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Study of the effect of a bulking agent on the biodrying of municipal solid waste

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Abstract: The characteristics of municipal solid waste in Indonesia tend to be wet and have a low calorific value. Therefore, a pre-treatment process is needed to dry the municipal solid waste before converting it into RDF. Biodrying is one of the solid waste drying methods that can be used for this purpose. This study aims to determine the effect of variations in bulking agents on the biodrying performance of municipal solid waste and to compare the resulting product with RDF standards. Reactor 1 consists of 100% organic waste without a bulking agent. Reactors 2, 3, and 4 contain organic waste mixed with straw, wood shavings, and rice husks, respectively, as bulking agents. The experiment lasted for 30 days. Measurements were taken for solid waste mass, temperature, moisture content, calorific value, proximate analysis (including volatile solids, fixed carbon, and ash content), and ultimate analysis. Statistical analysis of the test parameters showed that the addition of bulking agents significantly affected the moisture content and fixed carbon levels. A comparison between the biodrying results and RDF standards from several references shows that the biodried waste only meets RDF requirements for volatile content, chlorine, and sulfur. Among the variations tested, the organic waste mixed with straw (Reactor 2) yielded the most optimal results compared to other variations, with a moisture content of 54.33% (wet basis) and a calorific value of 5.4 MJ/kg.

Introduction

According to a summary of national municipal solid waste data, Indonesia produces 41,207,774.55 tons of waste annually, of which 64.97% (or 26,772,742.12 tons) is managed, while 35.03% (14,435,032.43 tons) remains unmanaged (Ministry of Environment and Forestry 2021). The proportion of organic waste in developing countries is relatively high (Zhou and Dan 2024). Meanwhile, the use of fossil fuels contributes to environmental issues such as global warming and air pollution, which negatively impact human health and quality of life (Martins et al. 2019) and contribute to looming energy crisis due to their limited availability (Zhao and Ci 2019). Refuse-Derived Fuel (RDF) can be produced from municipal solid waste (Chaerul and Wardhani 2020). Energy-from-waste (EFW), also known as waste-to-energy (WTE), is considered one of the most effective and efficient methods for lowering the volume of solid waste (Pasek, Gultom, and Suwono 2013). RDF represents one approach to implementing the waste-to-energy concept while also addressing the dual challenges of municipal solid waste management and the energy scarcity. By utilizing a drying process, RDF can be derived from municipal solid waste. Biodrying is an option for drying operations. It is anticipated that this technique can enable the production of RDF from municipal solid waste, which typically has a moist and humid composition (Cheremisinoff 2003).

The Mechanical-Biological Treatment (MBT) method includes biodrying, which aims to reduce the moisture content of waste by using heat generated through the microbial degradation of organic matter. This process increases the calorific value of the waste. By limiting the extent of organic matter degradation, biodrying has demonstrated an increase in the calorific value of the treated waste of around 30% (Cheremisinoff 2003). It can also reduce the moisture content of the waste by 40–66%. Biodrying has evolved into an effective pre-treatment procedure that reduces waste volume, facilitating easier transportation and short-term storage. Additionally, it helps mitigate secondary pollution issues, such as odor, during subsequent waste management operations (He et al. 2013). During the biodrying process, air is forced in one direction throughout the biomass, and moisture is released in the form of steam. The high temperatures generated during decomposition produce water vapor (Sugni, Calcaterra, and Adani 2005).

Additionally, the biodegradation of bulking agents contributed approximately 82.35-86.67% of the heat required for water vaporization (Liu et al. 2018). Straw and wood shavings are commonly used to facilitate sludge composting or biodrying processes (Zhao et al. 2011). In sludge biodrying, wood shavings and straws have been used as bulking agents. Research has shown that while wood shavings decompose slowly, straw undergoes more effective aerobic decomposition (Zhao et al. 2011). Another study tested sludge biodrying using various bulking agents such as corn stalks, rice husks, sawdust, and spent mushroom substrate. The findings indicated that these bulking agents improved the performance of the biodrying process, particularly when applied to kitchen waste. When combined with bulking agents, kitchen waste exhibited a higher moisture removal rate during the biodrying process, ranging from 55.6% to 65.4% (Yuan et al. 2019).

Based on the summary above, the author is interested in conducting research on biodrying as a pre-treatment method for producing RDF from municipal solid waste, using a variety of bulking agents, including straw, wood shavings, and rice husks. This study will investigate how different bulking agent impact the biodrying process, which serves as a pre-treatment step in RDF formation. Specifically, it aims to analyze the impact of bulking agent variation on temperature achieved, waste mass reduction, calorific value, proximate analysis (including moisture content, volatile matter, fixed carbon, and ash content), and ultimate analysis (C, H, O, N, S, Cl). Additionally, the study seeks to evaluate the quality of biodried municipal solid waste compared to the standards for fuel derived from waste. This research hypothesizes that bulking agents affect the characteristics of municipal solid waste after biodrying.

Materials and Methods

Tools and Materials

The tools used in this study include a biodrying reactor unit, where the biodrying process is carried out, and a non-woven polypropylene geotextile as a reactor cover. A digital compost thermometer with a display screen is used to measure the temperature of the waste inside the reactor. An airflow meter is employed to measure the air discharge flowing through the aerator hose into the reactor. Additional equipment includes an aerator hose for channeling air into the reactor, a perforated baffle to support the waste, a waste shredder to reduce the size of the organic waste, an aerator as the airflow source, and a stirrer for mixing the waste. Used bottles serve as leachate containers, and a set of scales is used to measure the mass of the waste. For the analysis of various parameters, other equipment includes ovens, desiccators, analytical balances, cups, and cup tongs. The materials needed for the study include bulking

Table 1. Characteristics of bulking agent

Composition	Straw	Wood Shaving	Rice Husk
Moisture content (%)	11 ±0,25 [c)]; 13.05 [d)]	-	9-11[a)]
Ash content (%)	11		18-21 [a)]; 18.5% [b)]
Carbon (%)	41.8 [e)]		37-40 [a)]; 40 [b)]
Hydrogen (%)	4.6 [e)]		5-6 [a)]; 5.37 [b)]
Nitrogen (%)	0.7 [e)]		0.6-0.7 [a)]
Oxygen (%)	36.6 [e)]		53.8 [b)]
Sulfur (%)	0.08 [e)]		0.4 [b)]
Rasio C/N			60-70 [a)]
Density (kg/m^3)	85.8 [d)]		110-120 [a)], 92 [b)]
Free air space (%)			90-100 [a)]; 91.69
Water absorption capacity (%)		430-450	330-340 [a)]
High heating value (kJ/kg)	16.28 MJ/kg [e)]	19,97-20,48	17.668 [b)]
Low heating value (kJ/kg)			15.740 [b)]
V*olatile matter* (%)	69 [e)]		65.77 [b)]
Fixed carbon (%)	17 [e)]		11.7 [b)]
Particle size (mm)	0-0.710 [f)]		0.212-0.850 [f)]

Source : [a](Chang & Chen, 2010) [b](Yuan et al., 2019) [c](Zhao et al., 2011) [d](Song et al., 2015) [e](Jameel et al., 2010) [f](Zhang et al., 2012)

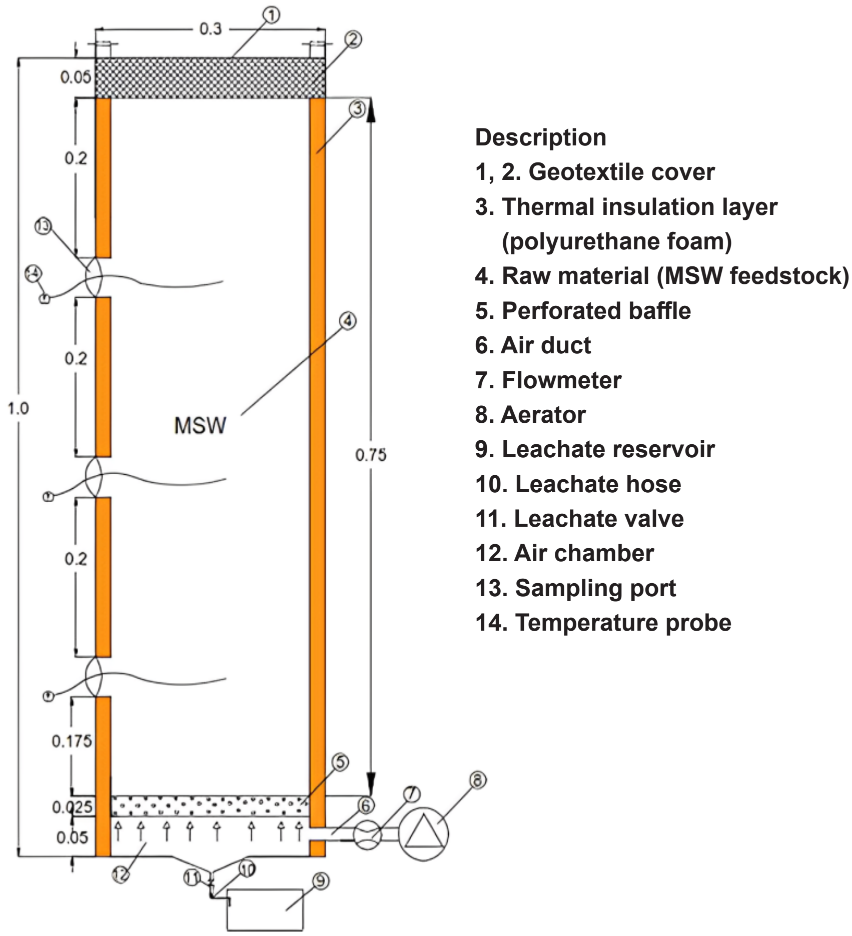

Figure 1. Design of the biodrying reactor

agents such as wood shavings, rice husks, and straw, as well as organic waste consisting of vegetable and garden waste.

Bulking Agents

Carbon sources, including wood chips, leaves and yard trimmings, corn cobs, stalks, and straw, are commonly used as bulking agents (Tun and Juchelková 2018). Agricultural waste is a major source of these materials, with straw and rice husk being two notable examples. In addition to agricultural residues, wood shavings are also frequently used as bulking agents due to their wide availability and extensive use in previous studies. The characteristics of straw, rice husk, and wood shavings are as follows.

Wood shavings, straws, and rice husks will be used as bulking agents in this research, comprising up to 15% of the total waste mass fed into the reactor (Yang et al. 2013). The dependent variables in this study include waste mass, temperature, calorific value, proximate analysis results (moisture content, volatile matter, fixed carbon, and ash content), and ultimate analysis results (C, H, O, N, S, and Cl). The controlled variables in this study are residence time, aeration rate, reactor cover, and stirring frequency.

Biodrying Reactor

This research used a column-type biodrying reactor (Zhang et al. 2008). The reactor was constructed from modified PVC and measured 30 cm in diameter and 100 cm in hight. To minimize heat loss, the inner wall of the reactor was lined with a 2 cm layer of polyurethane foam (Bilgin and Tulun 2015). Figure 1 presents the design of the biodrying reactor used in this study. The reactor is covered with a non-woven, thermally resistant polypropylene geotextile, which permits the release of water vapor. The reactor cover plays a crucial role in maintaining a stable internal temperature and facilitating efficient moisture removal through the porous geotextile fabric, which is essential for an effective biodrying process (Ab Jalil et al. 2016).

Preparation of Substrate (Feed)

This research used municipal solid waste composed entirely of organic material, consisting of 50% vegetable waste and 50% garden pruning waste. Preparation of the substrate involved weighing the required amounts of each component and manually mixing them to ensure even distribution of moisture content throughout the waste (Ab Jalil et al. 2016). Each reactor required a minimum of 25 kg of municipal solid waste (Yuan et al. 2019; Zawadzka et al. 2010). Reactors 1, 2, 3, and 4 are all contained the same organic waste composition: 50% garden pruning and 50% vegetable waste (Colomer-Mendoza et al. 2013). The aeration rate for the biodrying process was set at 0.012 m^3 kg^{-1} jam^{-1}. The reactors differed based on the type of bulking agent added. The specific compositions for each reactor were as follows:

Reactor 1: 25 kg of organic waste without a bulking agent
Reactor 2: 25 kg of organic waste and 3.75 kg of straw
Reactor 3: 25 kg of organic waste and 3.75 kg of wood shavings
Reactor 4: 25 kg of organic waste and 3.75 kg of rice husk.

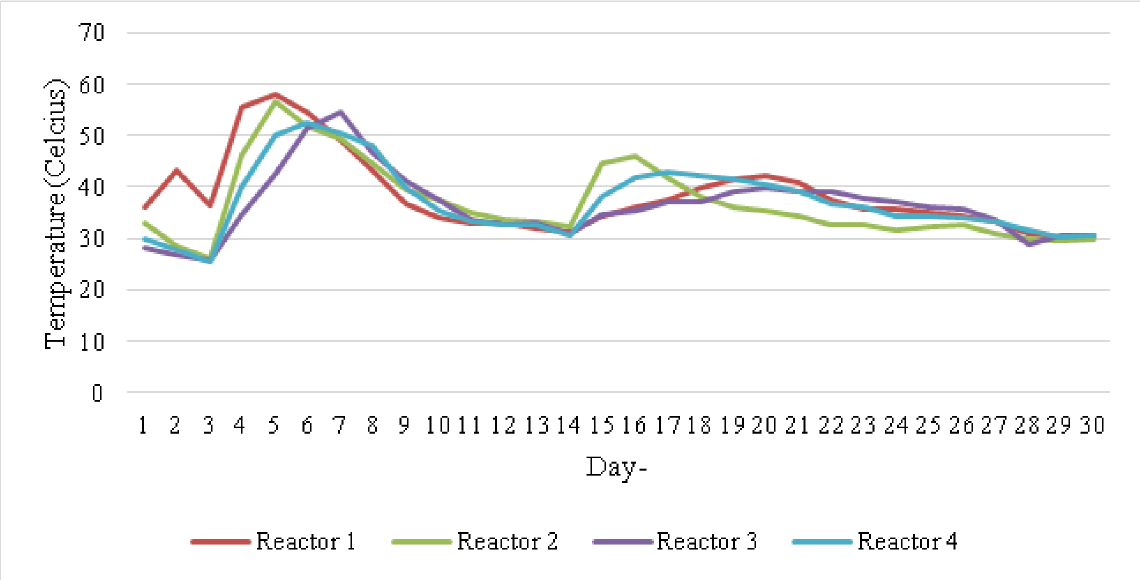

Figure 2. The average temperature of each reactor during the biodrying process

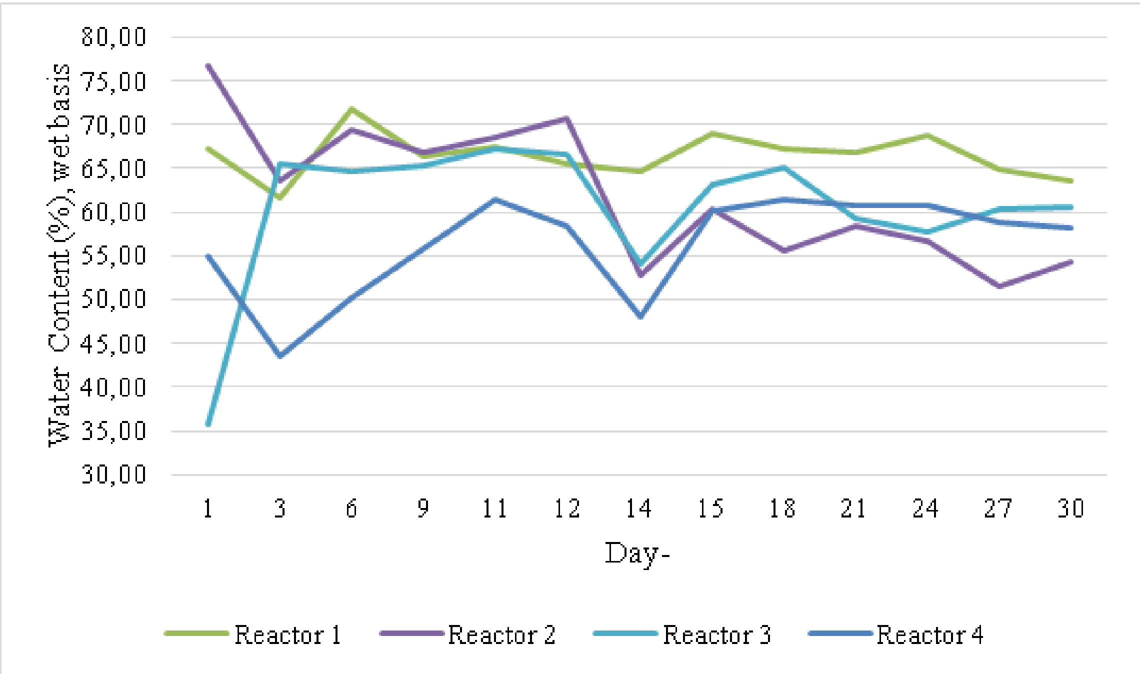

Figure 3. Moisture content on all biodrying reactors for 30 days

Table 2. Test Results of Initial Waste Characteristics

Reactor	Initial Temperature (Celcius)	Initial Moisture Content w.t (%)	Initial Volatile Content (%)	Initial Fixed Carbon %	Initial Ash Content (%)
1	36.17	67.32	74.89	2.04	25.11
2	33	76.63	83.21	1.39	16.79
3	28.33	35.74	87.16	0.95	12.84
4	30	54.93	81.04	1.75	18.96

Sampling Technique

In this study, sampling will be conducted at various stages of the biodrying process. Waste samples will be taken from each reactor for proximate and ultimate analysis, as well as calorific value testing. Approximately 300 grams of waste will be collected from three different points in the reactor (top, middle, and bottom) and then mixed to create a composite sample for testing. Moisture content will be measured every three days. Additionally, the waste will be manually stirred in the middle of the process (day 15) to prevent the formation of a moisture gradient. For each sampling event, approximately 100 grams of waste will be collected from each of the three points (top, middle, and bottom). These samples will be then combined to form a total of 300 grams, which will be tested for moisture content and other parameters (Ab Jalil et al., 2016).

Results and Discussion

Initial Municipal Solid Waste Characteristics

The initial municipal solid waste (MSW) characteristics used in the biodrying process depend on the category of the municipal solid waste and the bulking agent. The results of the initial MSW characteristics test for each biodrying reactor are listed below.

Table 2 shows the waste characteristics in each biodrying reactor, which are distinguished by their contents based on the composition of waste and bulking agent. The highest initial waste temperature was observed in the first reactor (control reactor) at 36,17^{o}C, while the lowest temperature was recorded in the third reactor at 28.33^{o}C. The highest initial moisture content was found in reactor two, which contained organic waste mixed with chopped straw, at 76.63%. In contrast, reactor three showed the lowest initial moisture content at 35.74%. Other parameters tested to determine the characteristics of the initial waste included proximate analyses consisting of volatile content, ash content, and fixed carbon. The lowest volatile content was found in reactor one at 74.89% (dry weight), while the highest volatile content was observed in reactor three at 87.16% (dry weight). Table 3 presents the ultimate analysis of the initial municipal solid waste in each biodrying reactor.

Temperature

One of the key parameters in the biodrying process is temperature, which must be monitored daily. Figure 2 presents the temperature measurement results over a thirty-day period for each biodrying reactor. The values shown represent the average temperature, calculated from measurements taken at three points within the reactor: the top, middle, and bottom.

Figure 2 shows the temperature trends in each biodrying reactor from day 1 to day 30. The temperature began to rise on the fourth day of the process and then gradually declined. After stirring the waste on day 14, the temperature in each biodrying reactor rose again until it stabilized around day 28. The increase in temperature observed on day 15 was likely triggered by the stirring conducted on day 14. Stirring the waste improves porosity, enhances the degradation of organic matter, increases oxygen availability, and exposes more undecomposed material (Kalamdhad and Kazmi 2009; Stanford et al. 2009). Stirring the waste itself was only carried out on day 14 in response to the downward temperature trend. Stirring is generally avoided during the temperature rise phase, as it can interrupt microbial activity and reduce the temperature (Cai et al. 2013). Temperature plays a crucial role in water evaporation, while ventilation affects the amount of moisture lost from the waste during the biodrying process (Yuan et al. 2017). The highest recorded temperature was 58^{o}C in reactor one (control) on the fifth day, whereas the lowest temperature was 25.5^{o}C in reactor three on the third day of the biodrying process.

Moisture content

The percentage of water in municipal solid waste is known as moisture content. It is one of the crucial factors in the conversion of municipal solid waste into refuse-derived fuel (RDF). Microorganisms require both water and oxygen during the organic degradation process for their metabolic functions. Eventually, the biodrying reactor reaches its saturation point for oxygen and moisture concentration (Sugni et al. 2005). Wood shavings have a moisture content ranging from 10% to 60% (Jameel et al. 2010). The moisture content test is carried out every three days by collecting 100-gram waste samples from the top, middle, and bottom layers. These samples are then mixed and tested for water content. The gravimetric-based moisture content testing method follows SNI 03-1971: 1990-87 (2004).

Figure 3 shows the moisture content on all biodrying reactors. According to the moisture content test, organic waste (vegetable and fruit waste) has a high water content of 90.68%. The moisture content of garden waste, such as leaves and small branches, is 29.39%. Without the addition of a bulking agent, the initial moisture content of municipal solid waste in reactor

Table 3. Ultimate Analysis of Municipal Solid Waste Characteristics

Reactor	Ultimate Analysis					
	C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)
1	47.86	5.89	20.47	0.79	0.40	1.29
2	39.45	4.74	30.33	0.75	0.10	0.97
3	41.96	5.38	27.96	0.75	0.17	1.13
4	49.48	5.54	24.25	1.48	0.32	0.48

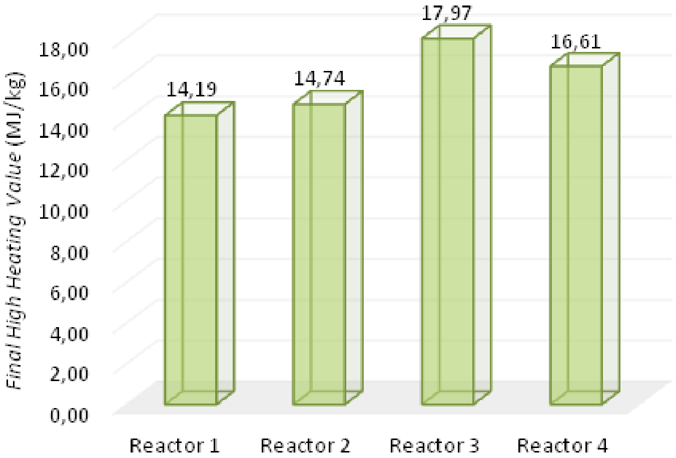

Figure 4. The Result High Heating Value of Municipal Solid Waste After Biodrying Process

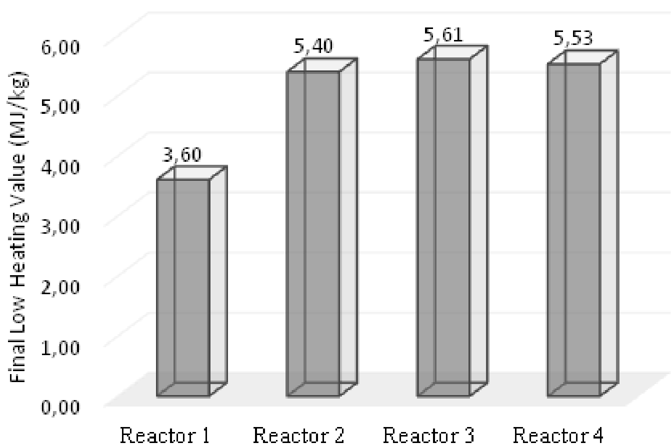

Figure 5. The Result Low Heating Value of Municipal Solid Waste After Biodrying Process

1 is 67.32%. When straw, wood shavings, and rice husks are added to reactors 2, 3, and 4, the corresponding moisture contents are 76.63, 35.74, and 54.93, respectively.

Calorific Value

The calorific value of municipal solid waste represents the amount of heat generated when the waste is completely combusted. Waste with a higher calorific value is more flammable and burns for a longer duration. The techniques such as bomb calorimetry, proximate analysis, and ultimate analysis are commonly used to determine calorific values (Damanhuri and Padmi 2019). In this study, the final calorific value was calculated based on laboratory measurement results. Figure 4 shows the results obtained using a bomb calorimeter, showing the calorific value of the waste in each biodrying reactor, expressed as HHV (High Heating Value.

Figure 5 shows the results of calorific value measurements in terms of the low heating value (LHV). To calculate LHV, the calorific value measured in HHV must be added to account for components that reduce the actual usable energy content. This adjustment corrects for the latent heat of water vapor formed from both moisture content and hydrogen combustion. In LHV calculations, the moisture content of the waste is included by subtracting the energy associated with water vaporization, particularly from hydrogen-bound water. The LHV of a substance is affected by the oxidation of organic matter (volatile solids) and the removal of water vapor during combustion (Adani 2002). When calculating LHV, the moisture content of municipal solid waste is a critical factor. The results show that the calorific value (both HHV and LHV) of municipal solid waste mixed with bulking agents is generally higher than that of waste without bulking agents. Previous studies have reported calorific values ranging from 6.75 to 10.98 MJ/kg (Zawadzka et al. 2010) and 16.41 3.74 to 17.97 1.25 MJ/kg (Chaerul and Wardhani 2020).

Analysis of the Effect of Variations Bulking Agent on Biodrying Process Results

After all parameters were statistically analyzed using SPSS, the following results summarize the effect of the bulking agent on several factors. Table 3 shows that the bulking agent significantly affects the moisture content and fixed carbon. However, it does not have a significant impact other parameters, such as temperature, volatile matter, and ash content.Adding wood shavings as a bulking agent may decrease the fixed carbon content of the waste in the biodrying reactor. The ash, sulfur, and chlorine content of the municipal solid waste were reduced by adding a bulking agent at the beginning of the biodrying process. Furthermore, the volatile matter content and the calorific value of the waste can be increased by adding a bulking agent.

Table 4. Summary of Test Results of the Effect of Bulking Agent on Temperature, Moisture, Volatile , Ash Contend and Fixed Carbon

No	Parameter	Statistical test used	Sig. value	Description
1	Temperature	Kruskal Wallis	0.688	No significantly affected
2	Moisture Content	Kruskal Wallis	0.001	Has significant effect
3	Volatile Content	Kruskal Wallis	0.168	No significantly affected
4	Ash Content	Kruskal Wallis	0.168	No significantly affected
5	Fixed Carbon	One Way Anova	0.000	Has significant effect

Table 5. Summary of comparison of biodrying product characteristics with Refuse Derived Fuel standard

Parameters	Reactor 1	Reactor 2	Reactor 3	Reactor 4	RDF Standard
Moisture content % (weight basis)	63.62	54.33	60.53	58.14	10-35[a] ; <20[f]; class 1 <15; class 2<20; class 3 <25[g]
Volatile content % (dry basis)	57.14	69.62	72.44	70.2	50-80[b] ; class 1 = 65; class 2 = 70; class 3 = 75[g]
Ash content % (dry basis)	42.86	30.38	27.56	29.8	15-20[a] ; class 1 <15; class 2<20; class 3 <25[g] ; 15[h]
Fixed carbon % (dry basis)	1.91	1.73	1.59	1.66	>10[c] ; kelas 1 >15; kelas 2 >10; kelas 3 > 5[g]
Chlorine % (dry basis)	0.637	0.543	0.537	0.307	0,15-1,5[d] class 1 ≤ 0,2; class 2 ≤ 0,6; class 3 ≤ 1[g] ; 0,8[h]
Sulfur % (dry basis)	0.103	0.087	0.103	0.08	0,2-0,5[d] ; class 1 s.d 3 ≤ 1,5[g] ; 0,5[h]
Calorific value - Low Heating Value (MJ/kg)	3.6	5.4	5.61	5.53	12-16[a;] 12,5[f] dan class 1 ≥ 20; class 2 ≥ 15; class 3 ≥ 10; 12,55[h]

Sources : [a](European Commision – Directive General Environment, 2003) ; [g](National Standardization Agency, 2021) ; [h](Semen Indonesia Group, 2019)

Comparison of MSW Biodrying Results with Refuse Derived Fuel (RDF) Standards

Th essential characteristics and parameters of the RDF used as fuel include calorific value, moisture content, ash content, sulfur content, and chlorine content. The results obtained from testing these characteristics are highly dependent on the waste source (e.g., household, office, construction), the waste collection system (mixed or separated), and the processing methods used, such as screening, sorting, shredding, and drying. A comparison between the results of the biodrying process and RDF standards from various references shows that municipal solid waste treated through biodrying process does not meet RDF standards in terms of moisture content, calorific value, ash content, and fixed carbon. However, it does meet RDF standards for volatile matter, chlorine, and sulfur content.

According to a comparison of the biodrying process results with RDF standards from various references, the biodried municipal solid waste does not meet RDF criteria in terms of moisture content, calorific value, ash content, and fixed carbon. However, it complies with RDF standards for volatile matter, chlorine, and sulfur content.

Conclusion

According to the results of statistical testing, bulking agents significantly affect the moisture content and fixed carbon but have no significant impact on temperature, volatile matter, or ash content. A comparison between the results of the biodrying process and RDF standards from various references shows that the biodried municipal solid waste does not match RDF criteria in terms of moisture content, calorific value, ash content, and fixed carbon. However, it does comply with RDF standards for volatile matter, chlorine, and sulfur content.

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