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Effect of Gelam Wood and Rice Husk Composition with Molding Pressure on the Combustion Performance of Biopellets

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ABSTRACT

This study investigates the effects of gelam wood (*Melaleuca leucadendron*) and rice husk composition in biopellet production, focusing on compaction pressures of 60, 80, and 100 kg/cm². Five biomass ratios (G100–RH0, G80–RH20, G60–RH40, G50–RH50, G0–RH100) were tested for moisture, ash, fixed carbon, volatile matter, calorific value, ignition time, burning rate, and combustion temperature. Results showed that moisture content ranged from 0.98% (G0–RH100, 60 kg/cm²) to 12.28% (G100–RH0, 80 kg/cm²), while ash content varied between 2.47% (G100–RH0, 60 kg/cm²) and 20.93% (G0–RH100, 80 kg/cm²). The highest calorific value reached 3968 cal/g (G100–RH0, 60–80 kg/cm²), though below the SNI 8675:2018 minimum of 4000 cal/g. Ignition times ranged from 52 s (G0–RH100, 60 kg/cm²) to 135 s (G100–RH0, 100 kg/cm²), with burning rates between 0.002072 g/s and 0.003778 g/s. Maximum combustion temperature varied from 249°C (G0–RH100, 60 kg/cm²) to 290°C (G100–RH0, 100 kg/cm²). These findings confirm that both composition and compaction pressure significantly influence pellet quality, where higher rice husk content enhances ignition and burning rate but reduces calorific value. In contrast, higher compaction pressure improves density and temperature but prolongs ignition. The study provides practical insights for producing energy-efficient biopellets from abundant local biomass in South Kalimantan.

Keywords: *Biomass combustion, bio-pellets, compression pressure, gelam wood, rice husk.*

I. Introduction

The growing global demand for energy has driven the search for alternative energy sources that are both sustainable and environmentally friendly. One emerging approach is the utilization of renewable energy, derived from naturally replenishing processes such as solar, wind, hydro, geothermal, and biomass energy. Biomass refers to organic materials originating from plants, animals, and other organic waste that can be converted into energy. Its advantages as a renewable fuel lie in its abundance and carbon-neutral properties, making it a promising candidate to replace depleting and polluting fossil fuels [1],[2]. In Indonesia, the use of biomass as an alternative energy source has garnered significant attention, especially given the vast untapped potential of agricultural and forestry waste. For example, Gelam wood (*Melaleuca leucadendron*), which is widely distributed in South Kalimantan, is estimated to reach a production potential of thousands of cubic meters annually from

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managed peatland and riverbank areas, reflecting its considerable availability as a biomass feedstock. Among the various forms of biomass, bio-pellets—solid fuels produced by compressing biomass—have been widely developed. However, a key challenge in utilizing biomass for bio-pellet production lies in the variability of raw material composition and physical properties, which significantly affect combustion efficiency and calorific value [3], [4],[5]. Therefore, further studies are needed to optimize bio-pellet formulations and processing conditions to achieve superior combustion characteristics.

Previous studies have investigated various types of biomass, such as sawdust, coconut shells, rice straw, and water hyacinth, in the form of briquettes and bio-pellets. Research by Mahoro *et al.* [6] and Sebastine *et al.* [7] reported that a combination of alaban wood charcoal and rice husk yielded briquettes with good flame stability. Study by Subagyo et al [8] found that compression pressure affects the physical and combustion properties of gelam wood briquettes. Ibitoye *et al.*[9] revealed that particle size and feedstock composition influence burning rate and pellet density. Nonetheless, knowledge gaps remain regarding the synergistic effects between biomass composition and compression pressure on the physical and thermal properties of bio-pellets [3],[10]. This study seeks to answer the research question: How do combinations of gelam wood and rice husk composition, along with different compression pressures, affect the combustion characteristics and physical properties of bio-pellets? The hypothesis proposes that there exists an optimal composition and compression pressure that can maximize the thermal and physical performance of gelam wood–rice husk-based bio-pellets.

Gelam wood (*Melaleuca leucadendron*) is a local species in South Kalimantan that thrives in peatland and riverbanks, known for its durability and strength. It contains approximately 2.44% cellulose and shows promise as a biomass feedstock due to its density and stability [11]-[13]. On the other hand, rice husk is an abundant agricultural by-product with high silica content and a decent calorific value [14]-[16]. The combination of both materials is expected to produce bio-pellets with balanced thermal efficiency and structural integrity. In this study, variations in gelam wood and rice husk composition (100:0, 80:20, 60:40, 50:50, and 0:100) as well as compression pressures (60, 80, and 100 kg/cm^2) are evaluated to examine their effects on moisture content, ash content, fixed carbon, volatile matter, calorific value, ignition time, burning rate, and combustion temperature.

Accordingly, this research aims to investigate the effects of gelam wood–rice husk composition and compression pressure on the physical and combustion properties of bio-pellets. The proposed strategy involves an experimental approach using a combination of biomass composition and compression variations, tested in the laboratory through relevant physical and thermal parameters. The findings of this study are expected to contribute to the advancement of biomass energy technology in Indonesia and to maximize the potential of local biomass waste as a renewable energy source.

II. Material and Methods

1. Materials

The primary materials used in this study were gelam wood powder and rice husk, both sourced from Jejangkit Timur Village, Barito Kuala Regency, South Kalimantan. Gelam (*Melaleuca leucadendron Linn.*) is a native plant found in shallow peatlands and along riverbanks, containing approximately 2.44% cellulose. Rice husk is an agricultural by-product with a volatile matter content of 7.8%, carbon 1.33%, hydrogen 1.54%, oxygen 33.645%, and silica 16.98%. The raw material blending ratios used in this research were

G100–RH0, G80–RH20, G60–RH40, G50–RH50, and G0–RH100 (G: Gelam; RH: Rice Husk).

2. Methods

A. Tools and Materials

The tools used in this study include: pellet mold, 60-mesh sieve (0.250 mm), electric heater with a capacity of 500–1000 watts, infrared thermogun (Benetech GM320, China) with a temperature range of -50°C to 800°C, 30 cm stainless steel ruler, drying oven with a temperature range of 40–120°C, 25 cm stainless steel spatula, electric blender with a power of 200–400 watts, digital scale with a capacity of 5–10 kg, and digital stopwatch. The materials were sourced from Marabahan, Barito Kuala Regency, South Kalimantan Province, namely gelam wood sawdust and rice husks, as shown in Figure 1.

Fig. 1. (a) Gelam wood sawdust and (b) Rice husk.

B. Research Procedure

The research preparation, as shown in Figure 2a, began with compiling a list of materials used in the study and determining their respective costs. The primary materials used—gelam wood and rice husks—were sourced from Marabahan, Barito Kuala Regency, South Kalimantan Province.

The next stage, illustrated in Figure 2b, involved drying the gelam wood sawdust and rice husks prior to the molding process. Drying was carried out at a temperature of 50°C for 28 hours to reduce the moisture content. Following this, the dried materials were sieved using a 0.250 mm mesh, as shown in Figure 2c. The gelam sawdust and rice husks were then weighed and mixed according to the following compositions: 100% gelam wood + 0% rice husks, 80% gelam wood + 20% rice husks, 60% gelam wood + 40% rice husks, 50% gelam wood + 50% rice husks, and 0% gelam wood + 100% rice husks.

The mixing process was carried out as follows: the finely ground rice husks and gelam wood were placed into a stainless-steel container. A starch-based adhesive was dissolved in hot water until it formed a liquid paste. The dry material mix was gradually added and stirred thoroughly using a spatula or mechanical mixer. Water was added gradually to achieve an optimal moisture content of approximately 15% for the molding process. The homogeneity of the mixture was checked visually—its color and texture had to be uniform. If clumps or dry areas were present, mixing continued until the mixture was consistent. Once homogeneous, the mixture was ready for biopellet molding.

The molding process, shown in Figure 2d, involved forming cylindrical biopellets with a length of 3 cm and a diameter of 1 cm, under varying compression pressures of 60, 80, and 100 kg/cm².

The combustion characteristics of the wood pellets were tested at the Industrial Research and Standardization Center (BARISTAND) in Banjarbaru, as shown in Figure 2e. The physical properties of the pellets were evaluated to assess their combustion performance. For this stage, the raw materials were tested using a bomb calorimeter and furnace. Test results were recorded on data sheets, capturing values for moisture content, ash content, volatile matter, fixed carbon, and calorific value. Combustion tests were conducted to determine the burning characteristics of the biopellets, carried out at the Mechanical Engineering Laboratory, Lambung Mangkurat University, Banjarbaru, as illustrated in Figure 2f. The combustion tests used a specific combustion testing apparatus, shown in Figure 3.

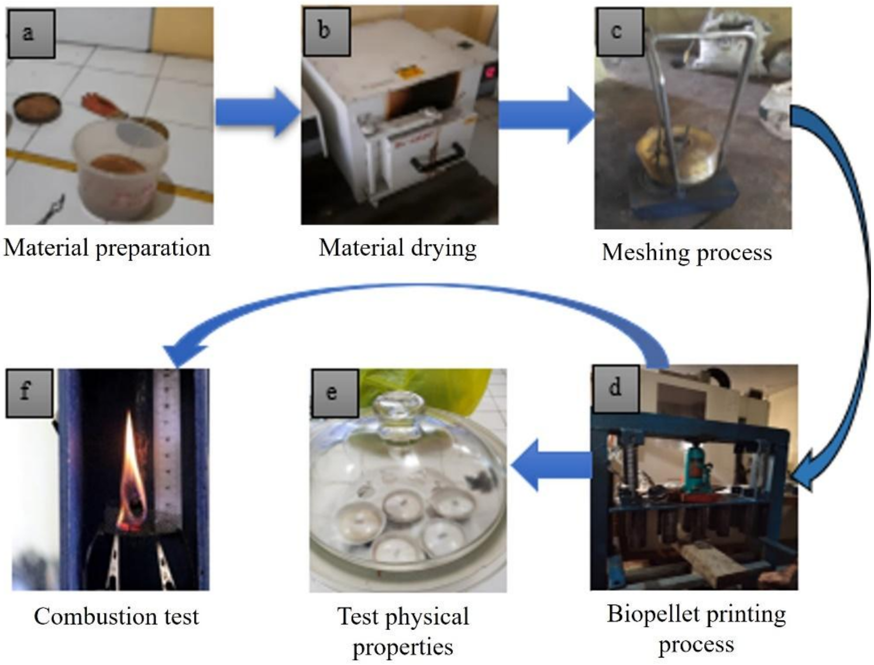


Fig. 2. Research procedure

C. Research Variables

The research variables in testing the physical properties and combustion characteristics of biopellets made from gelam wood and rice husks are as follows: (a). Independent variables include composition variations and pressure variations; (b). Dependent variables include moisture content, ash content, volatile matter, fixed carbon, calorific value, ignition time, combustion rate, and combustion temperature; and (c). Controlled variables include the testing temperature and the particle size, which was fixed at 60 mesh.

D. Bio-pellet Production and Testing

Bio-pellets were molded using a manual hydraulic press at compression pressures of 60, 80, and 100 kg/cm². Each composition and pressure variation was replicated three times to ensure data reproducibility. Figure 3 shows a manual-hydraulic vertical biopellet press that operates based on a vertical compression principle using a manual hydraulic jack (2) as its primary power source. The process begins by loading dry biomass into cylindrical steel molds (5) with a diameter of approximately 2.5 cm and a height of about 10 cm, accommodating a material weight of around 50–55 grams per mold. The hydraulic jack is then manually operated to push the pressing plate (4) downward, compressing the material tightly inside the mold. The return springs (3) assist in lifting the pressing plate back to its original position once the pressure is released. The main frame (1) supports the overall structure, while the base support (6) serves to hold the molds or guide the pellet discharge. This semi-manual tool requires no electricity, making it highly suitable for laboratory-scale applications. The unit is available and utilized at the Baristand Industrial Center in Banjarbaru, Indonesia, and can be easily replicated by other researchers using the same specifications.

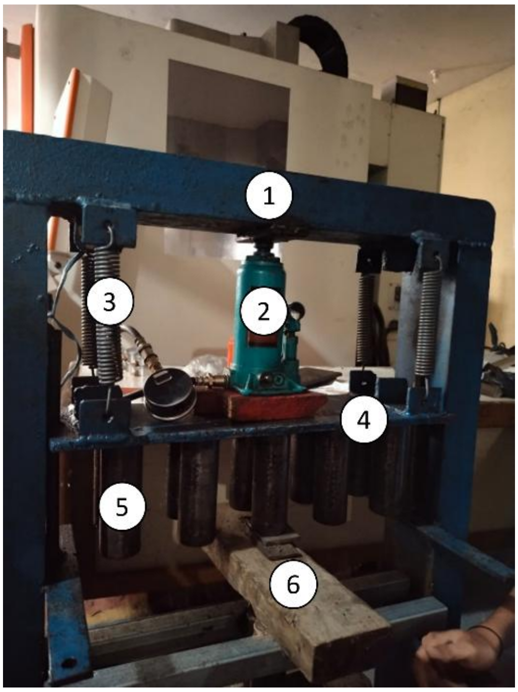


Fig. 3. Manual biopellet press machine at the Baristand Industrial Center in Banjarbaru, Indonesia

E. Physical Property Testing

The physical property testing of biopellets was conducted to evaluate the fundamental characteristics of the solid fuel produced. Moisture content was determined by measuring the weight difference of the sample before and after drying in an oven at 105°C for 24 hours, following the national standard SNI 8675:2018. This process aims to remove free moisture contained in the biopellets and provides an indication of the material's dryness level. Subsequently**,** ash content was measured by combusting the sample in a muffle furnace at 600°C for 3 hours, which burns off all organic components and leaves only mineral residues in the form of ash. Volatile matter was calculated based on the weight loss after rapid heating at 950°C for 7 minutes, representing the easily evaporated components in the fuel. Fixed carbon was determined indirectly using the formula: Fixed Carbon (%) = 100 – (Moisture + Ash + Volatile Matter), indicating the fraction of carbon remaining after the removal of moisture, ash, and volatile substances. Finally, the calorific value was measured using a bomb calorimeter, specifically the IKA C200 model (IKA Works, Staufen, Germany). This measurement involved combusting the sample in a sealed chamber and recording the temperature rise of the surrounding water, which was then multiplied by the calibration coefficient of the device to determine the total heat energy released. This testing is essential to assess the energy quality and efficiency of the produced biopellets.

F. Combustion Characteristic Testing

The combustion characteristics test of biopellets, as illustrated in Figure 4, is conducted using an electric heating system as the ignition source. The biopellet sample is placed on the heating element, which is activated via an on/off switch and powered by a transformer. Once the heater is turned on, the biopellet ignites, and the combustion process is monitored thermally using an infrared thermometer to record the maximum temperature and visually using a camera to capture the ignition time and the overall burning process. This test aims to determine the initial ignition time, burning rate, and maximum combustion temperature, which are crucial parameters for evaluating the thermal performance of biopellets as an alternative fuel. All tests were conducted at the Baristand Industrial Laboratory in Banjarbaru and the Manufacturing Engineering Laboratory at Lambung Mangkurat University. The technical standards and references used followed SNI 8675:2018 and the latest relevant scientific literature.

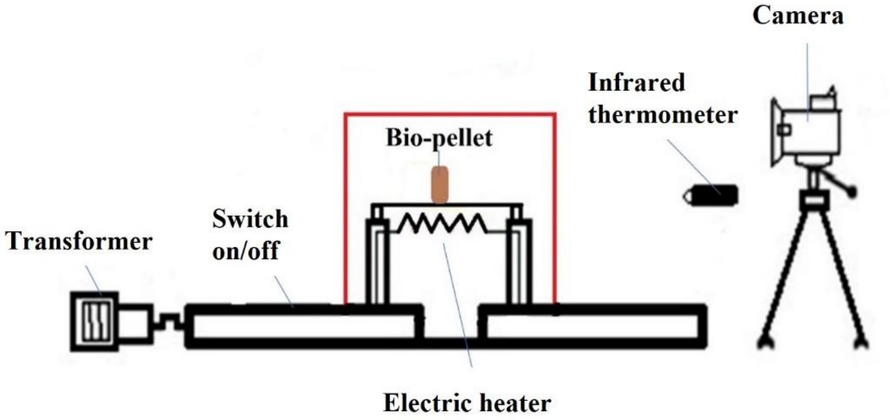


Fig. 4. Combustion characteristic testing

G. Analysis Statistics

To determine the significance of the effects of raw material composition and compaction pressure on the physical and combustion properties of the biopellets, statistical analysis was conducted using analysis of variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$). The analysis was performed using SPSS version 25 to evaluate whether variations in moisture content, ash content, volatile matter, fixed carbon, calorific value, ignition time, burning rate, and combustion temperature were statistically significant across different treatment groups. When significant differences were identified, Tukey's honest significant difference (HSD) post-hoc test was used to compare means between specific compositions and pressure levels. All experimental treatments were replicated three times, and results were expressed as mean ± standard deviation to reflect data consistency and variability. This statistical approach ensures the reliability and reproducibility of the experimental findings.

III. Results and Discussions

1. Results of Biopellet Characteristics and Combustion Tests

Figure 5 shows biopellet samples produced from five different raw material compositions consisting of gelam wood powder (G) and rice husk (RH), each sealed in clear plastic bags labeled G0–RH100, G50–RH50, G60–RH40, G80–RH20, and G100–RH0. All samples were compressed using the same compaction pressure of 100 kg/cm², as indicated on the labels attached to each bag. It is evident that the texture, color, and shape of the pellets vary depending on the material composition: G100–RH0 appears darker and denser, while G0–RH100 looks lighter in color and more fragile. These visual differences reflect variations in physical characteristics among the formulations, such as density, compactness, and mixture homogeneity [17], [18]. This documentation serves as qualitative support for evaluating the influence of raw material composition on the form and quality of the resulting biopellets.

Fig. 5. Pellets with various compositions

2. Moisture Content

The moisture content of biopellets is significantly influenced by the composition of raw materials and the applied compaction pressure, as shown in Figure 6. The G100–RH0 composition, consisting entirely of gelam wood, recorded the highest moisture content of 12.28% at 80 kg/cm², exceeding the maximum limit of 12% set by the Indonesian National Standard (SNI 8675:2018). In contrast, the lowest moisture content was recorded in the G0–RH100 composition, made solely of rice husk, with a value of only 0.98% at 60 kg/cm². Generally, a decreasing trend in moisture content is observed with increasing rice husk proportion in the mixture. This suggests that rice husk more readily releases moisture than gelam wood, likely due to its more porous and less dense structure. All composition variations containing rice husk, except G100–RH0 at 80 and 100 kg/cm², successfully met the moisture standard. These findings highlight the vital role of rice husk proportion in maintaining biopellet quality and the necessity of applying appropriate compaction pressure to keep moisture within the allowable limits.

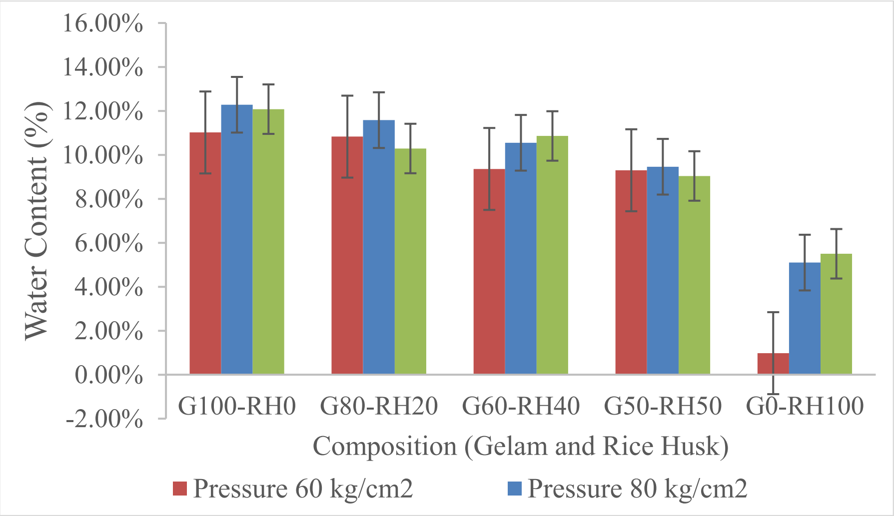


Fig. 6. Graph showing the relationship between the percentage of gelam wood–rice husk and compaction pressure on the moisture content of biopellets.

3. Ash Content

Figure 7 shows that the ash content of biopellets is highly affected by both the raw material composition and the compaction pressure. The lowest ash content was observed in G100–RH0 at 60 kg/cm², recorded at 2.47%, indicating that gelam wood contains low levels of non-combustible minerals. In contrast, the highest ash content was found in G0–RH100 at 80 kg/cm², reaching 20.93%, which reflects the high silica and inorganic content in rice husk [12],[13]. According to SNI 8675:2018, the maximum allowable ash content is ≤5%. Only two combinations met this standard: G100–RH0 and G80–RH20 at 80 kg/cm². This confirms that a higher rice husk fraction results in higher ash content, which can impair combustion performance and increase the risk of slag formation. Therefore, controlling the rice husk content is critical to ensure compliance with quality standards and maintain efficient usage.

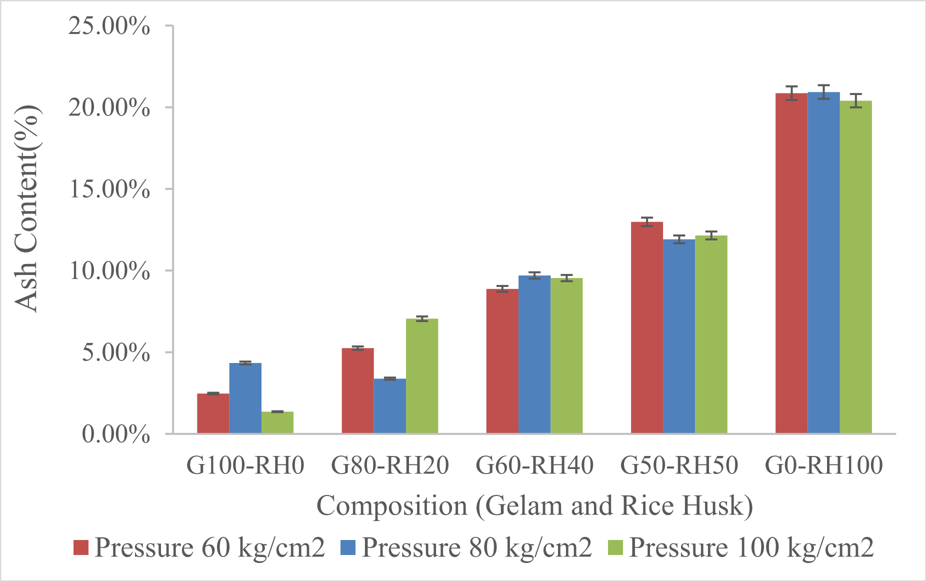


Fig. 7. Graph illustrating the relationship between the percentage of gelam wood–rice husk and compaction pressure on the ash content of biopellets.

4. Fixed Carbon

The fixed carbon content in biopellets is strongly influenced by the raw material composition and compaction pressure, as depicted in Figure 8. The highest value was obtained from G100–RH0 at 60 kg/cm², at 21.16%, reflecting the high fixed carbon content in gelam wood. Fixed carbon is a key indicator of the calorific value, directly contributing to energy release during combustion. As the proportion of rice husk increases, a significant decline in fixed carbon is observed, showing that rice husk has a lower fixed carbon content than gelam wood. Only G100–RH0 at 60 kg/cm² met the minimum fixed carbon requirement of ≥14% according to SNI 8675:2018. This implies that achieving high energy output and combustion efficiency requires a dominant proportion of gelam wood or pre-treatment of rice husk to enhance its fixed carbon content.

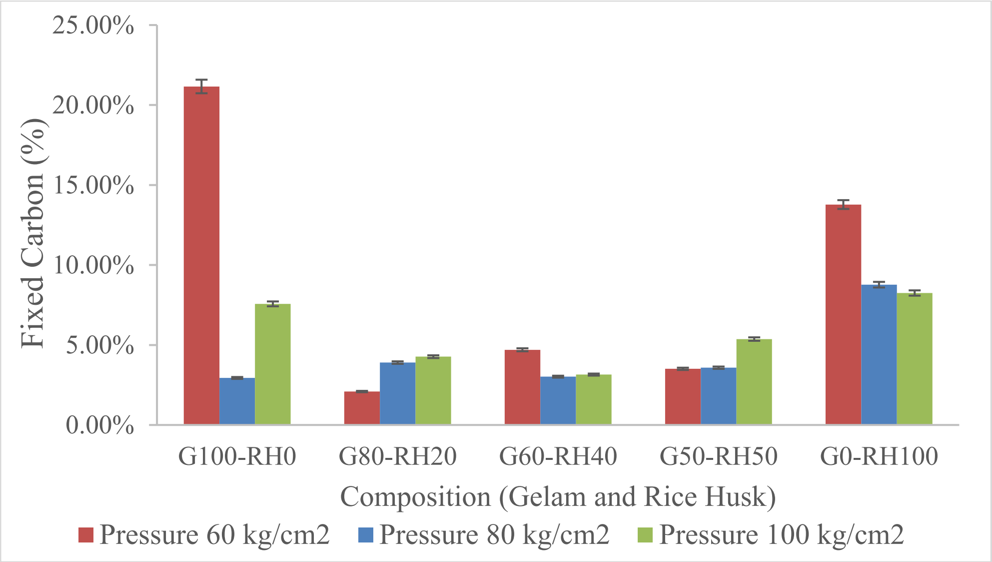


Fig. 8. Graph illustrating the relationship between the variation in gelam wood–rice husk percentage and compaction pressure on the fixed carbon content of biopellets.

5. Volatile Matter

Figure 9 illustrates that the volatile matter content in biopellets is significantly influenced by the composition and compaction pressure. G100–RH0 at 80 kg/cm² recorded the highest volatile content at 84.66%, indicating that gelam wood has a high level of volatiles, which facilitates ignition and rapid initial combustion. Conversely, G0–RH100 at 60 kg/cm² had the lowest value at 63.38%, indicating lower volatile content in rice husk, thus slower ignition. According to SNI 8675:2018, the maximum volatile matter allowed is 80%. Only G100–RH0 and G80–RH20 exceeded this threshold. Excessive volatile matter can result in rapid and unstable combustion, making it unsuitable for applications requiring gradual and efficient burning. Thus, selecting the appropriate raw material composition is crucial to balancing volatile content for stable performance.

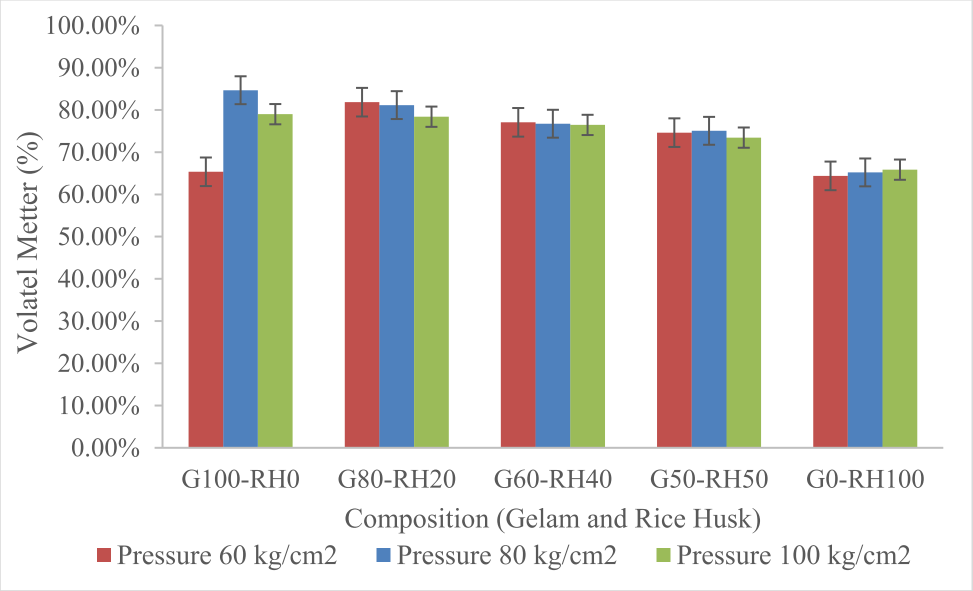


Fig. 9. Graph showing the relationship between the percentage of gelam wood–rice husk and compaction pressure on the volatile matter content of biopellets.

6. Calorific Value

Biopellet calorific value is highly influenced by the raw material composition and compaction pressure, as shown in Figure 10. The highest calorific value was achieved by G100–RH0 at 60 and 80 kg/cm², at 3967.977 cal, indicating that gelam wood provides more energy than rice husk. The lowest value was found in G0–RH100 at 80 kg/cm², at 3309.771 cal. None of the tested compositions met the SNI minimum calorific value of 4000 cal. This suggests a need for formula modification or the addition of high-energy additives to improve biopellet energy quality to meet standards and compete with conventional fuels.

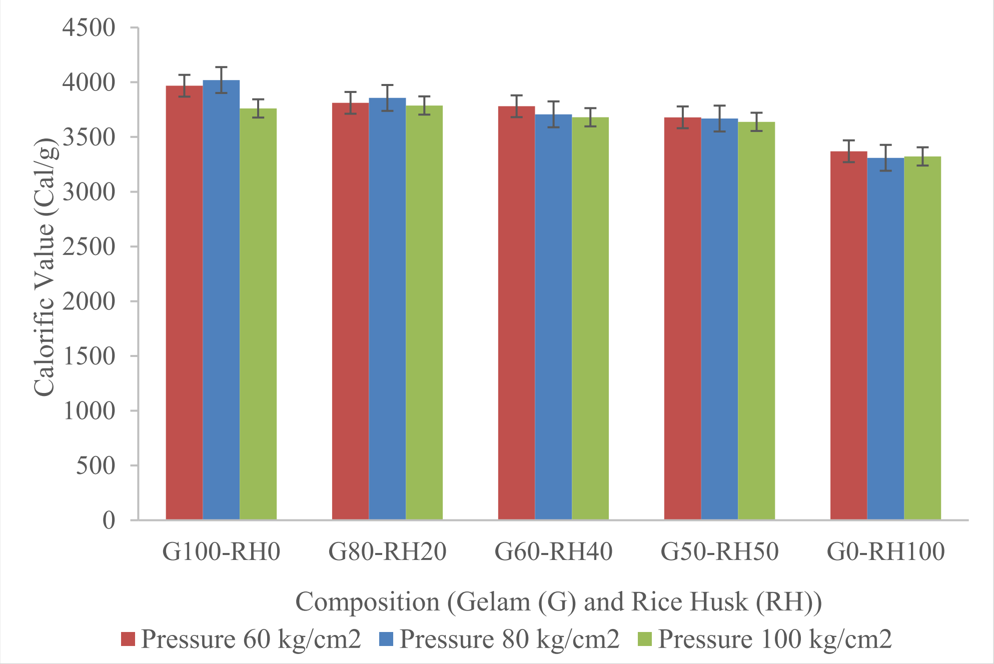


Fig. 10. Graph showing the relationship between the percentage of gelam wood–rice husk and compaction pressure on the calorific value of biopellets.

7. Initial Ignition

Figure 11 shows that the ignition time is significantly influenced by composition and compaction pressure. The fastest ignition occurred in G0–RH100 at 60 kg/cm², requiring only 52 seconds, due to the porous structure and high volatile content of rice husk. The slowest ignition occurred in G100–RH0 at 100 kg/cm², taking 135 seconds, as dense pellets hinder heat penetration and gas formation. In general, higher compaction pressure slows ignition due to increased density, which obstructs air flow. Therefore, achieving efficient ignition requires a balance between flammable materials and moderate pressure.

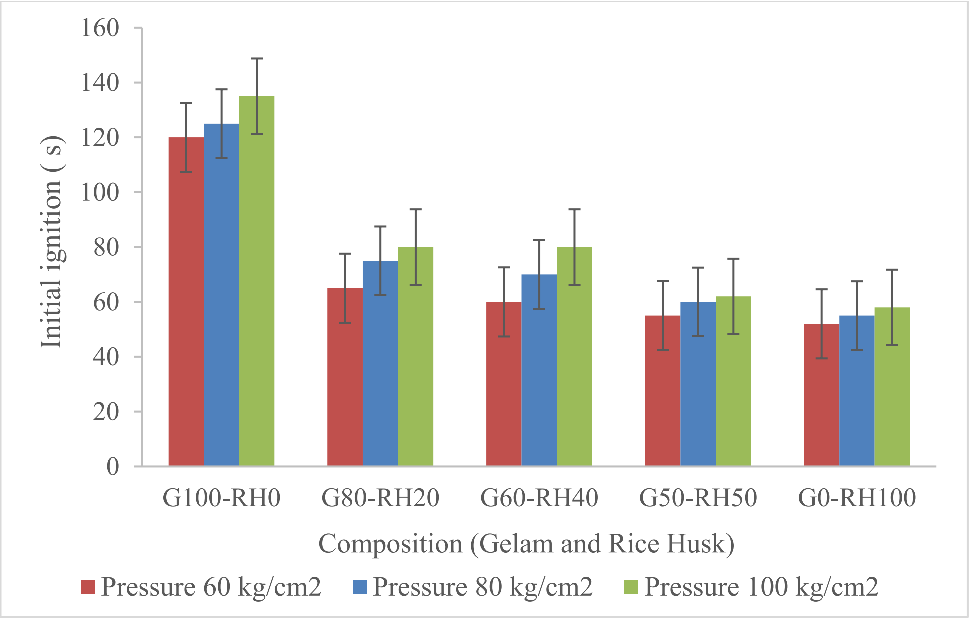


Fig. 11. Graph illustrating the relationship between the variation in gelam wood–rice husk percentage and compaction pressure on the initial ignition time of biopellets.

8. Burning Rate

The burning rate is influenced by both composition and pressure (Figure 12). The highest burning rate was observed in G0–RH100 at 60 kg/cm² (0.003778 g/s), attributed to rice husk's porous structure and high volatiles. The lowest rate was in G100–RH0 at 100 kg/cm² (0.002072 g/s), indicating that highly compacted gelam wood pellets burn more slowly due to restricted oxygen diffusion. Thus, optimal biopellet performance requires a balance between fuel composition and suitable densification.

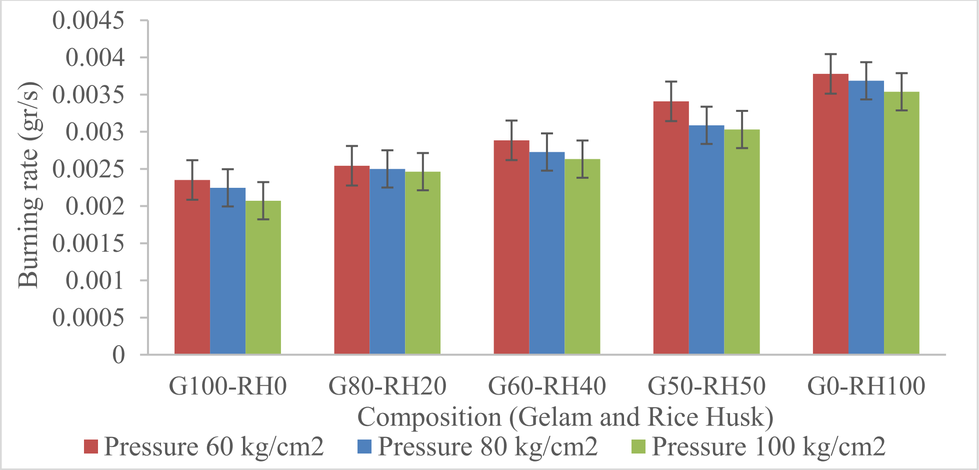


Fig. 12. Graph illustrating the relationship between the variation in gelam wood–rice husk percentage and compaction pressure on the burning rate of biopellets.

9. Combustion Temperature

Figure 13 demonstrates that combustion temperature is significantly affected by composition and pressure. The highest temperature (290°C) was recorded for G100–RH0 at 100 kg/cm², due to high fixed carbon and energy density in compacted gelam wood. The lowest temperature (249°C) was found in G0–RH100 at 60 kg/cm², reflecting the lower energy content of rice husk. These findings confirm that gelam-based biopellets exhibit superior thermal performance, especially at higher compaction pressures.

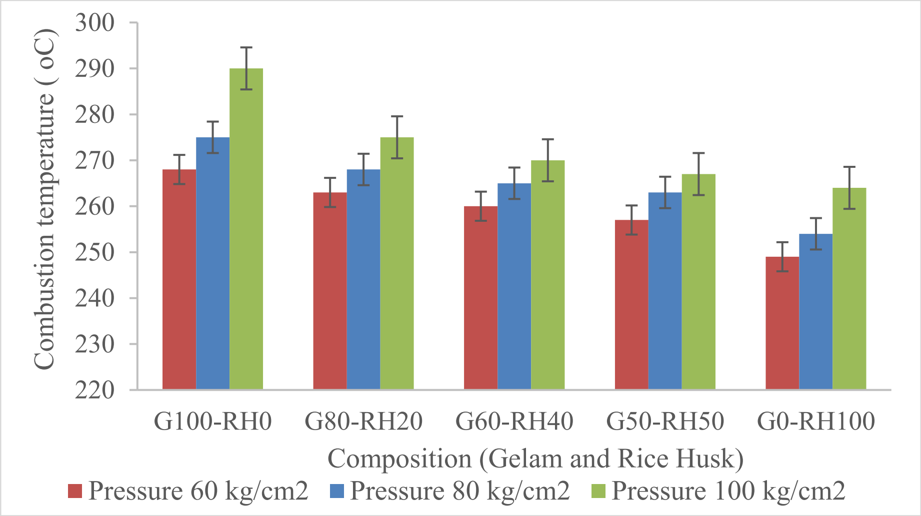


Fig. 13. Graph showing the relationship between the percentage of gelam wood–rice husk and compaction pressure on the combustion temperature.

10. Discussion

The ANOVA results show that Table 1 for various bio-pellet parameters indicates that all tested variables—including water content, ash content, fixed carbon, volatile matter, calorific value, ignition time, burning rate, and combustion temperature—exhibited infinite F-values (∞) and p-values of 0.0. This suggests statistically significant differences among the treatment groups for each parameter [19], [20]. In other words, the variations in raw material composition and compaction pressure used in this study had a significant effect on the physical properties and combustion characteristics of the resulting bio-pellets.

Table 1. Conclusion of ANOVA test

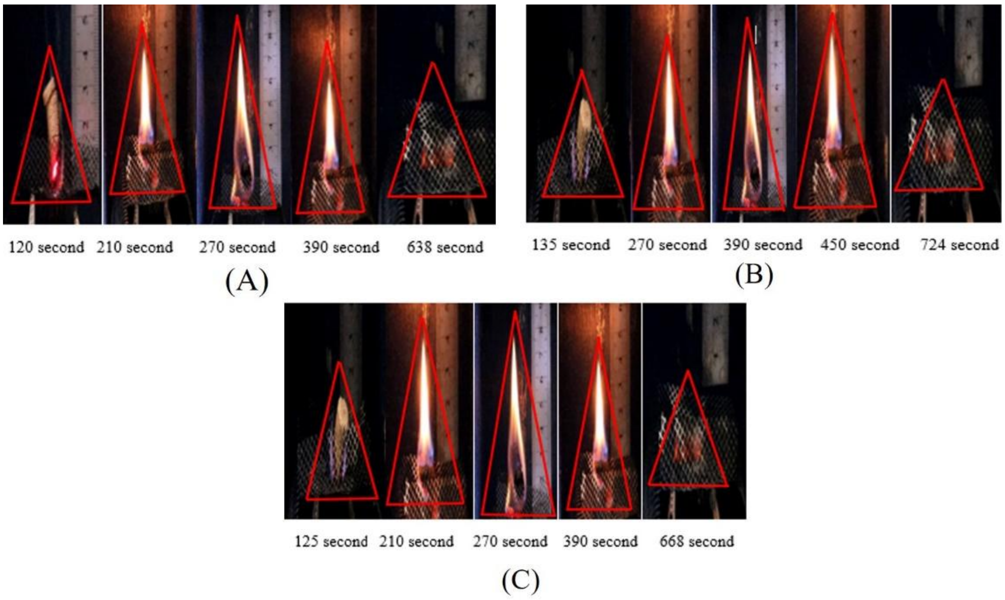
Stage	Parameter	F-Value	p-value	Significance
1	Water content	335.223	0.0	Significance
2	Ash content	335.139	0.0	Significance
3	Fixed content	335.453	0.0	Significance
4	Volatile matter	329.747	0.0	Significance
5	Calorific value	1428.816	0.0	Significance
6	Initial ignition	0.061	0.9803	Not Significance
7	Burning rate	335.983	0.0	Significance
8	Combustion temperature	788.395	0.0	Significance

The Tukey HSD test results show Table 2, that nearly all treatment pairs across each parameter—such as water content, ash content, fixed carbon, volatile matter, calorific value, ignition time, burning rate, and combustion temperature—exhibited statistically significant differences in mean values, indicated by a p-adjusted value of 0.0 and a reject status of True. This indicates that variations in raw material composition and compaction pressure produced distinct and significant effects on the bio-pellet characteristics [21], [22]. These significant differences, reflected in the mean differences between treatment combinations (meandiff), consistently observed across all parameters, reinforce the finding that changes in composition and pressure have a direct influence on the physical quality and combustion performance of the bio-pellets.

Table 2. Tukey HSD test results

Stage	Parameter	Significant Comparisons	Total Comparison	Significance Ratio
1	Water content	105	105	105/105
2	Ash content	105	105	105/105
3	Fixed content	105	105	105/105
4	Volatile matter	105	105	105/105
5	Calorific value	105	105	105/105
6	Initial ignition	102	105	102/105
7	Burning rate	105	105	105/105
8	Combustion temperature	102	105	102/105

The visual sequence of flame development in biopellets with different compositions over time reflects key combustion characteristics such as intensity, stability, and duration (Figure 14). In the initial stage (120–135 seconds), a small red flame emerges, indicating ignition. As time progresses (210–270 seconds), the flame becomes brighter and taller, signifying the active combustion phase with peak energy release. The flame reaches its apex around 270–390 seconds, characterized by strong, symmetrical orange-yellow flames, suggesting efficient combustion and good oxygen availability. The flame weakens after 390–450 seconds and eventually extinguishes after 600 seconds, indicating most of the fuel has been converted to ash or char. Minor variations in burnout time among samples suggest that differences in raw material composition and compaction pressure affect flame propagation and stability [23].



(A)

(B)

(C)

Fig. 14. Flame visualization of the G100–RH0 composition with Rice Husk at compaction pressures of (A). 60 kg/cm², (B). 80 kg/cm² and (C). 100 kg/cm².

Figure 15 illustrates the flame dynamics of biopellets from the ignition phase to extinction, observed in three different samples tested for over 600 seconds. In the early stage (65–80 seconds), the ignition process begins with the appearance of glowing red spots and a small flame at the base of the pellet. By 270 seconds, the flame grows rapidly into a tall conical shape, indicating the optimal active combustion phase, characterized by orange to yellow flame colors. Between 390 and 450 seconds, the flame becomes stable and exhibits maximum heat release, marked by an upright and intense flame. Following this, a gradual decline in flame intensity occurs, as indicated by a shrinking flame size and dimmer coloration, leading to complete extinction at around 590–609 seconds. This combustion pattern demonstrates that the biopellets used possess good combustion properties, with prolonged burn duration, stable peak flame, and relatively complete combustion, as evidenced by the minimal residue at the final stage [24]-[26]. Variations in initial ignition time and total combustion duration among the samples are likely influenced by differences in material composition and compaction density.

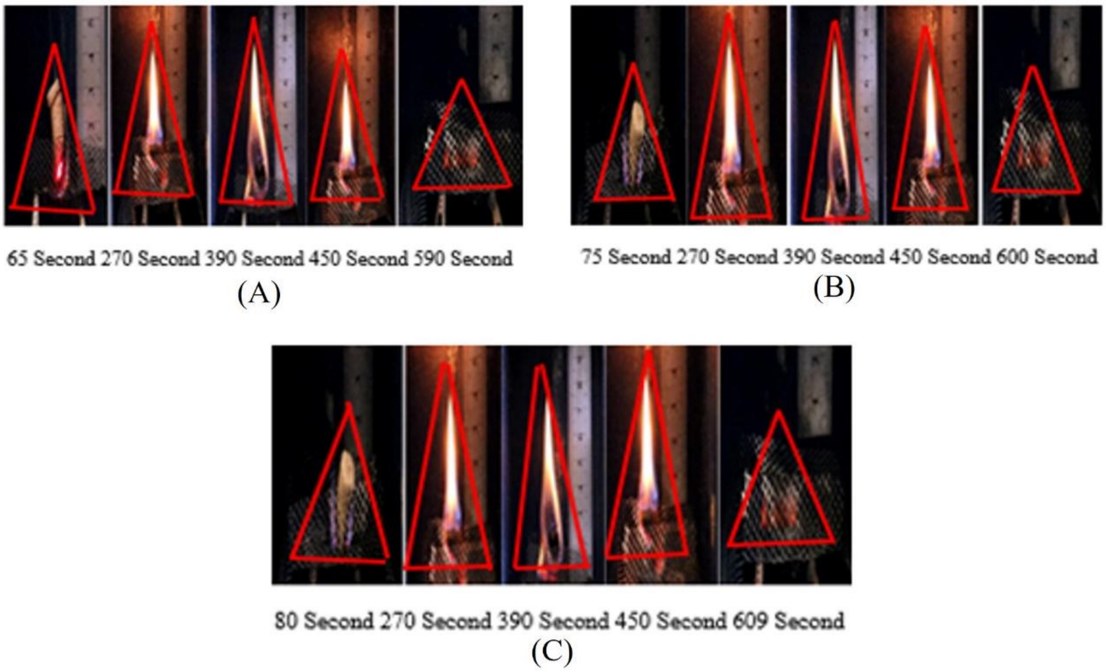


Fig. 15. Flame visualization of the G80–RH20 combustion composition at compaction pressures of: (A). 60 kg/cm², (B). 80 kg/cm², and (C). 100 kg/cm².

The results confirm that increasing the rice husk fraction (RH) influences all physical and combustion parameters. Ash content, fixed carbon, volatile matter, burning rate, combustion temperature, and ignition time increase with RH proportion [27], [28] while moisture and calorific value decrease. This aligns with the known properties of rice husk, which has low moisture and high silica and cellulose content.

Microscopic observations (Figure 16) show the effect of compaction pressure (60, 80, 100 kg/cm²) on the microstructure of gelam–rice husk biopellets. At 60 kg/cm², large gaps and coarse grains are visible, indicating low density. At 80 kg/cm², the gaps decrease, and particle distribution becomes more uniform, suggesting effective compaction. At 100 kg/cm², the gaps nearly disappear, and particles become highly compacted, indicating optimal densification. This suggests that increased pressure improves microstructure by reducing porosity and increasing particle cohesion.

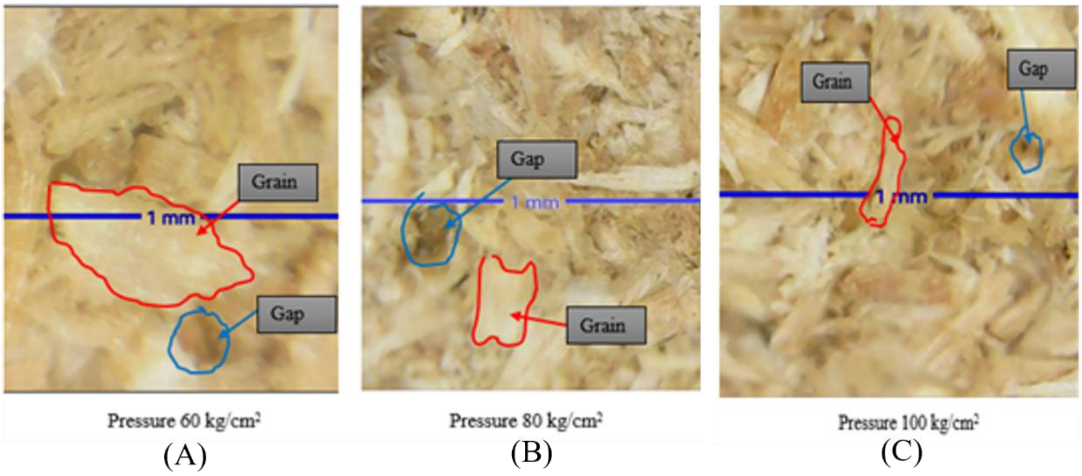


Fig. 16. Gaps between biopellet particles in the G100–RH0 composition at compaction pressures of: (A). 60 kg/cm², (B). 80 kg/cm² and (C). 100 kg/cm².

Figure 17 shows a detailed microscopic view of grain distribution and interparticle gaps in G80–RH20 biopellets. At 60 kg/cm², gelam and husk grains are loosely bound with wide gaps. At 80 kg/cm², contact between particles increases, although porosity remains. At 100 kg/cm², particle distribution is dense and uniform, gaps are minimized, and better interlocking is observed. These results indicate that higher compaction pressure enhances particle bonding and reduces porosity, potentially improving mechanical strength and combustion efficiency.

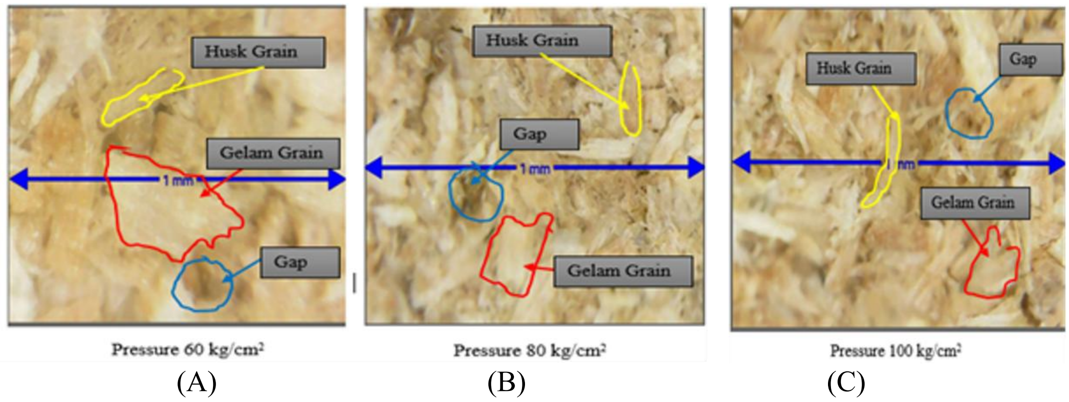


Fig. 17. Gaps between particles in the G80–RH20 biopellet composition at compaction pressures of: (A). 60 kg/cm², (B). 80 kg/cm² and (C). 100 kg/cm².

High compaction pressure significantly affects combustion parameters. It produces denser pellets with smaller gaps, enhancing heat transfer through conduction and radiation, but delaying ignition due to restricted airflow. These phenomena are supported by flame visualizations and microstructure observations, showing a negative correlation between gap size and pressure [29].

A new insight from this study is that both composition and compaction pressure not only influence physical characteristics but also modulate combustion dynamics through internal material structure. Optimizing these two parameters is key in developing efficient and sustainable biopellets using local biomass waste such as gelam wood and rice husk [26], [25].

IV. Conclusions

This study demonstrates that the composition of gelam wood and rice husk, combined with molding pressure, significantly influences the physical and combustion properties of biopellets. The lowest moisture content was obtained in G0–RH100 at 60 kg/cm² (0.98%), while the highest was in G100–RH0 at 80 kg/cm² (12.28%). Ash content increased with rice husk fraction, reaching 20.93% in G0–RH100 at 80 kg/cm², whereas the lowest was 2.47% in G100–RH0 at 60 kg/cm². The highest calorific value was 3967.98 cal/g (G100–RH0 at 60–80 kg/cm²), while the lowest was 3309.77 cal/g (G0–RH100 at 80 kg/cm²), showing that none of the formulations fully met the SNI minimum of 4000 cal/g. Combustion tests revealed that ignition was fastest in G0–RH100 at 60 kg/cm² (52 s), while the slowest ignition occurred in G100–RH0 at 100 kg/cm² (135 s). The maximum combustion temperature reached 290 °C in G100–RH0 at 100 kg/cm².

These findings indicate that a higher rice husk fraction accelerates ignition and burning rate but reduces calorific value, while greater molding pressure enhances density and combustion temperature but delays ignition. Limitations: This study was conducted at the laboratory scale with limited pressure variations (60, 80, 100 kg/cm²) and without long-term durability testing or emission analysis. Further research is needed to explore larger-scale pellet production, the addition of binders or high-calorific additives, and environmental impact assessments to align with industrial and regulatory standards.

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