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RESEARCH ARTICLE

Thermal Degradation-Induced Hydrophobicity and Improved Moisture Resistance of Pyrolyzed Betung Bamboo and Rubberwood Pellets

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ABSTRACT

The increasing global demand for sustainable energy highlights the need for efficient biomass utilization as an alternative to fossil fuels. This study investigates the effect of pyrolysis temperature on the moisture behavior, hydrophobicity, and storage stability of betung bamboo (*Dendrocalamus asper*) and rubberwood (*Hevea brasiliensis*) pellets. Pellets were pyrolyzed at 350°C, 400°C, and 450°C for 30 minutes, and their physical properties, including moisture content, water resistance, and water vapor adsorption, were evaluated. Results show that increasing the pyrolysis temperature significantly reduced the moisture content from 9.33% to 1.18% in bamboo pellets and from 10.18% to 1.10% in rubberwood pellets. Pyrolysis enhanced hydrophobicity, as evidenced by stable water vapor adsorption below 5% over 14 days, compared to more than 15% in untreated pellets. Pyrolyzed pellets also exhibited superior water resistance, retaining their structural integrity after 24 hours of immersion, whereas the control samples deformed completely. These improvements enhance storage stability, minimize the risk of self-ignition, and increase combustion efficiency by reducing water-related energy losses. The findings demonstrate that optimizing pyrolysis temperature effectively improves pellet quality, offering a promising approach for sustainable bioenergy production from forest-based biomass resources.

1. Introduction

Global energy demand continues to rise due to population growth and is expected to increase annually, including in Indonesia. This is attributed to economic growth, population growth, and rapid development of the industrial sector (Syafitri and Putri, 2022). Most of the energy demand is met by fossil fuels. However, the availability of fossil energy sources is minimal. The massive and prolonged use of fossil fuels can lead to acid rain and smog, as the burning of fossil fuels produces carbon monoxide and other toxic chemicals (Imawan et al., 2024). Environmentally friendly energy sources are needed to address energy needs and mitigate the adverse effects of fossil fuels, such as biomass (Papilo, 2015). Biomass from forests, used as energy, especially firewood and charcoal from both wood and non-wood forest products, provides energy for essential basic needs such as cooking and other heat energy needs (FAO, 2024). Biomass abundant in Indonesia includes betung bamboo (*Dendrocalamus asper*) and rubberwood (*Hevea brasiliensis*).

Bamboo is a biomass resource with significant potential for use. Betung bamboo is one of the widely utilized bamboo species in Indonesia (Saputra et al., 2022). Bamboo can be harvested at up to 30 tons per ha because it does not require much space to grow and develops to its maximum diameter in just 40–50 days (Putri et al., 2020). In addition to betung bamboo, other abundant biomass wastes available in Indonesia include rubberwood. During its productive period, rubber trees produce latex as their main product. However, rubber trees have a productive life span of 25 to 30 years for producing latex (Widyasari et al., 2015). After reaching the end of their productive life span, rubber trees are rejuvenated and can produce wood as a by-product.

Biomass remains challenging to utilize as an energy source due to several factors, including its low density, non-uniform size, hygroscopicity, and ease of water absorption, which can lead to self-ignition, as well as difficulties in transporting and storing the material due to its varying sizes (Rani et al., 2023). The solution to these problems is the densification of biomass into pellets. Pellets made from biomass waste can be used to produce renewable energy (Rahman et al., 2024; Rani et al., 2023). Additionally, further processing is necessary to improve the quality, such as through the pyrolysis process. Pyrolysis is a thermochemical process, a decomposition process that involves heating organic materials under conditions with limited or no oxygen, producing charcoal (Asmunandar et al., 2023).

According to Ridhuan et al. (2019), the typical temperature range for biomass pyrolysis is between 300°C and 1000°C, resulting in changes in the biomass's characteristics to form charcoal. Ridjayanti et al. (2023) conducted pyrolysis on rubberwood waste biomass, and Salim et al. (2019) conducted pyrolysis on betung bamboo, reporting that the pyrolysis process produced charcoal with low water content and hydrophobic properties, resulting in low moisture absorption, high fixed carbon, and higher heating value, and improved quality of the biomass. Pyrolysis offers numerous benefits for enhancing the quality of biomass pellets. However, research on the pyrolysis of betung bamboo and rubberwood pellets is still very limited. Therefore, this study aims to investigate the effect of pyrolysis at various temperatures on the moisture behavior of betung bamboo and rubberwood charcoal pellets, to utilize them as alternative renewable energy sources in the future.

2. Materials and Methods

This research was conducted at the Forest Product Technology Workshop of the University of Lampung, which served as the site for the pyrolysis process. The Forest Product Technology Laboratory, Department of Forestry, Faculty of Agriculture, University of Lampung, served as the site for testing the physical properties analysis of the pyrolysis results. This research was conducted from January to May 2025.

2.1. Pyrolysis Methods

Pyrolysis was carried out using a muffle furnace at temperatures of 350°C, 400°C, and 450°C for 30 minutes. For each pyrolysis process, 15 pellets were placed in a porcelain crucible and then covered with a lid. The muffle furnace was set to the target temperature. Once the furnace reached the target temperature, the prepared samples were inserted and left for 30 minutes. After 30 minutes, the samples were removed and buried in sand until they reached room temperature to prevent combustion.

2.2. Physical Properties Testing

2.2.1. Moisture content

The basic theory of moisture content (MC) in biomass is to remove the water content from an object until it reaches equilibrium with the moisture content of the surrounding air. This test is conducted following the SNI 8675:2018 standard. The air dry weight (m1) and oven dry weight (m0) of the pyrolysis pellets are determined by measuring the mass of the pellets before and after drying in an oven. The MC of pyrolysis pellets can be calculated using the Equation 1.

$$MC\ (\%) = \frac{m1 - m0}{m0} \times 100\% \tag{1}$$

2.2.2. Water resistance

This test was conducted by soaking bamboo pellets and rubberwood pellets in water and observing the visible physical changes that occurred in both types of pellets after soaking for 1 minute, 1 hour, 6 hours, 12 hours, and 24 hours.

2.2.3. Water vapor adsorption

An oven-dry pellet was positioned in a shielded open area to prevent interference and dust that could influence its weight. To monitor the weight gain from adsorbed water vapor, the pellet's mass was measured daily using a scale with a precision of 0.0001 g. This test was conducted by placing pyrolysis pellets at room temperature. The samples were measured for mass increase over a period of two weeks or 14 days, until they reached a constant weight.

3. Results and Discussion

3.1. Moisture Content

One of the key factors that significantly influences the quality of biomass charcoal pellets is their moisture content. The moisture content refers to the ratio of the water lost from the material during drying (Prasojo et al., 2022), in relation to the material's initial weight. The calorific value, ease of ignition, combustion power, and smoke production during biomass charcoal pellet combustion are all significantly influenced by the optimal moisture content (Lourentius et al., 2022). The combustion heat values of biomass charcoal pellets with a high moisture content are reduced, as some energy is utilized to evaporate the water (Hidayat et al., 2024). This leads to less efficient combustion, a more challenging ignition process, and increased smoke production, all of which contribute to reduced combustion efficiency. The combustion efficiency of biomass pellets with high moisture content tends to decrease, as the energy generated is used to evaporate water, thus diminishing the effective calorific value (Yuliati et al., 2019). This leads to an incomplete combustion process, resulting in the generation of excessive smoke. Furthermore, during storage, high moisture levels can lead to the development of mold and material deterioration.

Based on the measurement results in **Table 1**, the moisture content of the bamboo and rubberwood pellets was found to be 9.33% and 10.18%, respectively. After pyrolysis at a temperature of 350°C, the moisture content continued to decrease, reaching 1.18% for bamboo pellets and 1.1% for rubberwood pellets as the pyrolysis temperature increased. The reason for this is that at elevated temperatures, the water in biomass rapidly evaporates due to the heat energy, causing it to transform into steam. Furthermore, the chemical structure of biomass undergoes decomposition, which involves the breaking of chemical bonds, such as those of hydroxyl groups, that can release water. These alterations can diminish biomass's capacity to store water, resulting in increased hydrophobicity (Khater et al., 2024). Previous studies conducted by Saputra et al. (2022) using bamboo pellets and by Rubiyanti et al. (2019) using rubberwood pellets reported that the moisture content decreased with increasing temperature under controlled heating conditions. Another study was also conducted by Yulianto et al. (2020) on the moisture content of jabon wood using the under controlled heating conditions method and reported that the moisture content also decreased.

Rubberwood pellets have a relatively higher moisture content than bamboo pellets. After pyrolysis treatment at relatively high temperatures (400°C and 450°C), the moisture content (MC) of rubberwood pellets becomes slightly lower than that of bamboo pellets. This occurs due to differences in the chemical composition of the biomass. Bamboo has a higher holocellulose content than rubberwood. The holocellulose content is 83%–87% (Kusumaningrum et al., 2017; Yang et al., 2022), while the holocellulose content in rubberwood is 67%–70% (Umar et al., 2016; Vachlepi, 2019). Holocellulose consists of cellulose and hemicellulose (Cheng et al., 2016). The wood's hygroscopic nature is derived from the hydroxyl groups found in its constituent components. Hemicellulose draws water in more readily than cellulose does, and cellulose draws water in more readily compared to lignin (Gea, 2025).

This indicates that the under-controlled heating conditions method reduces the moisture content of biomass, which in turn affects its quality. The higher the water content, the greater the hygroscopicity (Ridjayanti et al., 2023). The moisture content of biomass greatly influences the quality of charcoal pellets. The quality of charcoal pellets decreases as the water content increases. This occurs because water evaporates first, using heat energy that should be used to increase energy (Kholil, 2017). Moisture content is a crucial factor in the charcoal production process, as it significantly impacts the quality of the charcoal after production. Increased moisture content can also reduce the calorific value of charcoal, which impacts its effectiveness as a fuel (Sanni et al., 2024). The combustion heat values of biomass charcoal pellets with a high moisture content are reduced, as some energy is utilized to evaporate the water (Abdullah et al., 2022). This leads to less efficient combustion, a more challenging ignition process, and increased smoke production, all of which further diminish combustion efficiency.

Table 1. Moisture content

Biomass	Temperature (°C)	MC (%)
Betung bamboo	Control	9.33 (0.01)
	350	4.71 (0.01)
	400	2.51 (0.02)
	450	1.18 (0.02)
Rubberwood	Control	10.18 (0.01)
	350	4.9 (0.02)
	400	2.4 (0.02)
	450	1.1 (0.01)

Note: The number in parentheses is the standard deviation.

3.2. Water Resistance

The absorption test was conducted by soaking biomass pellets in water at room temperature (**Table 2**). The results for both types of pellets showed that the control pellets underwent significant deformation, with noticeable visual changes occurring after just 1 hour of soaking. Both control pellets expanded, indicating water absorption, which caused the physical shape of the pellets to expand. After 24 hours of immersion, the control pellets had completely deformed, and the immersion water had become cloudy. In contrast, pellets produced through pyrolysis at 350°C, 400°C, and 450°C showed no changes in physical appearance or surrounding water color. They demonstrated resistance to water absorption after being immersed in water for 24 hours.

Table 2. Water resistance

Biomass	Temperature (°C)	Time				
		1 minute	1 hour	6 hours	12 hours	24 hours
Betung bamboo	Control					
	300					
	400					
	450					
Rubber wood	Control					
	350					
	400					
	450					

This is because the pyrolysis process at these temperatures causes the degradation of biomass components such as hemicellulose, cellulose, and lignin, which are responsible for their hydrophilic properties (Siyal et al., 2021). As explained by Hidayat et al. (2020), the pyrolysis process removes hydroxyl (OH) groups in biomass, thereby reducing the water absorption capacity of pellets and increasing their stability during storage. This results in a decrease in hydrogen bonds that can bind water, making the pyrolyzed material more resistant to water absorption (Cui et al., 2020). This explains that the pyrolysis method significantly reduces the hygroscopic properties of biomass pellets. This finding aligns with previous research conducted by Saputra et al. (2022) and Tambunan et al. (2023), which reported that the pyrolysis method applied to biomass renders pyrolyzed pellets more resistant to water immersion compared to pellets without pyrolysis treatment. The increased hydrophobicity of pyrolysis pellets improves their storage in humid conditions without significant degradation in quality (Tumuluru et al., 2021).

Additionally, there were differences between the two control biomasses; bamboo pellets showed different turbidity levels compared to rubber wood pellets, which was due to differences in extractive content between betung bamboo and rubberwood exhibit differences in extract content and composition, with bamboo having lower extract content (5.09–6.23%) (Gu et al., 2020) compared to higher extractive content in rubberwood (1.95–4.58%) (Cao et al., 2022), which affects the differing levels of turbidity.

3.3. Water Vapor Absorption

This test was conducted for 14 days until the pellet weight reached equilibrium moisture content. Equilibrium moisture content is the condition in which biomass pellets do not experience an increase in moisture content (Adi et al., 2025). As shown in **Figs. 1** and **2**, water vapor absorption in bamboo and rubber wood pellets was high and unstable. This was due to the high hydrophilic properties of these materials. The water absorption percentages of both reached over 15%, but after pyrolysis, water vapor absorption in bamboo pellets and rubber wood pellets subjected to pyrolysis at temperatures of 350°C, 400°C, and 450°C showed higher stability. The water vapor absorption of pyrolyzed pellets from both biomasses over 14 days showed stable values below 5%, indicating that the pyrolyzed pellets had transformed from hydrophilic to hydrophobic properties. This is because the pyrolysis process alters the hydrophilic (water-absorbing) properties of biomass pellets into hydrophobic (water-resistant) properties through thermal decomposition at high temperatures under oxygen-free conditions (Saputra et al., 2022).

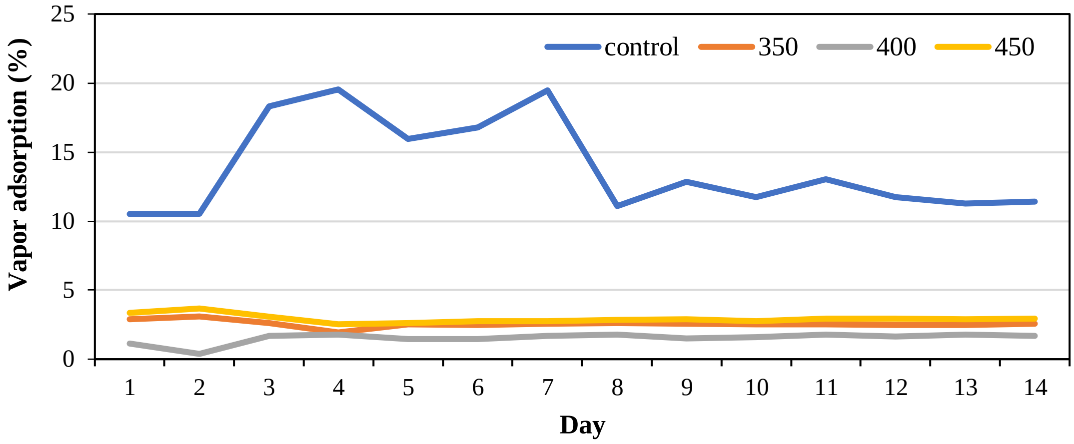

Fig. 1. Changes in water vapor adsorption of bamboo betung pellets for 14 days.

It can be seen that the water vapor absorption of the control bamboo pellets is higher, reaching 20%, compared to the control rubberwood pellets, which have a daily water vapor absorption of 15%. This indicates that the hygroscopicity of bamboo pellets is higher than that of rubber wood pellets, which is attributed to the higher content of hygroscopic compounds in bamboo, such as cellulose and hemicellulose, compared to rubberwood (Umar et al., 2016; Yang et al., 2022). During this process, the main components of biomass, such as cellulose, hemicellulose, and lignin, undergo significant chemical and physical structural changes (Zhao et al., 2018). The polar hydroxyl groups on the biomass surface also decrease, while the relatively heat-stable lignin content becomes more dominant, making the pellet surface more resistant to water and moisture. Similar results for moisture absorption were also observed in oil palm empty fruit bunches and pyrolyzed bamboo pellets. Previously, Irawan et al. (2015) and Saputra et al. (2022) observed moisture absorption of around 15% for both types of biomass, which were then pyrolyzed at 450°C for empty oil palm fruit bunches and 280°C for bamboo pellets, resulting in a decrease in water vapor absorption to 6%. This also explains that pyrolyzed pellets are more durable in storage because they are resistant to water vapor absorption, which could potentially serve as a breeding ground for microorganisms that damage biomass, such as fungi. This change makes pyrolyzed biomass pellets less susceptible to water absorption, directly improving storage stability and durability during transportation (Cahyanti et al., 2021). Additionally, the hydrophobic nature of the pellets increases their calorific value due to low water content, thereby enhancing combustion efficiency (Yulianto et al., 2020).

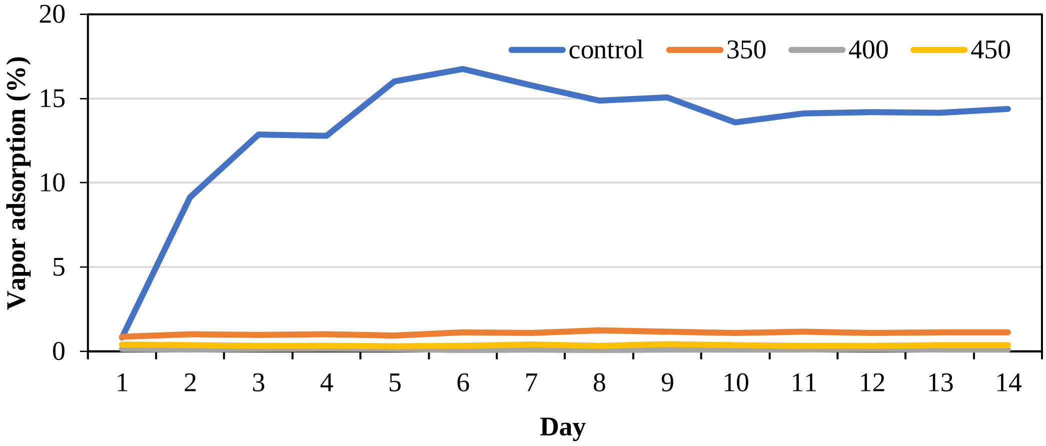

Fig. 2. Changes in water vapor adsorption of rubberwood pellets for 14 days.

This hydrophobic property is crucial for biomass pellets. Untreated pellets are hygroscopic, making them prone to water absorption. Microorganisms become active and begin decomposing due to the water in the biomass (Ungureanu et al., 2018). In pellet piles, heat energy is generated in the environment. Reactions in the pellet pile significantly increase the pile's temperature. If the temperature exceeds a certain threshold, it can trigger a reaction that leads to spontaneous combustion. If spontaneous combustion occurs, the pellet pile will burn on its own. Pellets that have undergone pyrolysis become hydrophobic, which directly reduces biological growth that can develop from the surrounding moisture content (Craven et al., 2015). Therefore, pyrolyzed pellets are more durable, as they are protected from decomposition by microorganisms and remain stable during storage. In addition to being more durable, storing pyrolyzed pellets provides higher safety against fire hazards caused by self-ignition (Yulianto et al., 2020). Future research could focus on optimizing pyrolysis and torrefaction parameters to produce pellets with ideal water resistance, mechanical strength, and energy efficiency.

4. Conclusion

Thermal degradation treatment and moisture behavior of bamboo pellets and rubber wood pellets show that as the treatment temperature increases for both types of biomass, it has a direct impact on their moisture behavior. Biomass pellets exhibited an improvement in pellet quality. The moisture content is decreased gradually, with the bamboo pellets control having 9.33% moisture content, which decreased to 1.18% at the highest temperature. A similar phenomenon occurred with the rubber wood pellets, whose moisture content decreased from 10.18% in the control pellets to 1.1% at the highest temperature, which will increase the efficiency of combustion when used as an energy source. Pyrolyzed pellets also show an increase in water resistance. Pyrolyzed pellets retain their physical form and color after 24 hours of immersion in water. In contrast, control pellets undergo significant changes in physical form and color of the immersion water. Pyrolyzed pellets also exhibit high hygroscopic properties, as evidenced by water vapor absorption data, which show that daily water vapor absorption remained below 5% over 14 days. In contrast, control pellets exhibit daily water vapor absorption exceeding 10% each day. A pyrolyzed pellet is more resistant to water. It has reduced water vapor adsorption, which enhances its durability in storage and prevents self-ignition, as it becomes hydrophobic after the pyrolysis process due to the degradation of the hydroxyl groups responsible for its hydrophilicity.

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