Synergistic Effects of Calliandra and Biomass Additives on the Fuel Quality of Biopellets for Sustainable Energy

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ABSTRACT

The growing demand for renewable energy has driven the utilization of biomass as an environmentally friendly alternative energy source. This study aims to develop high-quality biopellets based on *Calliandra calothyrsus* wood by incorporating *Eichhornia crassipes* (water hyacinth) and *Melaleuca cajuputi* (cajuput leaf waste) to enhance combustion efficiency and reduce ash content. Five biomass formulations were evaluated: pure calliandra, pure water hyacinth, pure cajuput leaves, calliandra–water hyacinth (75:25), and calliandra–cajuput leaves (75:25). The produced biopellets were analyzed for their physical characteristics, calorific value, and proximate properties, including moisture content, volatile matter, ash content, and fixed carbon. Results showed that the calliandra–cajuput mixture yielded the best performance, with a density of 0.84 g/cm³, low ash content (2.65%), and a high calorific value (18.2 MJ/kg). The addition of water hyacinth reduced volatile matter but increased ash content. The biopellets from the calliandra–cajuput blend met the SNI 8675:2018 standard for both household and industrial use. This study demonstrates that the integration of locally available biomass waste can significantly improve biopellet quality while supporting sustainable waste management and renewable energy diversification.

Keyword: Biomass, *Calliandra calothyrsus*, *Eichhornia crassipes*, *Melaleuca cajuputi*, Proximate Analysis, Renewable Energy

1. Introduction

The growing demand for environmentally friendly alternative energy sources has become increasingly urgent due to rising global energy consumption and the adverse environmental impacts of fossil fuel use. Renewable energy offers a strategic solution to support the transition toward a sustainable energy system. According to data from the Indonesian Central Statistics Agency, the production of primary energy from biomass reached 612.275 terajoules in 2023 [1], highlighting the significant potential of biomass as a naturally derived energy source. Biomass can be converted into secondary energy forms for direct human use. One of the most promising forms of renewable energy in Indonesia is bioenergy, particularly biopellets derived from biomass. The utilization of biomass for bioenergy has the potential to reduce greenhouse gas emissions generated by conventional energy sources such as coal and other fossil fuels [2].

Biopellets are cylindrical solid fuels produced through the densification of biomass. Compared to raw biomass, biopellets offer several advantages, including higher energy density, improved storage stability, and greater ease of distribution and utilization in modern combustion systems. The use of locally sourced biomass for biopellet production not only supports energy diversification but also contributes to organic waste management and adds value to local biological resources. Global demand for biopellets has increased significantly over the past decade, with growth exceeding 50%, reaching more than 10 million tons in the global market [3].

In response to the growing demand for efficient and environmentally sustainable solid fuels, the selection of appropriate biomass feedstock has become a critical factor in the development of high-quality biopelets. Not all biomass types possess the physical and chemical characteristics required to produce pellets with optimal combustion performance. Therefore, feedstocks with high calorific value, low ash content, favorable proximate composition, and sustainable availability are essential to ensure fuel quality and supply continuity. In this context, the exploration and utilization of fast-growing, high-productivity local energy crops represent a strategic approach to strengthening the competitiveness of biopelets as a viable substitute for fossil-based fuels.

Calliandra (Cal) is a promising plant species for the development of biomass-based energy, particularly in the form of biopellets that can serve as an alternative to coal. Indonesia, as a tropical country with abundant biodiversity, holds significant potential for utilizing various types of local biomass in biopellet production. *Calliandra calothyrsus*, a fast-growing leguminous plant, is especially attractive due to its high calorific value, making it a strong candidate as a primary feedstock for biopellets. According to [4], biopellets made from calliandra wood exhibit favorable calorific values and proximate analysis results that meet national standards for bioenergy production. Moreover, calliandra is known for its high productivity, with a harvesting cycle of approximately 2–3 months depending on soil conditions [5].

Although various types of biomass can be utilized for bioenergy production, *Calliandra calothyrsus* is selected as the primary feedstock due to its superior fuel characteristics and more reliable availability. Its rapid growth rate, high biomass productivity, and short harvesting cycle ensure a sustainable supply of raw materials and consistent quality, which are essential for large-scale biopelet production. Therefore, while other biomass resources may be incorporated to enhance resource efficiency and add value to waste materials, calliandra serves as a stable and high-quality base feedstock to maintain the performance and standard compliance of the resulting biopelets.

In addition to calliandra (*Calliandra calothyrsus*), numerous other types of biomass can be utilized for bioenergy production, particularly those classified as agricultural residues, invasive weeds, or industrial by-products. The use of such biomass not only adds economic value but also contributes to waste and weed management. Incorporating these materials as supplementary feedstocks in calliandra-based biopellets allows for the production of biofuels that still meet quality standards. In this study, the selected supplementary biomass sources include water hyacinth (*Eichhornia crassipes*), an invasive aquatic weed, and waste from the essential oil distillation process of cajuput (*Melaleuca cajuputi*), which primarily consists of leaves and twigs.

Water hyacinth (WH) is a free-floating aquatic plant with hanging roots, although it can occasionally anchor in soil. Belonging to the family Pontederiaceae, water hyacinth grows in clumps through interconnected root systems. This species is commonly found in polluted or nutrient-rich aquatic environments, such as shallow ponds, wetlands, marshes, slow-flowing streams, lakes, rivers, and even irrigation canals. Due to its rapid propagation, *E. crassipes* has become an invasive aquatic weed in many freshwater ecosystems across Indonesia. Despite its classification as a weed, water hyacinth has significant potential as a biomass source for bioenergy. It possesses a moderate calorific value and can be utilized in solid biofuel production, although certain performance parameters may still fall short of standard quality requirements [6].

The distillation of *Melaleuca cajuputi* (cajuput) leaves not only yields cajuput oil but also generates a substantial amount of residual biomass in the form of spent leaves. The oil yield from the distillation process is approximately 0.8%, meaning that 99.2% of the input material becomes distillation residue [7]. A portion of this biomass—around 20%—is typically reused as boiler fuel in the subsequent cajuput oil extraction cycles. However, the remaining 80% of the spent leaves often accumulates around the processing facilities, creating waste management concerns. Given its abundance and organic nature, cajuput leaf residue holds considerable potential as a raw material for bioenergy production [8].

Although calliandra biopelets have been proven to meet established fuel quality standards, most previous studies have primarily focused on single-feedstock utilization. Meanwhile, waste biomasses such as water hyacinth and residual leaves from cajuput oil distillation are abundantly available and hold potential as blending materials. However, when used individually, their characteristics often do not fully satisfy biopelet quality standards, particularly in terms of ash content, energy density, and combustion stability. To date, there remains limited research that systematically evaluates blending formulations combining calliandra as the primary base material with these waste biomasses to produce biopelets that are optimal in terms of energy performance and feedstock sustainability. Therefore, a comprehensive investigation is required to determine the optimal blending ratios and to assess their effects on the physical and chemical properties of the resulting biopelets. This study aims to identify the best formulation of biopelets derived from calliandra, cajuput waste, and water hyacinth as a renewable energy source with characteristics that comply with Indonesian National Standards (SNI).

2. Material and Methods
3.1. Material Preparation

The raw materials used in this study included *Calliandra calothyrsus* collected from Indramayu Regency (West Java), *Eichhornia crassipes* from Pekalongan Regency (Central Java), and *Melaleuca cajuputi* leaves obtained from Boyolali Regency (Central Java). All ingredients are dried in the sun to reduce the desired moisture content, which is around 12%. Water hyacinth was dried under direct sunlight for seven days, while calliandra and cajuput leaves were dried for three days.

After drying, the biomass materials were size-reduced using different equipment: water hyacinth and cajuput leaves were chopped using a mechanical chopper, and calliandra wood was processed using a ring flaker. A disc mill was then used to further reduce the particle size to 40 mesh to obtain uniform particles suitable for the pelletization process. Figure 1 shows the process of preparing raw material particles. The prepared materials were then blended according to the treatment formulations described in Table 1.
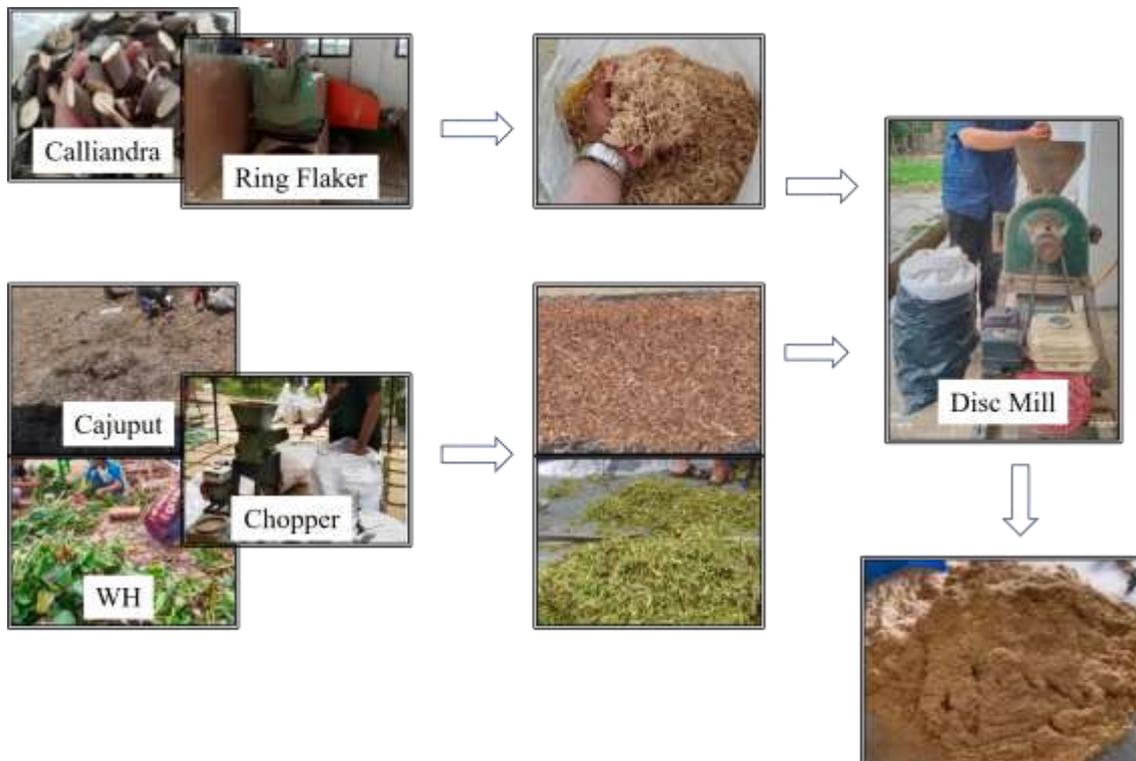
Figure 1. Raw material particle preparation process

Table 1. Biomass Composition Treatments Used in This Study

Biomass Composition	Code	Biomass Composition
100% Calliandra	Kal	100% Calliandra
100% Cajuput leaves	Cajuput	100% Cajuput leaves
100% Water hyacinth	WH	100% Water hyacinth
75% Calliandra + 25% cajuput leaves	Cal + Cajuput	75% Calliandra + 25% cajuput leaves
75% Calliandra + 25% Water hyacinth	Cal + WH	75% Calliandra + 25% Water hyacinth

3.2. Pellet Testing

The produced pellets were evaluated through proximate analysis (moisture content, volatile matter, ash content, and fixed carbon), bulk density, moisture resistance, and calorific value. Proximate analysis was conducted at the Integrated Laboratory of Bioproducts (ILaB), National Research and Innovation Agency, Cibinong, Bogor, following the standard procedures outlined in [9]. Calorific value analysis was performed at the Chemical Services Laboratory of the Instrument Standard Testing Center for Poultry and Miscellaneous Livestock, located in Ciawi, Bogor Regency, West Java.

3.3. Statistical Analysis

Statistical analysis in this study was conducted using a Completely Randomized Design, with the type of feedstock mixture as the treatment factor. All collected data were analyzed using analysis of variance (ANOVA). When significant differences were detected, the analysis was further followed by Duncan's Multiple Range Test (DMRT) at a 95% confidence level ($\alpha = 0.05$) to identify differences among treatments in greater detail [10]. Each treatment combination was performed in triplicate. Data processing was carried out using IBM SPSS Statistics version 22.

3. Results and Discussion

3.1. Physical Characteristics of Biopellets

Biopellets are a widely developed form of solid bioenergy product, serving as a renewable alternative to conventional fossil fuels. In this study, biopellets were produced using three types of biomass feedstocks: calliandra, WH, and distillation waste of cajuput. The pelletization process was carried out using a pellet mill, resulting in biopellets with varying lengths depending on the composition of the raw materials used. Figure 2 shows the visual appearance of biomass pellets derived from various types of biomass feedstocks.

Figure 2. Visual appearance of biomass pellets produced from various raw materials

The average length of biopellets across all treatments was 42.22 mm. The longest biopellets were produced from the calliandra and cajuput mixture, with an average length of 46 mm, followed by pure cajuput biopellets at 44.31 mm. In contrast, the shortest biopellets were obtained from the calliandra and WH mixture, with an average length of 39 mm.

These variations in pellet length are closely related to the physical properties of the feedstock materials, particularly their hardness and particle texture [11]. Cajuput pellets exhibited a harder texture compared to those made from calliandra or WH. Feedstocks with low hardness and binding capacity tend to produce pellets that are more prone to breakage after pelletization. Additionally, lignin content in each material significantly influences the physical integrity of the pellets. Lignin acts as a natural binder, contributing to both the density and structural strength of the biopellets [12]. In this study, calliandra contained 25.43% lignin, while cajuput had 37.23% and water hyacinth had 10.57%

The diameter of the produced biopellets was relatively uniform, as it followed the size of the die holes in the pelletizing machine. The average diameter across all treatments was 8.075 mm. This value complies with the Indonesian National Standard [13], which specifies that biopellet diameters should range between 4.00 mm and 10.00 mm.

Pellet diameter influences the combustion duration; pellets with larger diameters have smaller surface area-to-volume ratios, reducing oxygen contact and thereby slowing the combustion rate. This slower burn rate allows for more prolonged energy release [14]. Such a characteristic can be advantageous in achieving sustained thermal energy output. Furthermore, uniformity in pellet diameter contributes to consistent combustion performance, optimizing heat generation across various combustion systems [15].

Pellet density plays a critical role in transportation efficiency and storage compactness. Among the samples, biopellets made from calliandra exhibited the highest bulk density (0.95 g/cm³), while WH pellets had the lowest (0.55 g/cm³). Calliandra biopellets exhibit the highest density due to the combination of their compact woody structure and relatively high lignin content, which acts as a natural binder during pelletization. These characteristics result in stronger interparticle bonding and reduced internal porosity, producing biopellets with greater bulk density compared to non-woody biomass such as water hyacinth. According to the Indonesian National Standard [9], the minimum required bulk density is 0.6 g/cm³ for household use and 0.8 g/cm³ for industrial applications. The calliandra + cajuput mixture achieved a density of 0.70 g/cm³, and the calliandra + WH mixture reached 0.63 g/cm³—both meeting the household standard. Pure kalliandra and cajuput biopellets satisfied the industrial standard, while WH alone did not meet either threshold. Despite no specific requirements regarding pellet size in [9] the physical dimensions (length and diameter) of all biopellet samples remained within the ideal range for use in automated combustion systems.

Visually, the produced biopellets exhibited distinct physical characteristics depending on their feedstock composition. Biopellets made from calliandra had the lightest color, whereas those made from cajuput were the darkest. Biopellets derived from WH had a medium brown hue, positioned between the two. The combination of calliandra and cajuput resulted in a noticeably darker, almost black pellet color, while the blend of calliandra and WH did not show significant changes in color compared to their respective single-source counterparts.

In terms of hardness, biopellets made from WH exhibited the lowest mechanical strength, making them prone to crumbling or breakage. In contrast, biopellets produced from calliandra and cajuput showed higher hardness, indicating denser and more durable structures. This trend was also observed in the composite biopellets; the combination of calliandra and cajuput demonstrated relatively good hardness, while the calliandra and WH blend remained fragile. The low hardness of the WH-based biopellets is closely related to their low density, which results in internal voids within the pellet structure.

Biopellet density not only influences mechanical strength but also significantly affects the calorific value generated during combustion. The higher the density, the greater the calorific value, as the amount of fuel mass per unit volume increases [16]. Therefore, the selection and combination of raw materials that can produce optimal density is crucial for the development of high-quality biopellets.

3.2. Proximate Analysis of Biopellets

Pellet density has significant practical implications for logistical efficiency, distribution costs, as well as storage and combustion performance. Biopellets with higher density tend to be more compact, less prone to breakage during transportation, and capable of delivering a more stable energy supply in automated combustion systems. In this context, the use of calliandra as the primary feedstock offers technical advantages, as it produces pellets that meet or even exceed industrial standards, thereby providing flexibility for various scales of energy utilization. Meanwhile, blending with cajuput waste and water hyacinth enables the valorization of biomass residues without compromising suitability for household-scale applications. This demonstrates that blending strategies not only contribute to waste management and feedstock diversification but also maintain technical reliability and standard compliance in the practical implementation of biopellets as a renewable fuel.

All biopellet compositions tested exhibited moisture content below the maximum thresholds specified by the Indonesian National Standard [9], which are ≤10% for household use and 12% for industrial applications. The lowest moisture content was observed in pellets made from calliandra (6.06%), while the highest was

found in the mixture of calliandra and WH (7.74%). Low moisture content is essential for ensuring combustion efficiency and storage stability, as high moisture levels tend to reduce calorific value and increase the risk of microbial growth during storage. Pellets with high moisture content are more susceptible to mold infestation and biodegradation. Furthermore, higher moisture necessitates the use of additional energy for water evaporation during combustion, thereby lowering overall thermal efficiency. According to [17], moisture content is primarily influenced by the initial moisture levels of the raw materials rather than their compositional ratios. Therefore, proper drying of feedstock prior to pelletization is crucial to ensure the production of high-quality biopellets.

Volatile matter (VM) refers to organic compounds that readily vaporize when biomass is subjected to short-term heating. All biopellet compositions in this study complied with the standards specified in [9], which set a maximum VM content of 80% for industrial applications and 75% for household use, as presented in Table 2. A high volatile matter content generally accelerates the combustion process; however, it may reduce energy efficiency due to increased smoke production [18].

A high VM content in biopellets indicates that a substantial portion of the organic components volatilize during combustion, potentially leading to the release of gases such as carbon monoxide (CO), unsaturated hydrocarbons, and fine particulate matter as a result of incomplete combustion. Nevertheless, a lower VM content does not necessarily imply better fuel quality. Excessively low VM levels may slow down ignition and reduce ease of flame initiation. According to [19], biomass with high volatile matter content requires specialized combustion system designs to ensure efficient burning and to minimize harmful emissions. In biomass combustion systems, a close relationship exists between volatile matter and fixed carbon (FC). VM plays a dominant role during the initial combustion stage through the release of flammable volatile gases, whereas fixed carbon contributes to the subsequent char combustion phase, producing more stable and sustained heat. Therefore, a balanced proportion of volatile matter and fixed carbon is essential to achieve optimal combustion performance—characterized by easy ignition, stable heat output, and minimized emissions and energy losses due to incomplete combustion.

The addition of 25% water hyacinth (WH) to calliandra-based biopellets significantly reduced the VM content from 73.6% to 69.11%. Similarly, incorporating 25% cajuput decreased the VM content to 71.57%. This reduction in volatile matter contributes to improved combustion efficiency and lower smoke production.

The composition of raw materials significantly influences the ash content of biopellets. According to Standard (SNI 2018), the maximum allowable ash content for both household and industrial biopellets is ≤5%. Based on this standard, only the calliandra (2.36%) and the calliandra + cajuput (2.65%) biopellets met the requirement. The addition of 25% cajuput did not significantly increase the ash content and remained well below the maximum threshold. In contrast, biopellets made solely from WH exhibited the highest ash content (13.89%), exceeding the permissible limit and potentially reducing combustion efficiency due to higher residual formation.

Low ash content is a critical indicator of biopellet quality [17]. Ash is a non-combustible residue that not only reduces the heating value of the fuel but also contributes to operational issues such as slagging and fouling in combustion systems. These issues necessitate frequent cleaning and maintenance to sustain optimal performance. Therefore, minimizing ash content is essential for enhancing energy output and maintaining the reliability of combustion equipment.

Fixed carbon refers to the portion of carbon remaining in the sample after the removal of moisture, volatile matter, and ash. Its content is influenced by the elemental composition of the biomass, particularly carbon, hydrogen, and oxygen. Fixed carbon serves as a key indicator of fuel quality, as it directly correlates with the calorific value of the biomass [20]. According to the minimum standard specified in (SNI 2018), a fixed carbon content of at least 14% is required, and all biopellet compositions in this study met this criterion.

Table 2. Proximate Properties of Biopellets

Component	WH	Calliandra	Cajuput	Calliandra + WH	Calliandra + Cajuput	SNI 8675: 2018	
						Household	Industrial
Moisture (%)	5,9504[a]	6,0574[a]	7,5275[c]	7,7353[c]	7,0070[b]	≤ 10	≤ 12
Volatile Matter (%)	65,5233[a]	73,6034[d]	67,6234[a]	69,1107[b]	71,5717[c]	≤ 75	≤ 80
Ash (%)	13,8952[c]	2,3614[a]	5,7299[b]	5,2683[b]	2,6548[a]	≤ 5	≤ 5
Fixed Carbon (%)	14,6310[a]	17,9778[b]	19,1192[c]	17,8857[b]	18,7664[c]	≥ 14	≥ 14
Density (g/cm³)	0.5550[a]	0.9531[b]	0.7195[a]	0.6336[a]	0.6952[a]	≥ 0.6	≥ 0.8
Length (mm)	41,23[a]	40,97[a]	44,31[b]	39,03[a]	46,00[c]	-	-
Diameter (mm)	7,83[b]	8,22[d]	7,53[a]	8,03[c]	8,36[d]	-	-

*Values followed by different superscript letters (a, b, c, d) in the same row indicate statistically significant differences (p < 0.05)

The lowest fixed carbon content was observed in WH-based biopellets (14.63%). However, the addition of 25% WH to calliandra biopellets did not significantly reduce the fixed carbon level. In contrast, the inclusion of 25% cajuput significantly increased the fixed carbon content from 17.98% to 18.77%. This suggests that incorporating cajuput may enhance the energy density and combustion efficiency of biopellets.

Fixed carbon content plays a crucial role in determining fuel quality, as it directly affects the calorific value of the material [20]. It serves as an indicator of the amount of combustible solid material remaining after volatile components have been released. A higher fixed carbon content implies a greater potential for energy generation, resulting in a higher heating value. Conversely, low fixed carbon content is typically associated with lower fuel quality and reduced combustion efficiency [18].

3.3. Calorific Value

The calorific value is a key parameter that indicates the amount of thermal energy released during the complete combustion of a fuel. It serves as one of the primary indicators for assessing the quality and efficiency of biopellets as an alternative energy source [21]. A higher calorific value signifies greater energy potential and improved combustion efficiency, making the fuel more desirable for practical applications.

Figure 3 presents the calorific value test results of the biopellets, which ranged between 14 and 19.8 MJ/kg. All treatments exhibited values above the minimum standard specified in [9] (≥16 MJ/kg), except for the control sample made solely from WH, which only reached 14 MJ/kg. This finding indicates that WH, when used as a single feedstock, does not meet the quality standards for biopellets. The likely causes are its high ash content (13.89%) and low fixed carbon content (14.63%).
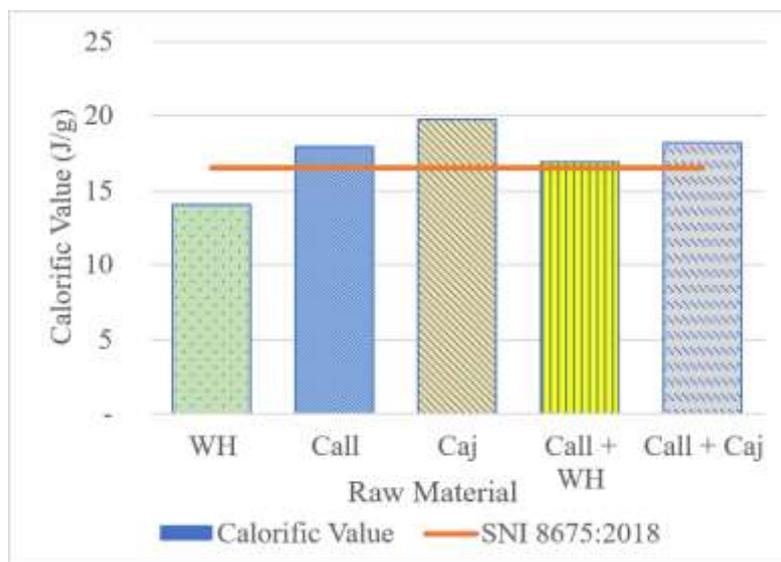
Figure 3. Calorific values of biopellets derived from various raw material compositions

The highest calorific value was observed in the control biopellets made from cajuput, reaching 19.8 MJ/kg, followed by calliandra at 18 MJ/kg. The combination of calliandra and cajuput also exhibited a relatively high calorific value (approximately 18.2 MJ/kg), while the blend of calliandra and WH yielded a moderate value of 16.9 MJ/kg. These results indicate that incorporating superior biomass sources such as calliandra can effectively enhance the fuel quality of lower-grade feedstocks like WH.

The calorific value of a biopellet is strongly influenced by its proximate composition, particularly the contents of fixed carbon, moisture, ash, and volatile matter. A study by [22] reported that calorific value is positively correlated with fixed carbon content and negatively correlated with ash and volatile matter contents. The findings of this study are consistent with that observation, where the highest calorific values were recorded in samples with high fixed carbon and low ash content (e.g., cajuput control: FC 19.12%; ash 5.72%). High fixed carbon content, as found in lignin-rich feedstocks like calliandra and cajuput, contributes significantly to increased energy content. In contrast, elevated ash and volatile matter contents exhibit a negative correlation with calorific value. Ash, particularly when rich in silica, is non-combustible and can lead to fouling and slagging in combustion systems, thereby reducing energy efficiency [23].

High moisture content contributes to a reduction in calorific value, as a portion of the combustion energy is diverted to evaporate the water during the burning process. The Calliandra + Eichhornia crassipes biopellet exhibited the highest moisture content (7.74%) and demonstrated a lower calorific value compared to other treatments, although it remained within the acceptable range.

Similarly, high volatile matter content decreases combustion efficiency. Volatile compounds tend to vaporize before complete combustion, thus reducing the effective heat released. Combustion of high-volatile biomass generally results in increased smoke production and inefficient energy utilization. Calorific value also determines the suitability of biopellets for various applications. Biopellets with high calorific values are more appropriate for industrial combustion systems, while those with lower calorific values may still be acceptable for household use.

3.4 Pellet Water Resistance (Hydrostability)

The water resistance test of biopellets was conducted to evaluate their physical durability when exposed to moist or wet environments. This parameter is particularly crucial for assessing the suitability of biopellets for storage and transportation, especially in tropical regions with high humidity levels. In such conditions, biopellets are at risk of losing their structural integrity before being utilized as fuel. Hydrostability directly affects the operational viability and user acceptance of biopellets, as poor water resistance may lead to disintegration, reduced calorific value, and compromised combustion performance during handling or storage.

Based on visual observations during immersion over a time span of 0 to 120 minutes (Figure 4), notable differences in hydrostability were observed among the biopellet types. Biopellets made from cajuput and the mixture of calliandra + cajuput exhibited relatively stable morphology up to 120 minutes, showing only minor swelling without significant disintegration. This indicates strong internal bonding and a compact structure, likely attributed to the high lignocellulosic content of the raw materials and the high-density outcome of the pelletization process. Furthermore, the residual oil content in cajuput biomass may contribute to enhanced water resistance, providing a hydrophobic effect that prevents rapid water absorption.

Water hyacinth-based biopellets, particularly in the control treatment and the calliandra + WH blend, began to exhibit signs of softening, swelling, and eventual disintegration in the aqueous medium starting at 60 minutes, with complete structural instability observed between 90–120 minutes. This phenomenon is likely attributed to the low lignin content of Eichhornia crassipes, considering that lignin functions as a natural binder responsible for internal cohesion and particle compaction during the pelletization process; lower lignin levels tend to result in weaker interparticle bonding and increased cracking in pellets [24]. The loss of physical integrity suggests that WH-based biopellets require the addition of binders or blending with high-binding-strength materials to meet acceptable standards for physical durability.
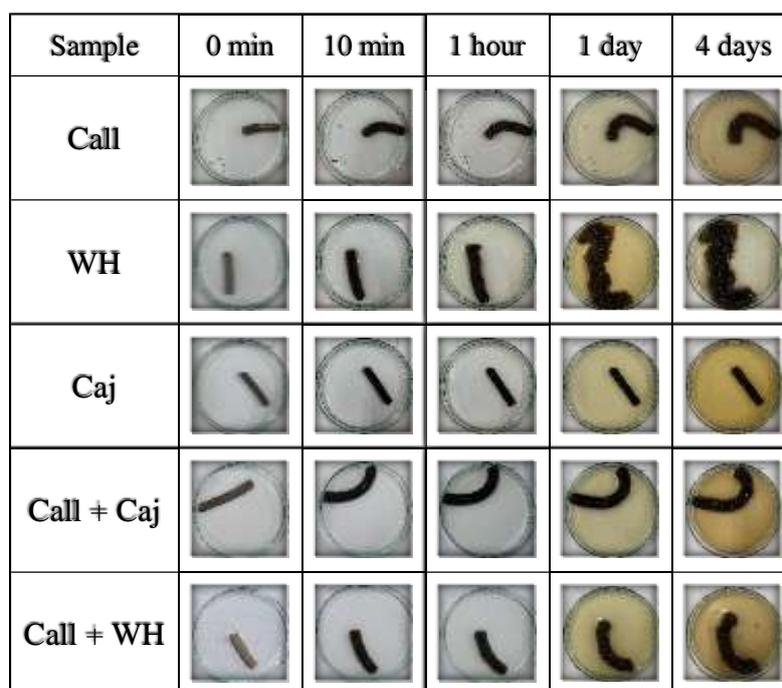
Figure 4. Hydrostability of biopellet samples over immersion time

This immersion test also reflects the mechanical performance of biopellets under humid environmental conditions, which is especially relevant for end-users storing fuel in open or semi-enclosed spaces. Therefore, immersion testing provides critical insights for ensuring product quality, enhancing logistical durability, and preventing physical degradation during distribution. Hydrophilic samples that readily absorb water are prone to increased microbial activity, such as bacterial and fungal growth, which accelerates decomposition and shortens storage life [25].

4. Conclusion

This study demonstrates that the utilization of locally sourced biomass, such as *Calliandra calothyrsus* (Calliandra wood), *Eichhornia crassipes* (water hyacinth), and *Melaleuca cajuputi* (cajuput leaves), can yield bio-pellets with diverse characteristics depending on their composition. The bio-pellets composed of a 75:25 blend of calliandra and cajuput leaves exhibited the most favorable properties, including high density, low ash content, and a calorific value that complies with the quality standards set by SNI 8675:2018. Although the addition of water hyacinth remained within SNI standards in most parameters, it exceeded the permissible ash content limit. Overall, proper selection and formulation of biomass feedstock—particularly those dominated by calliandra—can significantly enhance the energy efficiency and quality of bio-pellets, while promoting the sustainable utilization of biomass waste.

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