

Original Research Article

Towards Sustainable Energy: Densification Pressure Effects on *Khaya senegalensis* Fuel Pellet Properties

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Abstract: This research investigates the combustion properties of Malaysian *Khaya senegalensis* wood energy pellets and examines the effects of densification at different pelletizing pressures. Despite the potential of densified wood pellets as a renewable energy source towards utilizing a sustainable energy, the differentiated influence of densification on combustion properties, especially in connection with different densification pressures, is still insufficiently researched. The main objective is to quantify the combustion properties including ash content, fixed carbon, volatile matter and calorific value of energy pellets. In this study, this woody biomass was converted into pellets through a densification process that covered a pressure range of 6.28 to 31.4 MPa during pelletization. The resulting pellets were subjected to a series of tests to methodically characterize their combustion properties. The material exhibited an ash content of 3.69% when pelletized under a 6.28 MPa pressure, a fixed carbon content of 11.54% under a 6.28 MPa pressure, a moisture content of 10.48% when densified at 18.8 MPa of pressure, and a calorific value of 19.54 MJ/kg at 12.5MPa. Additionally, the volatile content was observed at 85.74% under a 25.1MPa pressure. In conclusion, this study determined that pelletization pressure significantly influences combustion properties and thus providing an improved understanding of the influence of compression on combustion behavior at different pelletization pressures.

Keywords: Biomass; biomass densification; pelletization; solid fuel; pellets; pellet quality; combustion properties

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1. Introduction

Wood pellets have emerged as a promising renewable energy source, offering a sustainable alternative to traditional fossil fuels. Among the various types of wood pellets, Malaysian *Khaya senegalensis* wood energy pellets stand out as a potential contributor to the renewable energy landscape. However, despite their potential, there remains a critical gap in understanding the impact of densification, particularly at different pelletizing pressures, on their combustion properties. This research aims to bridge this gap by delving into the combustion properties of Malaysian *Khaya senegalensis* wood energy pellets and investigating the effects of densification at various pelletizing pressures. While the utilization of densified wood pellets for energy production holds great promise, the nuanced influence of densification on combustion properties, especially concerning different densification pressures, remains inadequately explored. The primary objective of this study is to quantitatively assess the combustion properties, including ash content, fixed carbon, volatile matter, and calorific value, of energy pellets derived from Malaysian *Khaya senegalensis* wood. Through a meticulous densification process spanning a pressure range from 6.28 to 31.4 MPa tonnes during pelletization, the woody biomass was transformed into pellets. Subsequently, the resulting pellets underwent a series of tests to systematically characterize their combustion properties.

2. Materials and Methods

At the processing stage, the pelletization pressure and the interaction between these two main variables are known to affect wood pellets' combustion performance. One of the objectives in the current study is to find out the effect of pressure on *Khaya senegalensis* wood on pellet quality parameters. In this study, the raw khaya wood feedstock was pelletized with five levels of pressure, which are 1 tonne (6.28 MPa), 2 tonnes (12.5 MPa), 3 tonnes (18.8 MPa), 4 tonnes (25.1 MPa), and 5 tonnes (31.4 MPa); replicated 3 times. The ground biomass was pelletized using a Single Hot Press Hydraulic Machine with different pressures as shown in Figure 1.



Figure 1. Single Press Hydraulic Machine with temperature controller.

During the compaction process, portions of 1 gram was compacted at a time. Specifically, the biomass was pulverized and sieved to obtain a particle size of 0.5 mm, the moisture content of the raw material during compaction was 12%, the binder percentage was set at 8%, and the pelletizing temperature was fixed at 75°C. This approach allows for a focused examination of the impact of pressure on pellet quality while controlling other variables to ensure accurate and reliable results. Tapioca binder starch was used in this study. For this study, the compaction was carried out using a manual press, and there was no mechanism or equipment available to directly quantify the piston speed. Additionally, the design parameters of the working system have been specified: the matrix in this study refers to the die used during the compaction process. The inner diameter of the die (matrix) is 0.01 m, and the length (thickness or depth) is 0.1 m, both of which influence the compaction process and the durability of the pellets. Additionally, the die is an open-ended matrix, allowing the biomass to be extruded without restriction at the output. The properties of the pellets as a fuel, including their ash content, volatile matter, fixed carbon, and calorific value, were examined utilizing a muffle furnace (DAEYANG brand, model: MF-2511) as indicated in Figure 2.



Figure 2. Muffle Furnace.

Proximate analysis according to the American Standard Testing Material (ASTM International, 2019), specifically, ASTM E-872 standard method was conducted on *Khaya senegalensis* fuel pellets to ascertain key attributes relevant for combustion. To test the volatile matter, the sample was placed in a furnace set at 950 ± 0.5 °C for 7 minutes and then allowed to cool to room temperature. After cooling, the sample was weighed again to see how much weight it lost. Before calculating the volatile matter percentage, the moisture content needed to be factored in. To do this, the mass loss (B) of the sample when heated or dried was measured. Moisture loss (A) represents the part of mass loss due to moisture evaporating during heating. The percentage of volatile matter can then be found by subtracting the moisture loss (A) from the total mass loss (B). The moisture content of *Khaya senegalensis* was measured using a moisture analyzer (brand: AND, model: MX-50).

$$\text{Weight loss, } B (\%) = \frac{W_i - W_f}{W_i - W_c} \times 100\% \quad (1)$$

$$\text{Volatile Matter } (\%) = B - A \quad (2)$$

where W_i = initial weight of the pellet, crucible, and cover (g), W_f = final weight of pellet sample (g), and W_c = weight of crucible and cover (g).

ASTM E870 standard was used to determine the ash content. The ash content was determined by measuring the remaining mass after the sample underwent controlled heating in air, adhering to strict time, sample weight, and equipment parameters. The sample was placed in the furnace and heated for 60 minutes at around 700 ± 0.5 °C. The initial mass (mass

initial) and the final mass (mass final) after heating were recorded, and the ash content percentage in biomass pellets was calculated using Equation (3).

$$\text{Ash Content (\%)} = \frac{W_3 - W_1}{W_2} \times 100\% \quad (3)$$

where W_1 = weight of empty crucible (g), W_2 = weight of pellet sample (g), and W_3 = weight of crucible containing the ash (g).

Furthermore, this study also determined the calorific value and fixed carbon content. Fixed carbon content was determined by the difference between 100 and the total of the experimentally measured percentages of ash content, moisture content, and volatile matter in the proximate analysis. The predicted high heating value (HHV), also known as the calorific value, was determined based on the correlation in Equation (4). With an R^2 value of 0.827 and a standard deviation of 1.483 MJ/kg, this equation is, thus, trustworthy. The results of the experimental proximate analysis carried out in this study were used to determine the amounts of calorific value.

$$\text{Calorific Value} = 167.2 - 1.449 \text{ VM} - 1.562 \text{ FC} - 1.846 \text{ ASH} \quad (4)$$

where FC = fixed carbon, VM = volatile matter, and ASH = ash.

3. Results and Discussions

3.1. Ash Content

The experimental data on the ash content of khaya pellets pelletized at different pelletization pressures are shown in Figure 3. Ash content in pellets derived from plant materials, such as khaya pellets, represents the inorganic residue that remains after combustion. The graph below demonstrates a clear quadratic trend, indicating a curvilinear relationship between pelletization pressure and ash content. The resulting ash content, ranging from 3.69 to 4.20%, signifies the impact of different pelletization pressures on the final product. Within this range, the ash content tends to follow a quadratic curve, indicating that there may be an optimal or critical range of pressures leading to either a minimum or maximum ash content.

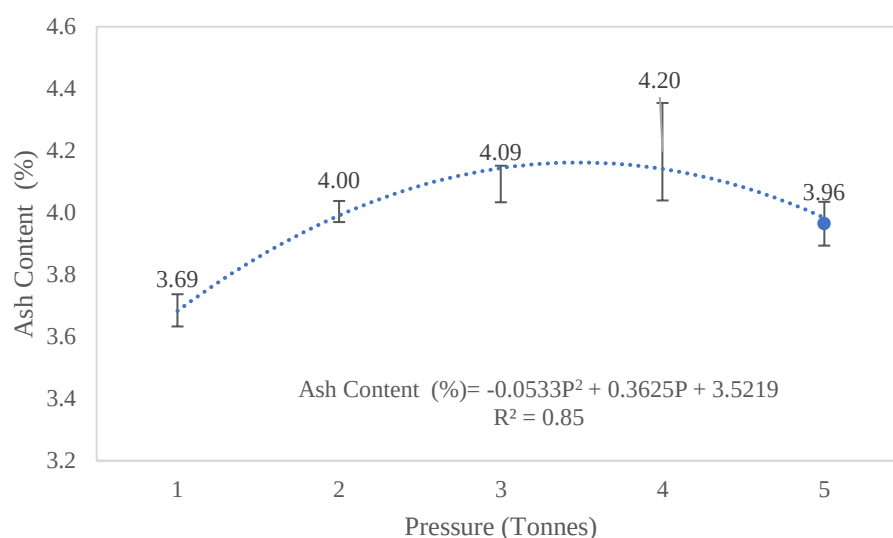


Figure 3. The effects of pelletization pressures on energy pellets ash content.

Higher ash content can negatively impact combustion performance. The combustion of organic material produces ash as a byproduct, and an excessive amount of ash can interfere with the combustion process, reducing efficiency and energy output. According to Siyal *et al.* (2023), higher ash content is undesirable as it influences the combustion performance and may cause fouling and slagging problems. As the pellets burn, the inorganic components in the ash can accumulate on heating surfaces, forming deposits (fouling) and potentially molten masses (slagging). The information from this author aligns with ordinary knowledge in biomass or fuel pellet production. This can reduce heat transfer efficiency, increase maintenance requirements, and damage combustion equipment. This is supported by the fact that ash content, negatively related to the energy value and associated with the risk of boiler corrosion. This is corroborated by Oliveira *et al.* (2020), who reported that ash content varies widely (1–4%) according to genotype and site conditions. Ash content is adversely correlated with energy value and linked to the danger of boiler corrosion. This could be due to the interplay of various factors in the pelletization process, where an initial increase or decrease in pressure has a more pronounced effect on ash content compared to further changes. These findings align with results reported by other publications in the literature. Stasiak *et al.* (2017) also examined the mechanical and combustion properties of sawdust and straw pellets. The ash contents range from 0.31–4.10, comparable to the current study. Moreover, the results are also at par as compared with Riva *et al.* (2019) analysis who studied the optimal temperature, pressure, and binder amount for the production of biocarbon pellets. The author found the ash content of biocarbon pellets with a mean value of $4.22 \pm 0.8\%$. The following

Equation (5) is derived from the data presented in Figure 1, with ash content modelled as a quadratic function of the pelletization pressure:

$$\text{Ash Content (\%)} = -0.0533P^2 + 0.3625P + 3.5219 \quad (5)$$

Besides, elevated ash content may result in higher emissions of particulate matter and other pollutants during combustion. This can have environmental implications and may be subject to regulatory restrictions. Ash itself does not contribute to the energy content of the pellets. Therefore, higher ash content implies a lower proportion of combustible material in the pellets, decreasing the overall energy content. This is supported by Rajput *et al.* (2020), who mentioned the same idea and found that the calorific value decreases as the ash content of the raw material increases. The ash contained in the pellets does not provide energy and leads to slagging problems and deposits on the burners. The high R^2 value of 0.85 suggests that 85 % of the variability in ash content can be explained by the quadratic relationship with pelletization pressures. This indicates a strong correlation between the independent variable (pelletization pressure) and the dependent variable (ash content). The statistical significance of the ANOVA test (p -value = 0.015, less than 0.05) provides strong evidence that the observed variations in ash content at different pelletization pressures are not due to random chance. This reinforces the conclusion that the quadratic trend is a meaningful and statistically significant pattern in the data. In summary, the quadratic trend in the ash content data, the high R^2 value, and the statistically significant ANOVA result suggest a strong and meaningful relationship between pelletization pressures and ash content in khaya pellets.

3.2. Volatile Matter

Figure 4 shows the experimental data of khaya pellets volatile matter content pelletized at various pressure levels. The trend observed is still described as quadratic. The R^2 value of 0.89 indicates that 89% of the variability in volatile matter content can be explained by the quadratic trendline. This suggests a moderate correlation between pressure levels and volatile matter content. The volatile matter content of the khaya pellets varies between 84.76% and 85.74% across different pressure levels. This suggests that the specific conditions of the pelletization process, especially the applied pressure, play a crucial role in determining the volatile matter content of the khaya pellets. A similar range was also observed in the study by Mohamad *et al.* (2024) for pellets made from a mixture of Palm Kernel Shell and polystyrene.

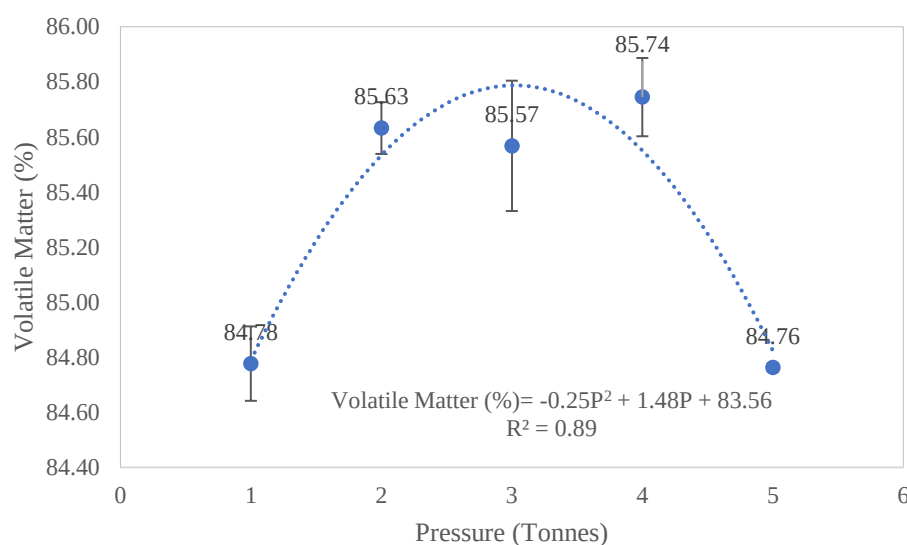


Figure 4. Pelletization pressure impact on khaya pellet volatile matter.

Two primary factors contribute to the generation of pressure during compression: internal friction resulting from the disruption of inter-particle connections and external friction between the biomass particles and the surface of the die. It is essential to apply a specific force to compress biomass particles. In order to ensure the feasibility of the pelletization process, energy consumption must be minimized, as heightened pressure necessitates a substantial amount of energy (Sarker *et al.*, 2022). This could partly be explained by understanding that pelletization involves compressing and compacting raw material, in this case, khaya biomass, under pressure to form pellets. The pressure applied during this process influences the physical and chemical characteristics of the resulting pellets. High pelletization pressure can induce physical changes in the biomass, such as particle deformation and compaction. These changes can increase intermolecular forces and contact points between biomass particles. An interesting point to note here is that the volatile matter in biomass consists of components such as water, volatile organic compounds, and other substances that can be released during the pelletization process. The application of pressure may influence the release and retention of volatile matter within the pellets. This theory is supported by the evidence in Mostafa *et al.* (2019), which supports the idea of the effect of applied pressure on energy pellets. The physical and mechanical properties of pellets are strongly influenced by the pressure applied. Based on the graphical representation in Figure 2, Equation (6) was formulated.

$$\text{Volatile Matter (\%)} = -0.25P^2 + 1.48P + 83.56 \quad (6)$$

The ANOVA single-factor analysis conducted to assess the significance of the differences in volatile matter content at different pressure levels. The p -value obtained from the ANOVA analysis is crucial for determining the statistical significance of the differences. A p -value less than 0.05 is typically used as the threshold for statistical significance. In this case, the p -value is extremely small, at 6.11×10^{-46} ($<< 0$), well below 0.05. This means that the differences in volatile matter content observed at different pressure levels are highly unlikely to have occurred by chance.

3.3. Fixed Carbon

The data presented in Figure 5 illustrates the fixed carbon content of khaya pellets, which were subjected to different pelletization pressures, unveiling a quadratic trend. The maximum fixed carbon content in the dataset is observed at 6.28 MPa of pelletization pressure, reaching 11.54%, while the minimum fixed carbon content is found at 25.1 MPa of pelletization pressure, registering at 10.06%. The variation in ash content across different pressures may be attributed to several factors within the sample or the measurement process. Ash content is typically determined by combusting a sample and measuring the residue, representing the inorganic components. Factors influencing ash content may include variations in the source material, combustion conditions, or sampling methods. The composition of the material being burned, the efficiency of combustion, and the accuracy of the measuring instruments can all contribute to the observed range in ash content. The difference in ash content between samples may be explained by the fluctuation in the content of unburned material within the boiler. This may occur due to operational factors or the condition of the material used for combustion (Hansted *et al.*, 2022). The application of pressure induces changes in particle packing, intermolecular forces, and possibly the activation of natural binding agents within the biomass material. This is supported by Sarker *et al.* (2022), who stated that natural binding factors such as lignin, fat, starch, protein, and carbohydrates are found in lignocellulosic biomass and are activated at high temperatures and pressures during pelletization. Higher pelletization pressure might enhance the densification of the biomass particles, affecting the arrangement of carbonaceous components. Hettiarachchi *et al.* (2019) reinforced this statement by affirming that pressure can improve particle interlocking and adhesion, resulting in appropriate strength in pellets as indicated for biomass densification. This could lead to increased fixed carbon content, as observed in some cases.

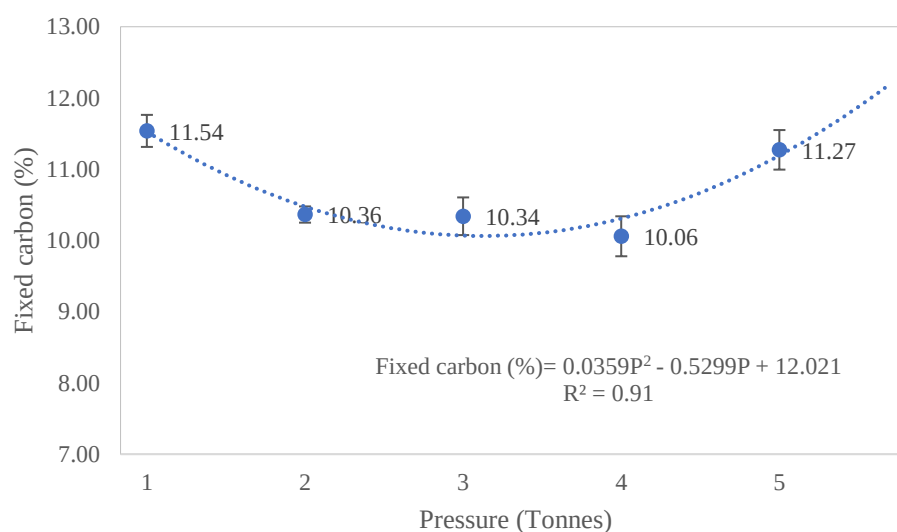


Figure 5. Fixed carbon variation with varying pelletization pressure.

Conversely, the relationship may exhibit a turning point where excessively high pressure might cause degradation or restructuring of carbon compounds, potentially leading to a decrease in fixed carbon content. The specific mechanisms contributing to the quadratic trend would require a more detailed analysis, possibly involving microscopic and chemical characterizations of the pellets at different pressures. Characterization of densified pellets is a multifaceted process that involves evaluating various aspects related to the quality of the pellets, as outlined by Miranda *et al.* (2015). The quality of pellets is influenced by a combination of factors, including the physical, chemical, and mechanical properties of the biomass used as raw material and the specific pelletization variables applied during the pelletizing process, such as pressure and temperature. On top of this, according to Demirbas (2004), the amount of fixed carbon is directly correlated with the amount of lignin present in the lignocellulosic material, which positively impacts the fuel's higher heating value. The *Khaya senegalensis* pellets should, therefore, have high fixed carbon values for this study because this parameter aids in the formation of solid products.

The high coefficient of determination ($R^2 = 0.91$) signifies that approximately 91% of the variability in fixed carbon content can be explained by changes in pelletization pressure. The extremely low p -value from the ANOVA test (3.41×10^{-17}), significantly less than 0.05 indicates that the observed differences in fixed carbon content at different pelletization pressures are highly unlikely to be due to random chance. This reinforces the statistical significance of the results. Equation (7) was developed by modeling the outcomes presented in Figure 3.

$$\text{Fixed carbon (\%)} = 0.0359P^2 - 0.5299P + 12.021 \quad (7)$$

3.4. Calorific Value

The data for calorific value of khaya pellets subjected to different pelletization pressures is shown in Figure 6. The linear trend with a clear decreasing pattern suggests a direct and consistent relationship between pelletization pressure and calorific value. The ash content of the khaya pellets ranges from 19.45 to 19.54%. This limited range implies that changes primarily influence the variations in calorific value in pelletization pressure rather than substantial fluctuations in ash content. Calorific value, representing the energy content of the pellets, is intricately linked to the composition and structure of the biomass material. As pelletization pressure increases, several mechanisms contribute to the observed decrease in calorific value. Higher pressure can lead to increased pellet density and compaction, potentially altering the distribution of carbon, hydrogen, and other combustible components within the pellets. This densification may result in reduced accessibility of these components during combustion, leading to a decline in calorific value.

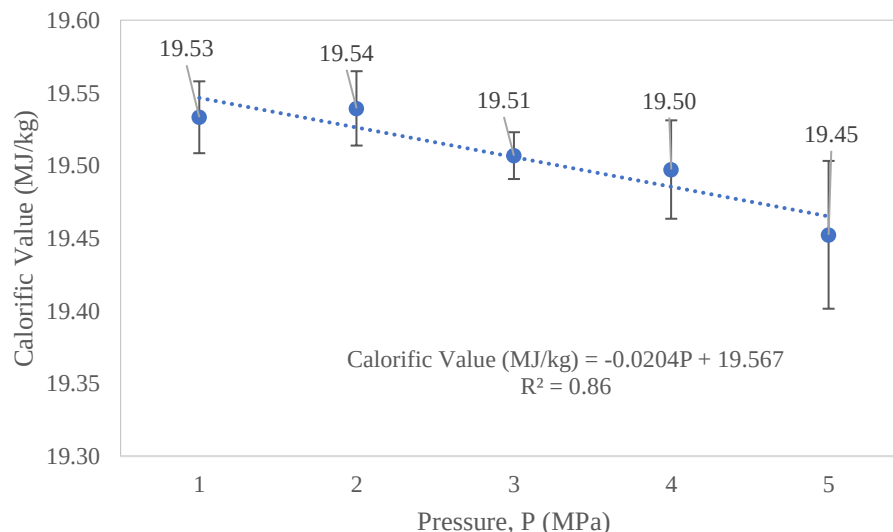


Figure 6. Influence of pelletization pressure distribution on the modulation of calorific value in khaya energy pellets.

Additionally, excessive pressure might induce thermal and chemical changes, causing the breakdown or rearrangement of organic compounds in the biomass, further impacting the energy content. The linear relationship suggests a systematic influence, where incremental changes in pressure directly correspond to a proportional reduction in calorific value. Nevertheless, striking a balance is crucial, as excessively low pressure may result in

inadequate pellet formation, affecting overall quality. Generally, an increase in calorific value correlates directly with higher levels of fixed carbon and volatiles, while it exhibits an inverse relationship with ash content (Jamradloedluk & Lertsatitthanakorn, 2017). Lignin, present in both woody and herbaceous biomass, is thought to be an essential binding agent for the creation of pellets. Lignin has a glass transition temperature below which it is brittle and can be crushed forcefully and above which it becomes viscous and swells over a greater surface area upon contact. As it cools, the lignin solidifies again, fortifying the densified biomass. Protein, waxes, and carbohydrates are among the other biomass components whose glass transition temperature is influenced by temperature, moisture content, and pressure (Tumuluru, 2018). Moreover, a previous study by Hegde *et al.* (2018) noted a negative correlation between the moisture content, volatile matter, and ash of densified samples and their calorific value.

The coefficient of determination ($R^2 = 0.86$) indicates that approximately 86% of the variability in calorific value can be explained by changes in pelletization pressure. This high R^2 value suggests a strong correlation, reinforcing the reliability of the linear model in describing the observed trends. The extremely low p -value from the ANOVA test (2.71×10^{-7} (< 0), significantly less than 0.05) provides robust evidence that the observed differences in calorific value at different pelletization pressures are unlikely to be due to random chance. The data presented in Figure 4 were utilised to formulate Equation (8).

$$\text{Calorific Value (MJ/kg)} = -0.0204P + 19.567 \quad (8)$$

4. Conclusions

The pellets underwent tests to examine their combustion properties. The results showed an ash content of 3.69% and fixed carbon content of 11.54% at a 6.28 MPa pressure, moisture content of 10.48% at 18.8 MPa, and a calorific value of 19.54 MJ/kg at 12.5 MPa. Additionally, volatile content was 85.74% under a 25.1 MPa pressure. In conclusion, the study highlights how pelletization pressure affects combustion properties, improving our understanding of compression's impact on combustion behavior at various pressures. Higher pressures generally led to increased volatile matter, which enhances combustion efficiency, but also resulted in varying moisture content, which can affect storage and handling. The findings align with existing literature, reinforcing the importance of optimizing pressure to balance fuel quality and durability. Understanding these relationships can aid in designing

improved biomass pelletization processes for sustainable fuel applications, particularly in industries aiming to enhance biomass energy production.

Author Contributions: The methodology was executed by R.I.I., while the validation process was undertaken by C.Y.K. Formal analysis was also conducted by R.I.I. Investigation and resource allocation were managed by R.I.I. The initial drafting of the manuscript was done jointly by R.I.I. and C.Y.K. Project supervision was provided by C.Y.K. and A.R.M. Project administration was overseen by C.Y.K. and A.R.M., with funding secured by R.I.I. Review and editing were carried out by L.Y.L., N.A.R., N.L.M., and M.H.B.M.J.B.

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Conflicts of Interest: The authors declare no conflict of interest.

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