and the total N ranged between 1.46 % and 1.50 %. The hemicellulose levels were 20 %, 18 %, 20 %, and 19 % for reactors R1, R2, R3, and R4, respectively.

3.2. Temperature

Biodrying involves the drying of solid waste through both heat generated from aerobic microorganisms and air flow rate mechanisms [26]. Temperature can be used as an indicator of metabolism by microorganisms and the addition of microorganism populations, and it influences the evaporation process [25], [27], [28]. The temperature profiles for 30 days are displayed in Fig. 2.

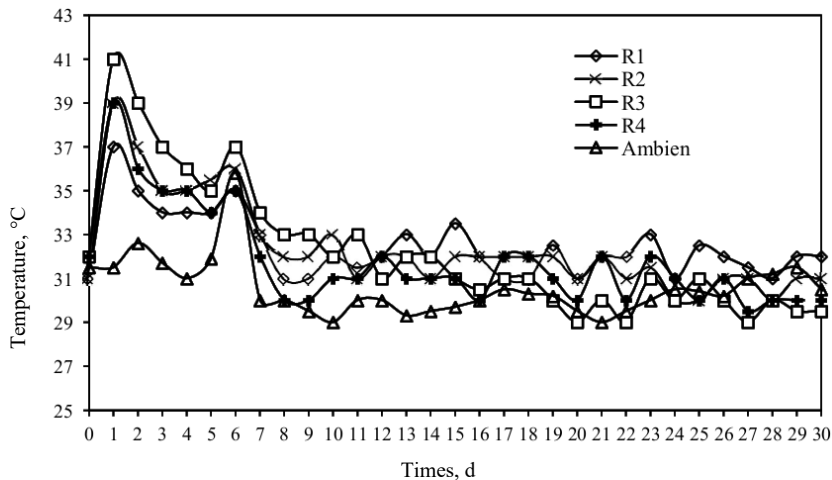


Fig. 2. Temperature profile during biodrying process.

In this study temperature measurements were performed every day for 30 days of biodrying to determine the temperature patterns of each reactor. According to Fig. 2, the initial MSW temperature at each reactor was relatively uniform: 31 °C at R1 and R2 and 32 °C at R3 and R4. In the biodrying process, the temperature was divided into three phases: the heating phase, cooling phase, and stable phase [29]. The heating phase occurred on day 1, as indicated by the occurrence of peak temperatures: the temperatures at R2 and R4 were as high as 39 °C, and that at R3 was as high as 41 °C, while that at the control reactor R1 was 37 °C. These results indicate that the presence of air flow can increase the MSW temperature, which reached 41 °C. In the studies by Sadaka *et al.* [30] and Tambone *et al.* [31], the peak temperature in the biodrying process was reached on day 2. In the current study, the achievement of the peak temperature on day 1 was due to the addition of mature compost (as a bulking agent), which caused the addition of microorganisms to the waste matrix, so that the lag phase could be shorter [29], [32]. The peak temperature shows the highest number of bacterial populations and the highest microorganism activity because the microorganisms produce heat during their metabolism [25]. The highest temperatures achieved in this biodrying study were moderate thermophilic temperatures. Jalil *et al.* (2016) state that biodrying is more effective at mesophilic temperatures (35–40 °C) or moderate thermophilic temperatures (40–45 °C) than at thermophilic temperatures (55–70 °C). This is because temperatures of >60 °C will kill some microbes, and only thermophilic microbes will survive

[52]. Temperature patterns on day 2 to day 30 in each reactor tended to decrease slowly and entered the mesophilic range. The temperature of R4 on the final day was lower than those of other studies. This is because a higher air flow rate will more quickly cool the material and stop microbial activity [30].

3.3. Water content

Water content is an important parameter in determining the effectiveness of the biodrying process. This is because the water content affects the chemical reaction associated with microbial growth and the biodegradation process of organic substances [4], [10]. At the beginning of the biodrying process, the initial water content levels generally ranged from 50 % to 75 %. If the initial water content is too low, then the microbial activity will be slow because microbial metabolism requires water. The water content variation result in the biodrying process is illustrated in Fig. 3.

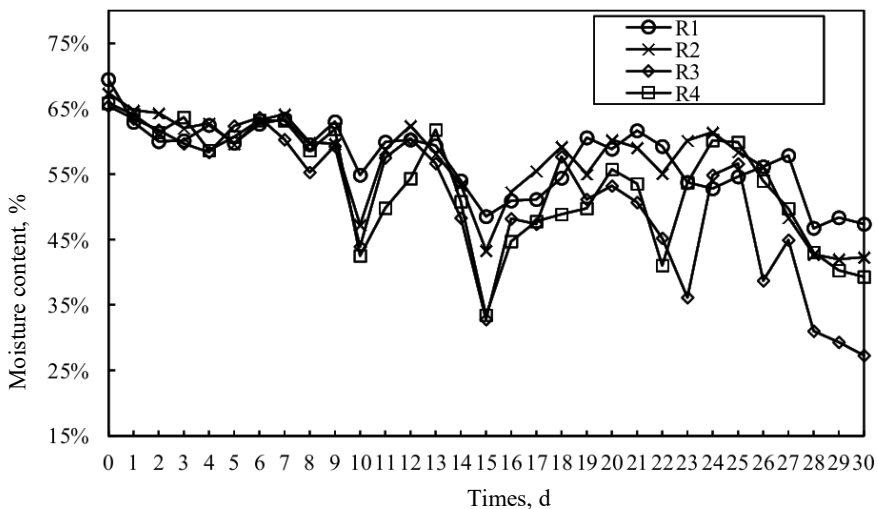


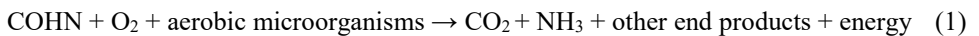
Fig. 3. Moisture content variation in the biodrying process.

According to Fig. 3, the initial water content was 69.4–65.41 %. The water content started to slowly decline on day 1, with a decrease of 9 % at R1, 4 % at R2, 3 % at R3, and 3 % at R4. In R1 (control), there was no air flow rate treatment; therefore, the decreased water content was due to the leaching in R1 (control), whereby the amount of liquid leached out was as much as 10 mL, whereas no leaching occurred in R2, R3, and R4, due to phase change from water to steam. The water content in the biodrying process can be reduced by the evaporation of water molecules from the surface of the waste into air as the liquid phase changes into steam; then, the water that evaporates moves from the material (MSW) to the outside air because it is carried by air flow; nonetheless, the pile of material absorbs a small portion of water as leachate because of the gravity-induced downward movement of water [10], [33]. A significant decrease in water content occurred between days 10 and 15; thus, in this period, active microbial activity occurred, breaking down the cell wall so that the water content in the MSW evaporated faster. On day 15, all reactors tended to experience a significant decrease in water content. According to Velis *et al.* [10], the biodrying process runs effectively for around 7–15 days.

At the end of the study, the air flow rate of 4 L/min/kg (R3) produced the driest waste, with a final water content of 27.28 %. Based on statistical tests, the sig. value was 0.033. The sig. value was smaller than 0.05, which means that the air flow rate has a significant influence on the water content. This corresponds to the work by Sen [28], which states that the higher the air flow, the more probable the MSW pile will dry only physically, without the heat generated by aerobic degradation, because the thermophilic phase is not reached.

3.4. Analysis of organic C and total N

Carbon and nitrogen are needed for bacteria metabolism in the decomposition process for energy production and cell formation [34]. In the biodrying process, the carbon and nitrogen decomposition is minimized to maintain the calorific value and realize optimum combustion [35]. The organic C profile in this study is shown in Fig. 4. The carbon and nitrogen decomposition reaction in the aerobic process is expressed in Eq. (1) [28].



According to Fig. 4, initial organic C in each reactor was 86.73 % for R1, 80.54 % for R2, 84.07 % for R3, and 80.42 % for R4. On day one, there was a significant decrease in the organic C levels. This happened because of the high microorganism activity that requires a high carbon source for the microorganism metabolism and corresponds to the achievement of peak temperatures on day one [4], [36]. The organic C content decreased because of the decomposition of carbon material into CO_2 and energy [37].

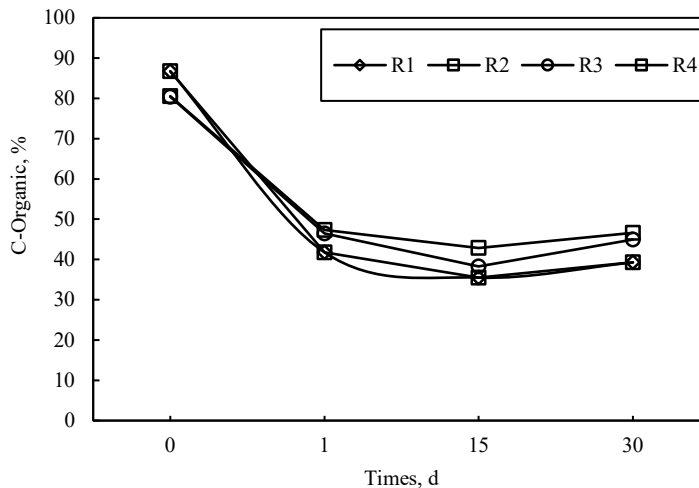


Fig. 4. Variations of organic C biodrying process.

On day 15, the rate of organic C decrease was not very significant; this shows that the microorganism activity on day 15 was not as high as that on day 1, and the reactor entered the cooling phase on day 15 [29]. On day 30, the organic C increased because of a decrease in the microorganism activity, so that the degradation of organic C slowed, and dead microorganisms became biomass that was measured as organic C [38], [39].

The lowest organic C (42.15 %) occurred in R2, with an air flow of 2 L/min/kg, while the highest decrease (54.72 %) occurred in R1, with 0 L/min/kg. This corresponds to the result

of the study by Rada [40], which states that a good biodrying process occurs with a slow degradation process. A slow degradation process can increase the calorific value at the end of the biodrying process [4].

The trend of the total N levels for 30 days in the biodrying process is presented in Fig. 5. According to the figure, the initial total N content in each reactor was 1.82 % for R1, 1.50 % for R2, 1.46 % for R3, and 1.51 % for R4.

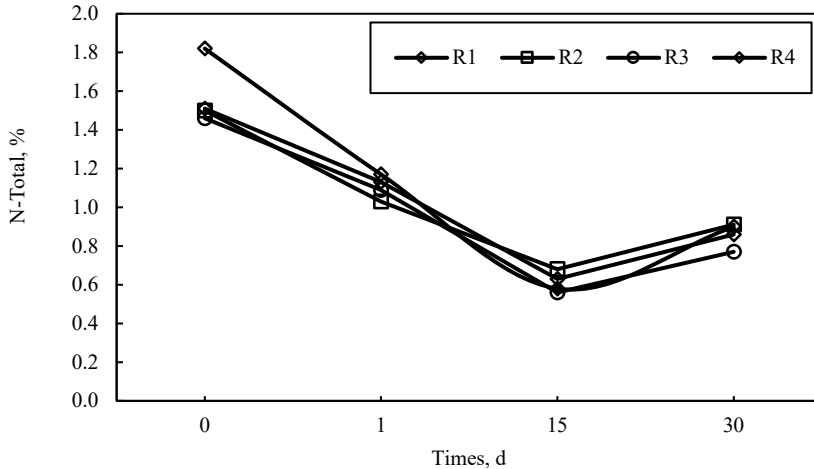


Fig. 5. Variations of total N biodrying process.

The lowest decrease (54 %) occurred in R2, with an air flow of 2 L/min/kg, while the highest decrease (68 %) occurred in the control reactor. The total N decreased because most of the nitrogen present in the matrix was converted to NH_3 , and this process occurred after the thermophilic process [41]. On day 30, the total N levels in all reactors increased. This occurred because of the nitrification process that converts nitrogen into NH_4^+ . These results agree with the research on high-water-content MSW by Tom *et al.* [42]: that is, the total N content increased due to the formation of NH_4^+ in the last 15 to 30 days of biodrying.

3.5. Hemicellulose

Hemicellulose is a complex component of carbohydrate polymers, and its main components are xylem and heteropolysaccharides [43], [44]. In the biodrying process, microorganisms use carbon compounds in the matrix for metabolism; the carbon compounds can be sourced from starch, cellulose, hemicellulose, and lignin [4]. In the decomposition process, bacteria first use cellulose rather than hemicellulose because degrading cellulose is easier [20]. The main component of cellulose is glucose without branches, while hemicellulose is composed of a C=O bond and glucose with many branches [45]. The hemicellulose levels for 30 days in the biodrying process in this study are shown in Fig. 6.

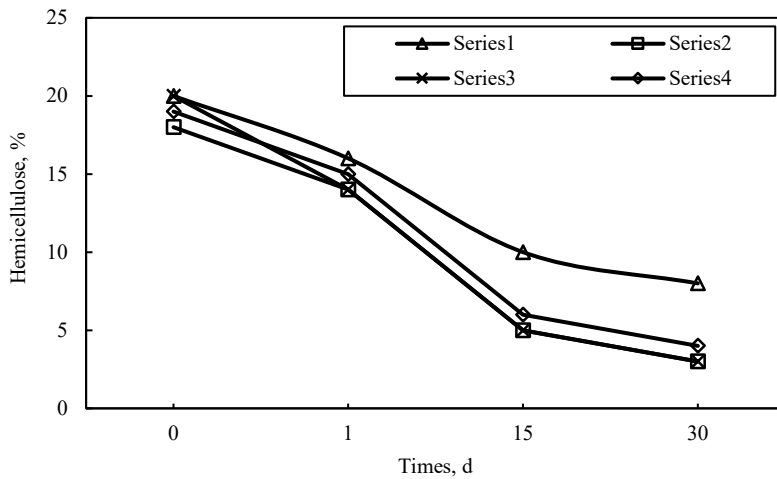


Fig. 6. Variations of hemicellulose biodrying process.

During the biodrying process, the hemicellulose levels decreased by 59 % in R1, 81 % in R2, 85 % in R3, and 80 % in R4. The lowest decrease occurred in reactor R1, and the highest occurred in reactor R3. The enzymes β -xylosidase and xylanase were formed during the most thermophilic phase [46]. The hemicellulose levels decreased during the biodrying process. These results accord with the study by Tom *et al.* [42], in which the lignocellulosic levels decreased during the biodrying process. Hemicellulose degradation occurs because hemicellulose decomposition will be converted into pyruvate, and energy that will be used in the biodrying process will be released [4]. A decrease in the hemicellulose content after peak temperatures occurred because many organisms die after the peak temperatures [37]. Based on statistical testing, the sig. value was obtained as 0.681, which is less than 0.05, indicating that the air flow rate has no significant effect on hemicellulose levels.

3.6. Calorific value

The calorific value is an indicator of the energy content of a substance. Biodrying can process MSW into fuel with high energy content. The calorific value measurement result is illustrated in Fig. 7.

The unit of calorific value is generally MJ/kg [47]. The product from reactor R3 had the highest calorific value, 17.63 MJ/Kg, which was 55.3 % higher than the calorific value of the unprocessed MSW; meanwhile, R1, R2, and R4 could increase the calorific value by 4.7 %, 4.7 %, and 33.9 %, respectively, compared with the calorific value of the unprocessed MSW. The product from R1 had the lowest calorific value, 8.06 MJ/Kg. The calorific value is influenced by the fixed carbon in the sample [48]. According to Qu *et al.* [49], the calorific values of lignocellulose and lignin are 13.4 and 20.6 MJ/Kg, respectively. According to Nasrullah *et al.* [50], the presence of plastic in the sample also results in high calorific values.

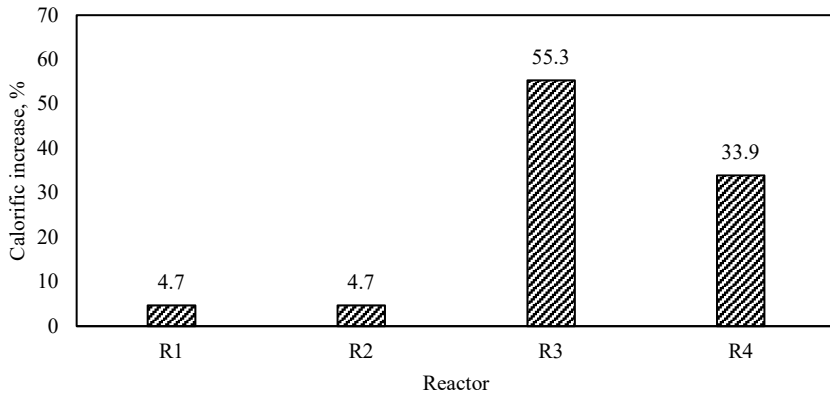


Fig. 7. Variations of calorific increase biodrying process.

Based on this research, solid-recovered fuel (SRF) with a calorific value of 17.63 MJ/Kg can be classified into class 3 (i.e., >15 MJ/Kg), while class 2 SRF has a calorific value of 20 MJ/Kg [51]. Moreover, SRF with a calorific value of 17.63 MJ/Kg can be used in cement, hard coal, brown coal, and fluidized bed combustion [9]. Considering that the sig. value of 0.010 obtained from the statistical test is less than 0.05, the air flow rate has a significant influence on the calorific value.

4. CONCLUSION

The main objective of this research is to increase the calorific value of MSW in the Jatibarang Landfill, Semarang, Central Java, Indonesia. The results show that the calorific values of the MSW processed in the biodrying reactor and the control reactor were 55.3 % and 4.7 % higher than that of the unprocessed MSW, respectively. The air flow rate had a significant effect on the calorific value (sig.<0.05). The highest calorific value was 17.63 MJ/kg, at an air flow rate of 4 L/min/kg. Hemicellulose degradation due to air flow rate reached 80–85 %. The air flow rate did not significantly influence the hemicellulose degradation (sig.>0.05). The highest temperature in the biodrying process was 41 °C, and the reduction in water content was 58.29 %. The biodrying process is the right method to increase the calorific value, as it can increase the calorific value while reducing the MSW water content, thus promoting the realization of waste to energy. The final product had a calorific value of 17.63 MJ/Kg which offers a good substitute for brown coal that can be used in cement, hard coal, brown coal, and fluidized bed combustion. Biodrying creates a mindset that solid waste can be seen as a source of energy rather than just as waste.

ACKNOWLEDGMENT

Thank you to Diponegoro University for funding this research through RPP grant for financing year 2019.

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