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Effects of Torrefaction Temperature on the Characteristics of Betung (*Dendrocalamus asper*) Bamboo Pellets

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ABSTRACT

*The objective of this study was to evaluate the effects of torrefaction temperature on the physical and mechanical properties of betung bamboo (*Dendrocalamus asper*) pellets. Torrefaction was conducted in an electric furnace at 200 °C, 240 °C, and 280 °C for 50 minutes. The physical properties evaluated included color change, density, moisture content, water resistance, and water adsorption. The mechanical properties were also investigated by compressive strength test. The result showed that torrefaction affected the color properties of betung bamboo pellets with ΔE values of more than 12 or totally changed. The density and moisture content of torrefaction bamboo betung pellets decreased with increasing torrefaction temperature. The results also showed that the hydrophobic properties of the bamboo betung pellets improved with the increased of torrefaction temperature. The highest compressive strength value was obtained by bamboo betung pellets torrefied at 200°C and the values decreased with the increase of temperature. In conclusion, there were differences in the physical and mechanical properties of bamboo betung pellets that were torrefied at different temperatures. Torrefaction with an electric furnace effectively improved the quality of betung bamboo pellets.*

1. INTRODUCTION

The development of renewable alternative energy is needed to replace fossil energy and meet increasing human needs (Alkusma *et al*., 2016). Biomass is one of the potential renewable energy sources. Organic material produced from the process of plant photosynthesis, both in the form of products and waste, is defined as biomass. Biomass in the form of waste and has low economic value, tends to be used as fuel (Parinduri & Parinduri, 2020). Indonesia has a biomass energy potential of around 49.810 MW, but its utilization is only 302.4 MW or about 0.6% (Pranoto *et al*., 2013).

The potential of Indonesia's biomass is very diverse, one of which is bamboo. of the 600 - 700 species of bamboo that exist in the world, at least 125 species can be found in Indonesia (Arsad, 2015). Bamboo is biomass with great potential for utilization. One of the bamboo species that is widely used in Indonesia is betung bamboo (*Dendrocalamus asper*). Betung bamboo can be used for crafts, furniture, construction materials, and other applications (Pujirahayu, 2012). Betung bamboo has tenuous clumps consisting of about 15 stems per clump that can grow up to 20 m with long and thick internodes (Putro & Murningsih, 2014). Bamboo biomass is still difficult to use as an energy source due to several factors such as low density, non-uniform size, hygroscopic nature or easy absorption of water, and difficulty in transporting and storing the material due to its various sizes (Rani *et al*., 2020). One solution to this problem is the densification of biomass into pellets.

Biomass densification aims to increase the density of biomass so that it is easier to transfer, store, and make the size more uniform (Frida *et al*., 2019). According to Fakhruzy (2018), the density value of bamboo betung is still relatively low, which is around 0.50 g/cm^3, so that it does not meet the SNI 8021-2014 standard, which is 0.60 g/cm^3 for household scale and 0.80 g/cm^3 for industrial scale. In addition, there needs to be further treatment to increase the quality, such as through torrefaction. Torrefaction is a thermochemical treatment at a temperature of 200 – 300 °C under conditions of little or no oxygen and a low heating rate which results in changes in the characteristics of the biomass to a harder form of charcoal (Nur, 2014; Syamsiro, 2019; Tumuluru *et al*., 2011). This technology can improve the quality of biomass pellets and increase their shelf life (Basu, 2018).

Purnomo *et al*. (2022) conducted torrefaction of oil palm empty fruit bunches (OPEFB) pellets with a rotary reactor at a temperature of 260 °C for 35 minutes and reported that the torrefaction process produced pellets with low water content and hydrophobic properties so that their moisture absorption power was low. Hidayat *et al*. (2020) also reported that OPEFB pellets torrefied with a Counter-Flow Multi Baffle (COMB) reactor with temperatures between 230 – 280 °C had hydrophobic properties, so that when the water resistance test was carried out, there were no changes in the pellet form even after 12 hours of observation. Siyal *et al*. (2020) conducted a torrefaction study on rice husk and sawdust pellets at temperatures of 230 °C, 280 °C, and 300 °C with residence times of 15, 30, 45, 60, and 120 minutes and reported that the torrefied pellets were ideal for long-term storage due to its hydrophobic nature.

Torrefaction has many benefits to improve the quality of biomass pellets, especially on hydrophobic properties. However, research on the torrefaction of bamboo pellets, especially the type of bamboo betung (*Dendrocalamus asper*) is still very limited. Therefore, this study aims to determine the effect of torrefaction at different temperatures on the physical and mechanical properties of betung bamboo pellets so that it can be used as an alternative renewable energy source in the future.

2. MATERIALS AND METHODS

The research was carried out at the Forest Products Technology Workshop at the Integrated Field Laboratory, Faculty of Agriculture, University of Lampung from December 2021 – January 2022. Physical and mechanical properties were evaluated at the Forest Products Technology Laboratory, Department of Forestry, University of Lampung. The material used was biomass pellets made from betung bamboo with a diameter of ± 0.8 cm and a length of ± 4 cm.

2.1. Torrefaction Method

Torrefaction was carried out using an oven (BJPX - Summer, PT. Innotech System, Jakarta, Indonesia) at 200 °C, 240 °C, and 280 °C for 50 minutes. For each torrefaction process, 12 pellets were wrapped with aluminum foil. Each wrap was then perforated with a needle on the side to allow little air to escape. The oven is set to the target temperature and overstated by 20 °C as the temperature will drop when the oven cover is opened. After the oven reaches the target temperature, the prepared sample is introduced and the temperature is set to the specified torrefaction temperature. When the oven temperature has reached the torrefaction temperature, the time is calculated. After 50 minutes, the sample was removed and cooled at room temperature ranging from 20–30 °C and covered with a cloth to prevent combustion. The torrefaction scheme can be seen in Figure 1.

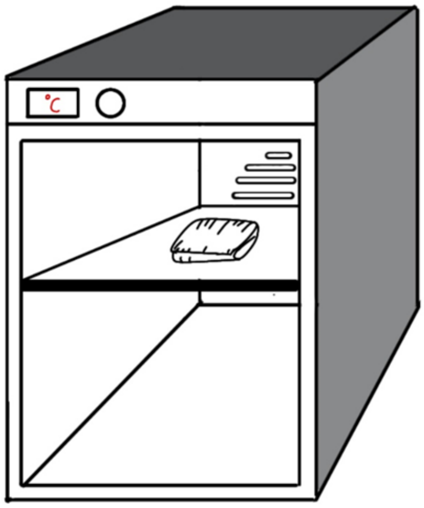


Figure 1. Schematic of torrefaction using an oven

2.2. Physical properties testing

2.2.1. Color Change

Color change of bamboo pellets before and after torrefaction was measured based on the CIE-Lab system using a Colorimeter (AMT507, Amtast, China). Color measurement was carried out on a random pile of pellet samples for 5 repetitions. The parameters used in this test are *L**, *a**, and *b**. The *L** axis represents brightness with a maximum value of 100 which means perfect white, and a minimum value of 0 which means perfect black. Red/green chromatization is represented by the *a** axis with a positive value in the red direction and a negative value in the green direction. The *b** axis represents yellow/blue chromatization with a positive value in the yellow direction and a negative value in the blue direction (Hidayat *et al*., 2017). The overall color change due to heating treatment or denoted by *E** can be calculated by the following formula:

$$\Delta E^* = (\Delta L^{*2}+\Delta a^{*2}+\Delta b^{*2})^{1/2} \quad (1)$$

Classification of the degree of color change can be seen in Table 1 (Valverde & Moya, 2014).

Table 1. Classification of color changes

No	Range value	Classification
1	$0.0<\Delta E^*\leq 0.5$	Negligible
2	$0.5<\Delta E^*\leq 1.5$	Slightly perceivable
3	$1.5<\Delta E^*\leq 3$	Noticeable
4	$3<\Delta E^*\leq 6$	Appreciable
5	$6<\Delta E^*\leq 12$	Very appreciable
6	$\Delta E>12$	Totally changed

2.2.2. Density

Density was calculated based on the standard SNI 8021-2014 which is a comparison between the mass of pellets with their volume. The measurement of pellet density was carried out by measuring the dimensions of the pellets in the form of tubes to obtain their volume and weighing the weight of the pellets in air dry and oven dry conditions. The formula used to measure pellet density (*D*) is:

$$D = \frac{m}{v} \tag{2}$$

where m is mass of pellet (g) and v is pellet volume (cm^3).

2.2.3. Moisture Content

Measurement of moisture content (*MC*) was carried out by weighing a sample of bamboo betung pellets, then dried by placing it in an oven at 100 °C for 24 hours. The dried sample was then cooled in a desiccator and weighed again. The *MC* of pellets based on SNI 01-1506 can be calculated by the following equation:

$$MC = \frac{m_1 - m_0}{m_0} \times 100\% \tag{3}$$

where m_1 is air dry weight (g) and m_0 is oven dry weight (g).

2.2.4. Water Resistance

Observation of pellet resistance in water was carried out to see physical or visual changes and was conducted by immersing the sample in water for 1 minute, 5 minutes, 30 minutes, 1 hour, 6 hours, 12 hours, and 24 hours. This observation was carried out to determine the ability of pellets under immersion conditions without absorbing water which was useful for determining the durability of pellets being stored for a long time. According to Rubiyanti *et al.* (2019) torrefied pellets tend to have hydrophobic properties or are more resistant to water.

2.2.5. Water Vapor Adsorption

Observation of water vapor adsorption was carried out for 30 days. An oven-dry pellet was placed in an aluminum container and then left in a protected open space to avoid interference and dust that may affect its weight. The weight of the pellet was weighed every day using a scale with an accuracy of 0.0001 g to see the weight gain due to adsorbing water vapor. Observations were made for 30 days because during that time the pellets were expected to be in a state of equilibrium moisture content (EMC).

2.3. Mechanical Properties

The mechanical properties of bamboo betung pellets were obtained by performing a compressive strength test using a Universal Testing Machine (M500-50AT, Testometric, Rochdale, United Kingdom). Betung bamboo pellet was crushed at each end so that it could stand upright, and its diameter was measured. Then the pellet was pressed with the machine and the time was calculated until the pellet cracked or broken. After the pellet was broken, the machine automatically stopped and showed a graph and the value of the force or load of the object. The compressive strength value (σ, N/mm^2) was calculated from maximum test load (*P*, N), and cross-sectional area (*A,* mm^2) as the following :

$$\sigma = \frac{P}{A} \quad (4)$$

3. RESULTS AND DISCUSSION

3.1. Color change

Visual color changes in bamboo betung pellets after torrefaction can be seen in Figure 2. Whereas, the graph of color changes based on brightness (*L**), red/green chromatization (*a**), and yellow/blue chromatization (*b**) can be seen in Figure 3 – 5. Torrefied bamboo pellets decreased in brightness continuously with increasing temperature (Figure 2). Torrefied bamboo pellets decreased in brightness continuously with increasing temperature (Figure 3). Visually the color of the pellets changes from bright to blackish so that torrefied pellets are called black pellets (Sulistio *et al*., 2020). This is in line with research conducted by Rubiyanti *et al*. (2019) which conducted torrefaction of rubber wood pellets where the value of *L** decreased as the torrefaction temperature increased. Suri *et al*. (2021) reported that oil-heat treatment and air-heat treatment on *Paulownia tomentosa* and *Pinus koraiensis* caused the wood color to darken, and the *L** value decreased with increasing temperature and duration of treatment. Degradation or decrease in hemicellulose during the heating process causes a visual color change, causing a decrease in *L** (Salca *et al*., 2016). Color changes in biomass after exposure to high temperatures can be caused by changes in chemical composition (Hidayat *et al*., 2021).

Figure 2. Visual changes of betung bamboo pellets after torrefaction at different temperatures for 50 min.

The red/green chroma (*a**) in the torrefied bamboo betung pellets increased at 200 °C, then decreased at 240 °C and 280 °C (Figure 4). This was also reported in the torrefaction of rubber wood pellets with the Counter-Flow Multi Baffle (COMB) reactor, where the *a** value increased at 200 °C and then continued to decrease at 250 °C and 300 °C (Rubiyanti *et al*., 2019). The heating process causes the degradation of extractive substances which also contain color composition due to loss of water content, causing color changes (Krisdianto *et al*., 2018).

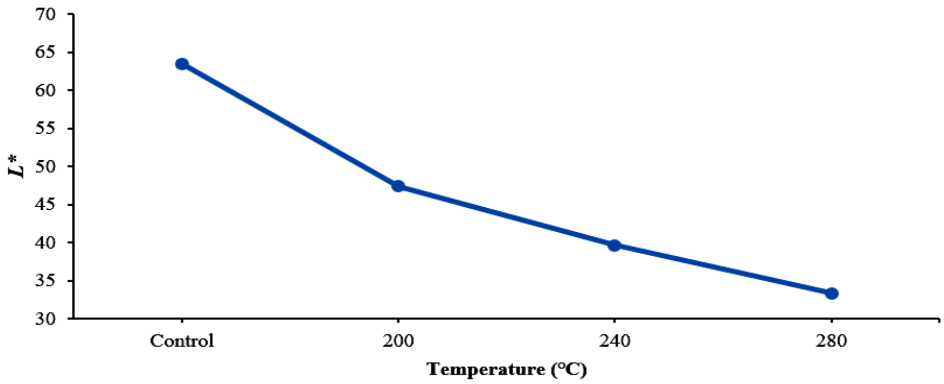


Figure 3. The effect of torrefaction temperature on changes in the value of *L**

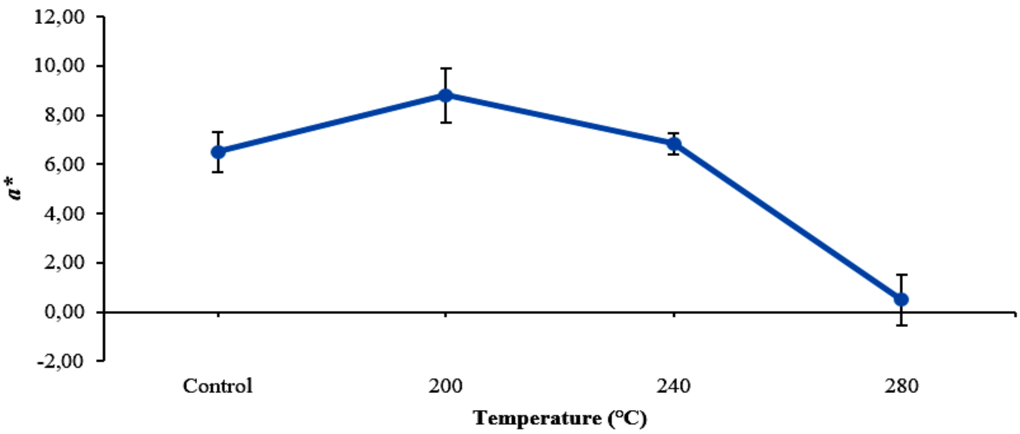


Figure 4. The effect of torrefaction temperature on changes in the value of *a**

Changes in the value of yellow/blue chroma (*b**) have the same trend as changes in the value of *L** where the value decreases with increasing torrefaction temperature (Figure 5). Hidayat *et al*. (2015) stated that heat treatment of Okan wood (*Cylicodiscus gabunensis* [Taub.] Harms) resulted in a decrease in the value of *b** with increasing temperature. The cause of the color change due to this heating treatment is due to the oxidation of phenolic compounds and the formation of dark compounds due to the hydrolysis of hemicellulose (Widyorini *et al*., 2014). The water content lost during the heating process can also cause changes in the color of the biomass (Bahanawan & Krisdianto, 2020). Visually it can be seen clearly (Figure 2) that the torrefied bamboo pellets have a darker color as the torrefaction temperature increases.

The overall color change (Δ*E**) increased with increasing temperature (Table 2). Changes that can be seen clearly are in the decrease in the brightness value (Δ*L**) or the color of the sample is getting darker (Hidayat *et al*., 2017). The results of the overall color change of bamboo betung pellets at temperatures of 200 °C, 240 °C, and 280 °C based on the results of calculations that have been carried out show that the value of *E** > 12 (Table 2), which means the color was totally changed. This can be clearly seen in Figure 2, where the color of the bamboo pellets changes from bright to dark as the temperature increases. Hidayat *et al.* (2015) stated that the temperature between 180 –200 °C significantly affected the color change during the heating treatment.

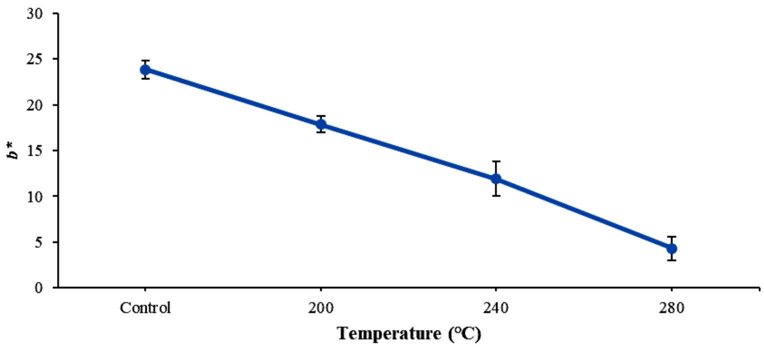


Figure 5. The effect of torrefaction temperature on changes in the value of *b**

Table 2. Overall color changes of betung bamboo pellets

Temperature (°C)	Parameter				Color change classification
	ΔL*	Δa*	Δb*	ΔE*	
200	16.1 (0.27)	-2.3 (1.10)	5.92 (0.85)	17.35 (0.48)	Totally changed
240	23.82 (0.16)	-0.34 (0.44)	11.88 (1.92)	26.67 (0.94)	Totally changed
280	30.14 (0.18)	6.00 (1.02)	19.5 (1.28)	36.42 (0.92)	Totally changed

*Number in parenthesis is deviation standard

3.2. Density

Observations showed that the density of torrefaction pellets produced from air-dried pellets decreased with increasing the given temperature. Bamboo betung pellets in air dry conditions had a density of 1.29 g/cm^3 and continued to decrease after torrefaction at temperatures of 200 °C, 240 °C, and 280 °C (Table 3). Torrefied pellets under air dry conditions are torrefied pellets that have been left in open space for 30 days to reach equilibrium or EMC (equilibrium moisture content). Sulistio *et al.* (2020) reported the results of research on torrefaction on jabon wood pellets with an Electric Furnace for 20 minutes and Counter-Flow Multi Baffle for 3-5 minutes at temperatures of 260⍰ and 280⍰, the density value decreased with increasing torrefaction temperature. Peng *et al.* (2013) conducted torrefaction of pine and spruce softwood waste with torrefaction temperatures of 240 °C, 270 °C, 300 °C, and 340 °C for 60 minutes using a tube reactor and reported that the wood decreased in density with increasing temperature. The decrease in density values occurred due to a decrease in the mass and volume of bamboo pellets due to the heating treatment (Rubiyanti *et al.*, 2019). During the torrefaction process, biomass decomposition occurs so that it breaks down hydroxyl groups and reduces hydrogen bonds that can bind water and make it more difficult for the torrefaction pellets to absorb water (Manouchehrinejad & Sudhagar, 2018; Peng *et al.*, 2015; Zhang *et al.*, 2020). Therefore, after being left in an open space, the pellets will not absorb much water to cause an increase in density.

Similar to pellets under air dry conditions, torrefaction pellets produced from oven dry pellets showed a decrease in density with increasing temperature. Oven dry pellets are pellets that have been oven-dried at 100 °C for 24 hours to remove the free water content contained therein. The density of oven-dried bamboo betung pellets was 1.27 g/cm^3 and continued to decrease at temperatures of 200 °C, 240 °C and 280 °C (Table 3). Research conducted by Ma'ruf *et al*. (2021) stated that there was a decrease in the density of Gmelina arborea and Cocos nucifera wood as the temperature increased in the oil heat treatment. The decrease in density occurs because during the heating process, there is a decrease in pellet mass due to the evaporation of moisture contained in the pellet (Yu *et al*., 2021). In this case, the bamboo betung pellets that have not been and have been subjected to torrefaction meet the standards of SNI 8675-2018 with a minimum density for the household scale of 0.6 g/cm^3 and 0.8 g/cm^3 for the industrial scale.

Table 3. Density of betung bamboo pellets

Temperature (°C)	Density (g/cm^3)	
	Air dry	Oven dry
Control	1.29 (0.05)	1.27 (0.03)
200	1.27 (0.03)	1.26 (0.05)
240	1.20 (0.02)	1.18 (0.02)
280	1.12 (0.02)	1.11 (0.03)

*Number in parenthesis is deviation standard

3.3. Moisture content

The measurement of moisture content (MC) uses the principle of evaporating the free water contained in the sample by using heat energy until it reaches an equilibrium condition between the MC of the sample and the surrounding air. Based on the measurement results, it is known that the MC of bamboo betung pellets continues to decrease in line with increasing temperature. The MC of bamboo betung pellets before torrefaction was 10.25%, it met the SNI 8675:2018 standard as an industrial-scale biomass pellet standard where the MC was not more than 12%, but did not meet household-scale standards with a maximum MC of 10%. After torrefaction at 200 °C, 240 °C and 280 °C the MC decreased (Table 4). Haryanto *et al*. (2021) reported that in the torrefaction of palm oil empty fruit bunch pellets with a rotary reactor there was a decrease in MC of more than 90%. Torrefaction treatment with high temperatures causes the MC and extractive substances in the bamboo betung pellets to evaporate so that the weight decreases and the MC decreases (Widarti, 2017). The MC will greatly affect the characteristics of the betung bamboo pellets. MC that is too high will cause the pellets to be susceptible to microorganisms and fungi so that the pellets will easily expand in the distribution and storage process (Lestari *et al*., 2019).

Table 4. Moisture content of betung bamboo pellets

Temperature (°C)	Moisture content (%)
Control	10.25 (0.0014)
200	8.62 (0.0012)
240	7.15 (0.0006)
280	6.21 (0.0011)

*Number in parenthesis is deviation standard

3.4. Pellet Resistance to Water

Pellet resistance to water was tested with a period of 1 minute, 30 minutes, 1 hour, 6 hours, 12 hours, and 24 hours. Control pellets or those which were not subjected to torrefaction had begun to change shape at the 1st minute, and continued to expand until the 5th minute. The 30th minute and so on, the water starts to turn yellowish which indicates the amount of extractive substances contained in the pellet and disintegration begins to occur so that the shape of the pellet is no longer intact and the initial form is no longer visible (Table 5). This is in line with the research conducted by Sulistio *et al*. (2020) by conducting a pellet resistance test against water for jabon wood pellets which began to change shape after soaking for 1 minute. Yulianto *et al*. (2020) also reported that the oil palm empty fruit bunches (OPEFB) pellets were damaged in the water after 5 minutes of testing and completely destroyed in 1 hour of immersion. Bamboo betung pellets that have not been torrefied have hydroxyl groups that will form hydrogen bonds, so that the pellets will more easily absorb water (Tumuluru *et al*., 2011).

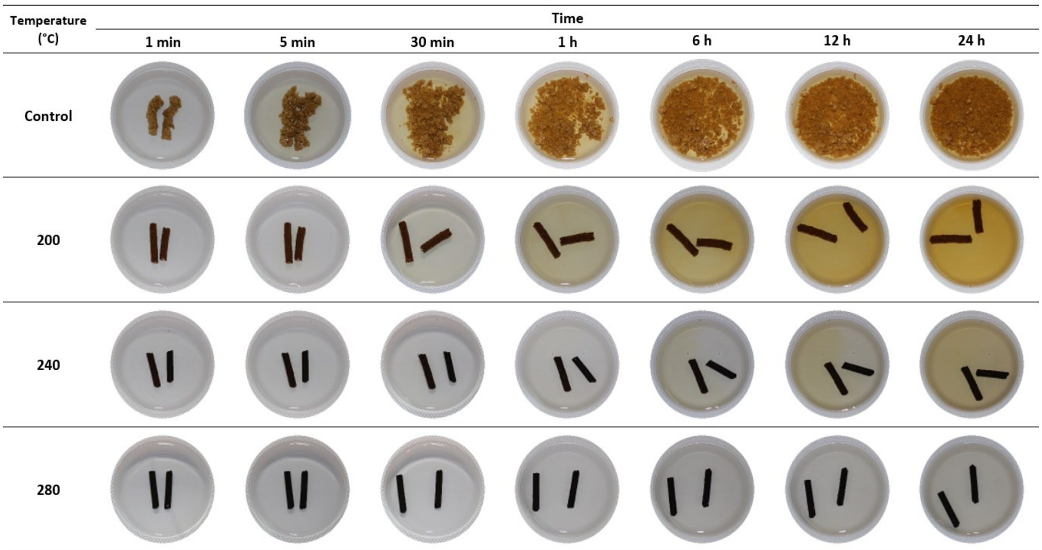
Bamboo betung pellets that have been torrefied at temperatures of 200 °C, 240 °C and 280 ⍰ did not change shape and did not expand at all until observation within 24 hours. This is in line with the research conducted by Hidayat *et al*. (2020) by conducting torrefaction on OPEFB pellets that did not experience significant changes after soaking for 12 hours. Another study by Iryani *et al*. (2019) also stated that the pellets of palm oil empty fruit bunches that were not torrefied completely disintegrated in the 30-minute test, while the pellets that had been torreffied did not change even after 12 hours of testing, indicating that they are good for long-term storage. The visible change is a change in the color of the water to yellowish which indicates that the extractive substances contained in the bamboo betung pellets have not completely evaporated in the torrefaction process. The pellets which were torrefaction with a temperature of 200 °C began to show changes in the color of the water in the observation.

Period of 1 hour and became darker from time to time. Meanwhile, for pellets that were torrefied with a temperature of 240 °C, there was a change in the color of the water within 12 hours and for pellets torrefaction at 280 °C there was no change until a period of 24 hours. This is in line with the statement of Sulistio *et al*. (2020) that pellets torrefied at a higher temperature tend to be more resistant to water than those pelleted at a lower temperature. The increasing hydrophobicity along with the high torrefaction temperature indicates that the pellets will be more resistant to storage for a long time.

3.5. Water Vapor Absorption

Based on Figure 6, it is known that the water content of bamboo betung pellets that are not subjected to torrefaction tends to be unstable, still influenced by external factors such as temperature and humidity. Bamboo betung pellets that have not been torrefaction have hydrophilic properties or easily absorb water which causes the increase in water content to be unstable. Meanwhile, bamboo betung pellets that have been tormented at temperatures of 200 °C, 240 °C and 280 °C tend to be more stable because heat treatment at high temperature torrefaction causes a change in the nature of the pellets from hydrophilic (absorbs water) to hydrophobic (water resistant) (Sulistio *et al*., 2020). Pah *et al*. (2021) reported that the absorption of moisture in untorrefied bamboo pellets had a very fluctuating moisture content value because it was influenced by relative humidity. The limited absorption of water vapor in pellets that have been subjected to torrefaction indicates that no biological degradation has occurred so that the resistance of the pellets is increasing (Nunes *et al*., 2014).

Table 5. Comparison of pellet resistance to water due to torrefaction at different temperatures



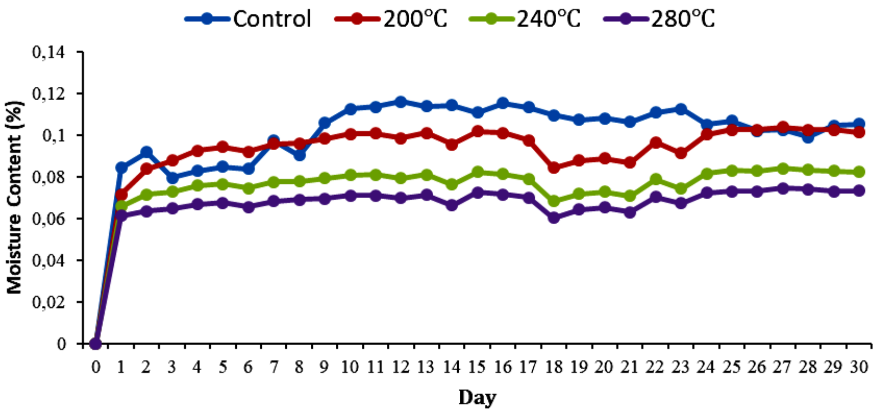


Figure 6. Changes in water vapor adsorption of bamboo betung pellets for 30 days

3.6. Compressive Strength

The compressive strength value shows the firmness or resistance of a biomass to disturbances in the form of external pressure that causes the material to crumble or break (Hendra, 2012). Based on the test results, it is known that the compressive strength value of bamboo betung pellets that are not treated with torrefaction is 6.23 N/mm^2 then after torrefaction with a temperature of 200 °C the value increases to 6.43 and continues to decrease at a temperature of 240 °C and 280 °C (Fig. 7). The temperature of 200 °C can be said to be a critical temperature that does not cause a decrease in strength, while temperatures above 200 °C will experience a decrease in compressive strength. The decrease in the compressive strength of pellets torrefaction with temperatures of 240 °C and 280 °C was due to reduced lignin content in pellets due to high temperature treatment so that the bonding between particles was reduced (Wibowo *et al*., 2017).

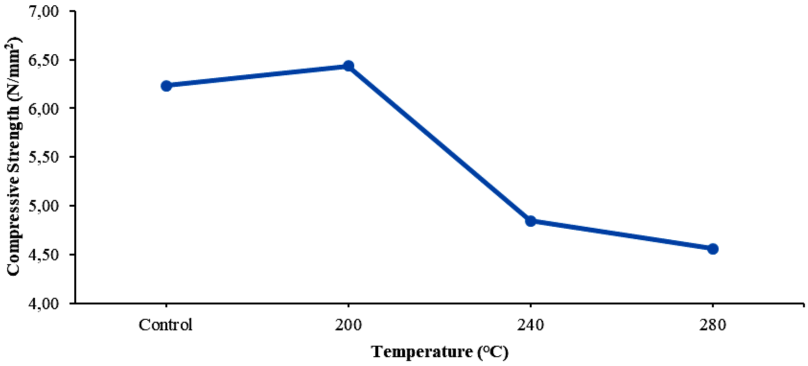


Figure 7. Compressive strength of betung bamboo pellets based on torrefaction temperature

4. CONCLUSIONS AND RECOMENDATION

Torrefaction treatment with temperatures of 200 °C, 240 °C, and 280 °C caused all pellet samples to change color completely with an E value of more than 12. The density of bamboo betung pellets in either air-dried or oven-dried conditions also decreased significantly. after torrefaction caused by a decrease in pellet mass and volume. Betung bamboo pellets that have been torrefaction also experienced a decrease in water content from 10.24% to 6.21% at torrefaction with a temperature of 280. The water resistance of bamboo betung pellets that had been torrefaction at temperatures of 200 °C, 240 °C and 280 °C did not change at all for 24 hours of observation. The water vapor absorption test for torrefaction bamboo pellets has a more stable value than those without torrefaction, because the torrefaction pellets have hydrophobic properties or are water resistant. The highest compressive strength value was found in bamboo betung pellets which were torrefaction at 200 °C and continued to decrease with increasing temperature used. This study shows that temperature affects the physical and mechanical properties of torrefaction bamboo betung with the higher the temperature used, the greater the changes that occur. Torrefaction can improve the quality of bamboo betung such as color, density, moisture content, and resistance to water, but the reduced water content in torrefaction pellets causes the compressive strength value to decrease. It is necessary to develop a torrefaction scheme with a larger capacity and shorter time, because torrefaction can improve the quality of biomass pellets which can be used as alternative renewable energy sources.

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