Effect of Torrefaction Temperature on Physical Properties of Biopellet from Variant Biomass Waste

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Abstract- This study was conducted to analyze the effect of torrefaction temperature on biopellets, which are densified biomass from cassava stems, corncobs, elephant grass, bagasse, and rice straw. The torrefaction temperature factors were non-torrefied biopellet, 220 °C, 240 °C, 260 °C, and 280 °C. The experimental design used was a two-factor completely randomized design with three replications. When tested for least significant difference (LSD) on moisture content (MC) parameters, the results showed a significant difference where temperatures of 220 °C, 240 °C, and 260 °C resulted in the lowest mean MC value of 0.71%. The torrefaction temperature also showed a significant difference in the density parameter, with the highest average density produced at 220 °C and 240 °C at 0.66 N/m^3. The torrefaction temperature did not show a significant difference in water absorption. However, when compared with non-torrefied biopellets, the average water absorption value showed a significant difference in the LSD test, 16.07% for non-torrefied biopellets and 13.09% for torrefied biopellets. The hydrophobicity test showed that the best torrefaction temperature for corncob biopellet was 280 °C. At this temperature, the biopellet did not experience physical and watercolor changes for 24 hours under extreme conditions (immersed in water).

Keywords Biopellet, Torrefaction, Moisture Content, Water Absorption, Density, Hydrophobicity.

1. Introduction

The energy crisis has caused renewable energy resources to be considered the main source of future power generation [1][2]. Renewable energy also offers a clean and inexpensive option compared to fossil fuel [3]. As a country with abundant agricultural commodities with great benefits, Indonesia is directly proportional to biomass energy as a significant potential renewable energy resource [4][5]. The Ministry of Energy and Mineral Resources of the Republic of Indonesia [6] reports that energy consumption from biomass in 2018 is estimated to reach 67.75 million barrels of oil equivalent (BOE) or 7.24% of the total energy consumption of 936.33 million BOE. Biomass which is used as an energy source (fuel) in Indonesia in general, has low economic value or is a waste that has been taken from its primary product. The potential of biomass resources in Indonesia is estimated at 49.810 MW, which comes from plants and waste. Currently, the enormous potential of existing biomass for energy is waste from plantation products such as oil palm, coconut, and sugar cane, and forest product waste, such as sawn waste and wood production waste [7]. The advantage of using biomass as an energy source, according to W. Liu [8], is that it can reduce carbon dioxide in the atmosphere because there are fewer combustion products so that it can be reabsorbed by plants (carbon neutral). However, K. Sivalaban [9] reports that biomass as a direct fuel has weaknesses in its physical properties, such as relatively low energy density, and causing handling and storage constraints in transportation. To overcome these problems, biomass waste can be reduced in size and compacted to a cylindrical shape as a biopellet.

Biopellet is biomass that has undergone a densification process, and this aims to increase the density of biopellet to facilitate handling, storage, and transportation because they have a uniform size [10]. However, biopellet still has weaknesses in low energy density, low heating value, and high moisture content [11]. Moisture content (MC) is one parameter that affects the calorific value, combustion efficiency, combustion temperature, and humidity balance related to biopellet storage conditions [12]. Biopellets also not be stored for a long time because of their high water absorption capacity [13].

One of the methods used to overcome this problem is the torrefaction process, heating the biomass slowly with a temperature range of 200-300 °C with little or no oxygen. The biopellet torrefaction process can change the hygroscopic nature of biopellet to become more hydrophobic [14]. This study aims to determine the effect of torrefaction temperature on the physical properties of biopellet derived from waste cassava stems, corncobs, elephant grass, bagasse, and rice straw. Physical properties observed included water content, absorption, density, and hydrophobicity of biopellet. This study will obtain information on the best quality of biopellet based on the temperature given in the torrefaction process from variant biomass waste.

2. Materials and Method

The research was carried out at the Laboratory of Energy and Agricultural Machinery, University of Lampung (5°22'7" S, 105°14'33" E). The material used is agricultural waste biomass, namely cassava stems, corncobs, elephant grass, bagasse, and rice straw. The biomass waste obtained from farmers around Bandarlampung is then cleaned from dirt and sorted as raw material for making biopellet. The sorting process is done by chopping the raw materials into rough grains, then mashing using a hammer mill. After that, the raw material with fine particles will go through a drying process to reduce the moisture content and increase the calorific value [15]. This raw material is done by drying in the sun for 3-4 days in sunny weather conditions. The dried biomass was then sieved using a ten mesh sieve to uniform the size of the raw material [16]. After the raw material preparation is complete, the biomass is pressed into biopellet using a Bench Type Hydraulic Press at a pressure of 2 tons with mold size of 1.3 cm in diameter and a cylinder length of 10 cm.

Biopellets from five types of biomass that have been prepared will go through a torrefaction process. Torrefaction was carried out by wrapping the biopellet using aluminum foil and heating it in a furnace (Vulcan D-550) at various temperatures of 220 °C, 240 °C, 260 °C, and 280 °C for 20 minutes. This temperature variation was chosen because torrefaction is a mild pyrolysis process with temperatures ranging between 200 °C and 300 °C [17].

2.1. Experimental Design

This study examines the effect of torrefaction temperature on the physical properties of biopellets from several types of biomass. For this reason, the research design used was a completely randomized design with two factors. The first factor is the torrefaction temperature (non-torrefied, 220 °C, 240 °C, 260 °C, and 280 °C) and the type of biomass (cassava stalks, corncobs, elephant grass, bagasse, and rice straw). All treatment combinations were repeated three times so that 75 experimental units were completely randomized.

2.2. Analysis and Measurement

The parameters of the physical properties of the biopellet observed were MC, water absorption, density, hydrophobicity, and calorific value. The water content analysis took 1 sample material without a cup and placed it in a porcelain dish with a known weight. The sample was then dried in an oven at 105 °C for 24 hours until constant MC. The sample is then cooled in a desiccator until the temperature is stable and weighed. The MC value can be calculated by the equation below.

$$MC = \frac{B_i - B_a}{B_i} \times 100\% \quad (1)$$

Where B_i is the weight of the sample before being dried and B_a is the weight of the sample after being dried in an oven.

Parameters of water absorption were carried out by leaving the biopellet in an open space and observing the increase in mass periodically for one month. Density analysis was carried out by comparing the weight of the biopellet to its volume. The calculation of density (N/m^3) was carried out using the equation below.

$$Density\left(\frac{N}{m^3}\right) = \frac{w}{v} \quad (2)$$

Where w is the weight of the sample (N) and V is the sample volume (m^3).

Observation of the hydrophobicity of biopellets was carried out by immersing the biopellet into the water to see how long the biopellet took to absorb water. Immersion time is determined from 1 minute, 3 hours, 12 hours, and 24 hours. During immersion time, changes in the physical shape of the biopellet that occurred due to the effect of immersion were visually observed.

2.3. Data Analysis

Statistical analysis of the observed data was carried out to see the distribution and data pattern [18][19]. The MC, water absorption, and density data were analyzed using the ANOVA method to see any significant difference between factors at the α = 0.05. Then the least significant difference (LSD) test was performed when the difference between the population means was statically different. The ANOVA and LSD tests were performed using Microsoft Excel and SAS 9.4.

3. Results

Table 1 shows the effect of torrefaction temperatures T0 (non-torrefied), T1 (220 °C), T2 (240 °C), T3 (260 °C), and T4 (280 °C) on the physical properties of biopellet V1 (cassava stem), V2 (corncob), V3 (elephant grass), V4 (bagasse), and V5 (rice straw). The physical properties of the biopellets observed included MC, water absorption, and biopellet density. Figure 1 shows a graph of biopellet water absorption observed every day for 30 days at various torrefaction temperatures, in line with the humidity value at the same time.

The hydrophobicity test was carried out by immersing the biopellet into the water, and the physical changes of the biopellet were observed visually for 24 hours with several intervals of observation. Fig. 1 shows the physical changes of non-torrefied corncob biopellet (V2) and V2 using four temperature variations when immersed in water for 24 hours.

4. Discussion

4.1. Moisture Content

The MC average value of the biopellet from five types of non-torrefied and torrefied biomass in this study is shown in Table 1. Based on Table 1, the torrefied biopellet has a relatively low average percentage of MC, from 0.38 to 1.51%. This MC value follows the characteristics of torrefaction biopellets in the research of V.T.P. Sidabutar, [20], with an MC range between 1 - 5%. The highest average MC was observed in corncob biopellet, torrefied at a temperature of 280 °C (T4V2) of 1.51%. The sugarcane bagasse biopellet has the lowest average MC, torrefied at 220 °C (T1V4) of 0.38%. Meanwhile, the MC of non-torrefied biopellet ranged from 8.34 to 11.10%, with the highest mean MC in rice straw biopellet (V5) and the lowest average water content in corncob biopellet (V2).

Table 1. Effect of torrefaction temperature on the physical properties of biopellets

Moisture content (MC) (%)						
Temp	V1	V2	V3	V4	V5	Average
T0	9.82	8.34	9.64	9.58	11.10	9.69^{a}
T1	0.67	0.76	1.09	0.38	0.42	0.66^{c}
T2	0.57	0.78	0.52	0.69	0.64	0.64^{c}
T3	1.04	0.83	0.66	0.73	0.88	0.83^{c}
T4	1.37	1.51	1.24	1.26	1.46	1.37^{b}
Average	2.69^{AB}	2.44^{B}	2.63^{B}	2.53^{B}	2.89^{A}	
Water Absorption (%)						
T0	16.42	15.89	20.97	11.07	16.00	16.07^{a}
T1	12.92	13.04	20.25	8.49	13.32	13.60^{b}
T2	12.86	13.26	18.23	8.26	13.91	13.30^{b}
T3	11.32	11.44	18.79	8.11	14.08	12.75^{b}
T4	10.61	10.31	20.81	8.70	13.10	12.71^{b}
Average	12.82^{C}	12.79^{C}	19.81^{A}	8.93^{D}	14.08^{B}	
Density (N/m^{3})						
T0	0.68	0.71	0.82	0.87	0.78	0.77^{a}
T1	0.61	0.58	0.72	0.73	0.66	0.66^{b}
T2	0.54	0.63	0.73	0.75	0.64	0.66^{b}
T3	0.52	0.54	0.64	0.73	0.61	0.61^{c}
T4	0.50	0.50	0.63	0.71	0.61	0.59^{c}
Average	0.57^{D}	0.59^{D}	0.71^{B}	0.76^{A}	0.66^{C}	

Note: numbers followed by the same letter are not statistically different at α = 0,05; small letters for column (types of biopellet), capital letters for row (temperature).

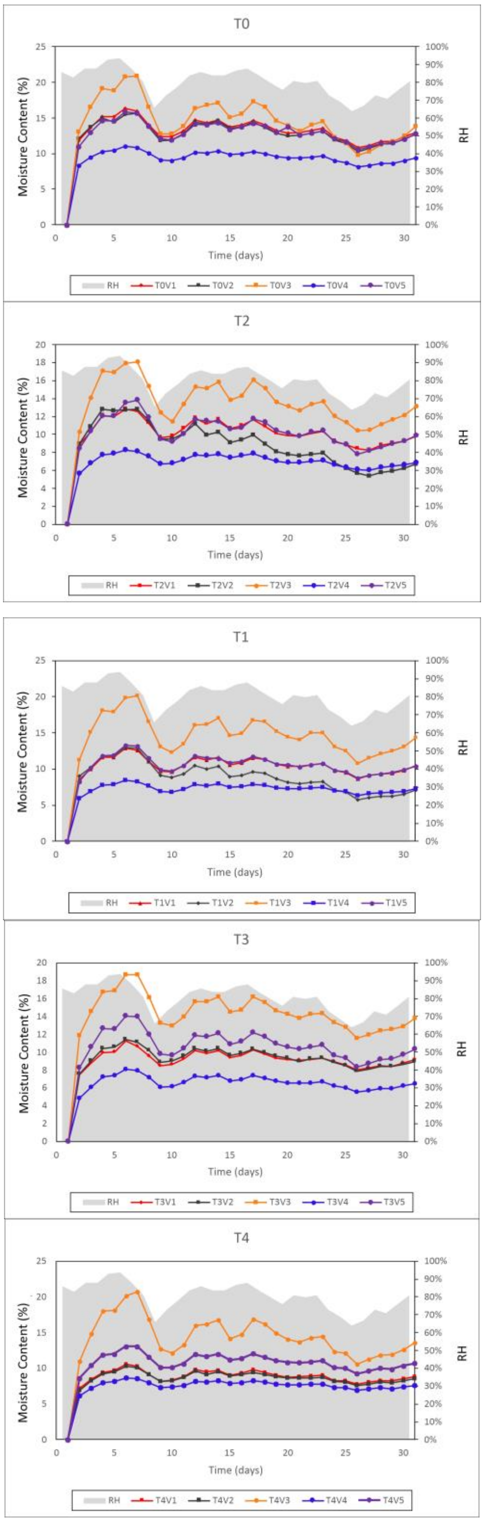

Fig. 1. Biopellet water absorption and relative humidity (RH) vs. time at variation of torrefaction temperature

The ANOVA showed a significant difference at the α = 0.05 for the effect of torrefaction temperature and type of biopellet on the MC values. In the torrefaction temperature treatment, the LSD test showed that the non-torrefied biopellet (T0) was significantly different from all other temperature treatments (T1, T2, T3, and T4) with an average high moisture content of 9.69%. The best temperature treatments to get the lowest water content values are T1, T2, and T3, where these treatments have the same notation on the LSD test.

Table 1 also presents the results of the LSD test on the variation of biopellets carried out, where the cassava stem biopellet (V1) and rice straw biopellet (V5) did not differ significantly at the level α = 0.05 with each value of the average MC of 2.69% and 2.89%. However, the MC of the V5 biopellet was significantly different from that of the V2, V3, and V4 biopellets.

The analysis results showed that the MC of the torrefied biopellet had a lower MC than the non-torrefied biopellet. Torrefaction using higher temperatures causes evaporation of water and extractives and degradation of hemicellulose so that the water content decreases [21].

4.2. *Water Absorption*

Analysis of water absorption was carried out by leaving the biopellet in an open room and observing the increase in mass periodically for one month. Figure 1 shows the results of observing the water absorption of torrefaction and non-torrefaction biopellets with measured humidity. On the fifth day, all biopellet moisture content increased due to 94% humidity, and on the eighth day decreased due to 66% humidity. After the eighth day, the water content of the biopellet tends to show a stable number in all treatments.

Figure 1 also indicates that elephant grass biopellet (V3) produced the highest water absorption with and without torrefaction, while the lowest water absorption was produced by bagasse biopellet (V4).

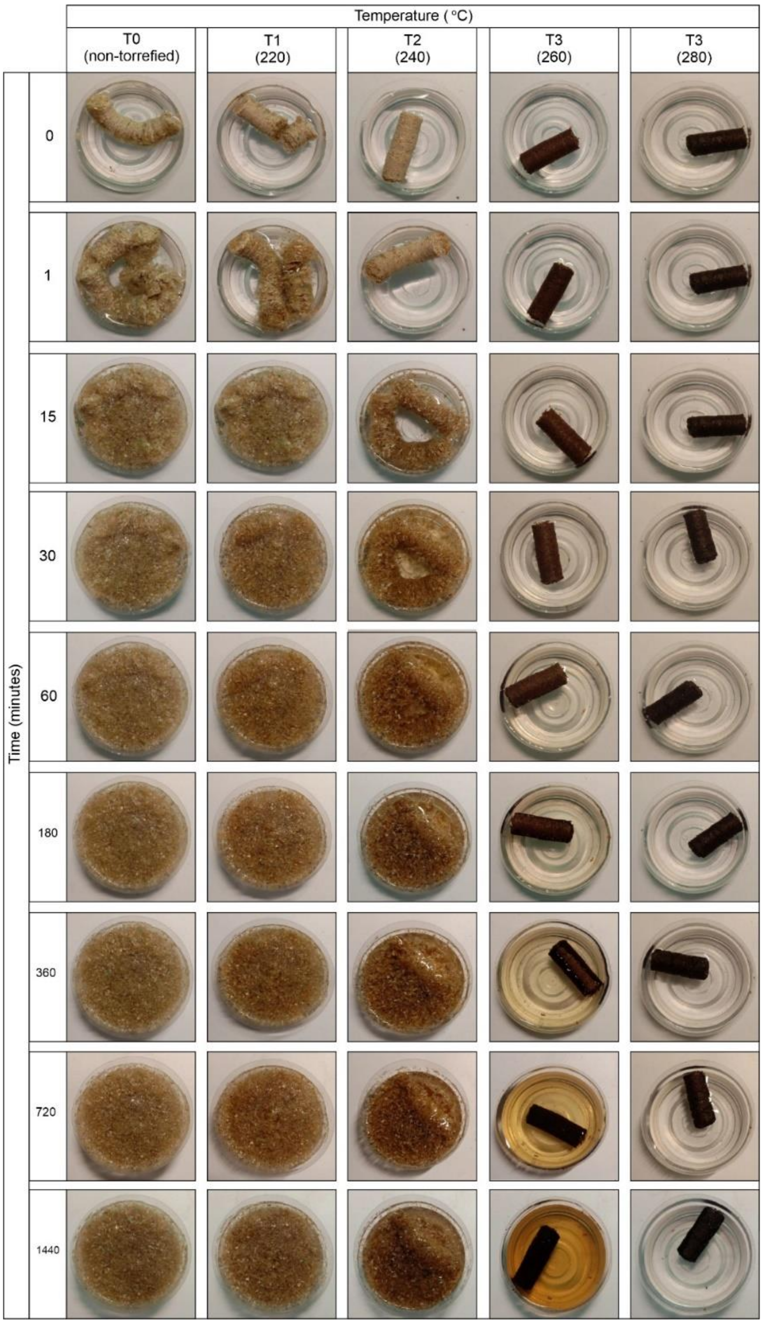

Fig. 2. Hydrophobicity of corncob biopellet (V2) at various torrefaction temperature for 24 hours

The ANOVA test showed that the non-torrefied biopellet and the torrefaction biopellet showed a significant difference at the level of $\alpha = 0.05$ for the water absorption parameter. However, variations in torrefaction temperature did not show a significant difference in the LSD test. Variations in the types of biopellets also showed significant differences when tested for LSD at the $\alpha = 0.05$, with biopellet V4 showing the lowest water absorption of 8.93%. The highest water absorption was produced by elephant grass biopellet (V3) of 19.81%. Significantly different water absorption values in various types of biopellets can be caused by chemical content such as tannins or lignin contained in biopellets, these contents can slow down the evaporation process because the higher the temperature, the tannin or lignin will melt and become natural adhesives for biopellets. The higher the biopellet density, the lower the ability of the biopellet to absorb water [22].

Based on the observations of the water absorption of biopellets, it can be concluded that changes in the weight of biopellets are influenced by humidity at the time of data collection. If the humidity is high, the weight of the biopellet will also increase. Biopellets with high water absorption can cause problems during storage because they cannot be stored long [13].

4.3. Density

Making biopellets in this study was carried out by applying pressure to the biomass. Compacting the material with high pressure will increase its density so that the weight of the material per unit volume will also increase [23].

The density of biopellets observed is presented in Table 1, where the density of non-torrefied biopellets ranges from 0.68 – 0.87 N/m3 while the density of biopellets with torrefaction ranges from 0.5 – 0.75 N/m3. The density value of non-torrefied biopellet has an average more significant than that of the biopellet that undergoes the torrefaction process. This is because the biopellet shrinks in shape after torrefaction. According to Munawar [10], the high and low density is also influenced by the particle and pellet size, the higher the thickness of the raw material, the higher the density value will be. The particle size affects the performance and quality of the density, strength, and flowability of densified biomass [24].

The ANOVA test results showed a significant difference at $\alpha = 0.05$, so there was a difference between the torrefaction temperature treatment and the biopellet types treatment. Table 1 presents the LSD test for observing density parameters. Non-torrefied biopellets (T0) were significantly different from those biopellets with torrefaction. Meanwhile, the torrefied biopellet at the temperatures of 260 °C (T3) and 280 °C (T4) produced the lowest average density, 0.59 N/m3, and 0.61 N/m3. This shows that the higher the torrefaction temperature, the lower the specific gravity of the biopellet because the biopellet will shrink and become thicker.

Meanwhile, the biopellet types factor showed a significant difference after testing the least mean difference (LSD). Biopellet V1 and V2 had the lowest average density of 0.57 N/m^3 and 0.59 N/m^3, while biopellet V4 produced the highest average density of 0.76 N/m^3. The density of the biopellet determines the energy value it contains, so the smaller the density of the biopellet, the higher the storage and transportation costs compared to the biopellet with a high density per Megajoule of energy.

4.4. Hydrophobicity

The biopellets hydrophobicity observation was carried out to determine the resistance of biopellets to water under extreme conditions (immerse in water). Shows in Fig. 2 the physical change of corncob biopellet (V2) in the observation interval of 0 – 1440 minutes in each treatment of torrefaction temperature. The non-torrefied biopellet (T0V2) started to disintegrate in the first minute of observation, as did the T1V2 biopellet. Then this physical damage was followed by T2V2 biopellets at 15 minutes, which indicated that the biopellets were still hydrophilic.

The watercolor change occurred in the T3V2 biopellet when the observation time entered 360 minutes. The watercolor change occurred when the biopellet was immersed because the extractive substances came out of the biopellet and decomposed in the water. This can cause the calorific value of T3V2 biopellet to decrease because the levels of extractive substances can affect the calorific value of biomass materials. Biomass with a high extractive substance content tends to produce a higher combustion calorific value [25].

Meanwhile, biopellet V2 at 280 °C did not experience any physical changes or changes in the watercolor. Torrefaction with higher temperatures causes the biopellet to become completely dry and changes its hydrophilic to hydrophobic properties. The advantage of the torrefaction process is that the product's water content is decreasing, and it is increasingly difficult to absorb water from the air [26].

The results showed that biopellets that had been torrefied at temperatures of 260 °C and 280 °C were able to show their resistance to water under extreme conditions (immersed in water). This follows Haryanto et al. [27] which stated that the torrefaction pellets showed good hydrophobicity when immersed in water for 24 hours. The hydrophobic nature of biopellets is beneficial in the storage of biopellets that require a long period.

5. Conclusion

The torrefaction process of biopellets showed significantly different results at $\alpha = 0.05$ than non-torrefied biopellets on MC, water absorption, specific gravity, and hydrophobicity parameters. Variations in torrefaction temperature also showed significant differences when tested for LSD on MC parameters where temperatures of 220 °C, 240 °C, and 260 °C resulted in the lowest average MC value are 0.71%. This water content value meets the Indonesian [28] and European [29] biopellet quality standards where the required biopellet quality standards are a maximum of 12% and 10%. In the density parameter, variations in torrefaction temperature also showed significant differences, with the highest average density produced by temperatures of 220 °C and 240 °C with a value of 0.66 N/m^3. The variation in torrefaction temperature did not show a significant difference in water absorption parameters. Still, when compared with non-torrefied biopellets, the LSD test showed a significant difference, 16.07% for non-torrefied biopellets, and the average water absorption value was 13.09% for biopellets with torrefaction. The hydrophobicity test showed that the higher the torrefaction temperature, the more difficult it would be for the biopellet to absorb water. The best torrefaction temperature for corncob biopellet (V2) is 280 °C. At this temperature, the biopellet does not experience physical changes and changes in watercolor for 24 hours under extreme conditions (immersed in water).

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