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Research Article

Analysis of pine resin potential as an additive on the physical and combustion characteristics of coconut shell bio-briquettes

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Abstract. Indonesia is still heavily reliant on fossil fuels; however, the growth of renewable energy sources, such as biomass, offers a promising alternative energy source. Because of its high calorific value (6,500–7,600 kcal/kg) and widespread availability, coconut shell was selected for this investigation as bio-briquette. This study aimed to analyse how the properties of coconut shell bio-briquettes were affected by the carbonization time and the concentration of pine resin added as an additive. This study investigates the production and characterization of coconut shell bio-briquettes as a sustainable solid fuel. Coconut shell charcoal was carbonized at 600°C for 120, 180, and 240 min, then ground and sieved to a particle size of –60+80 mesh. Tapioca starch (5%) was used as a binder, and pine resin, derived from *Pinus merkusii*, was applied externally as an ignition-enhancing additive at concentrations of 2%, 4%, 6%, 8%, and 10%. The resulting bio-briquettes were analyzed for proximate parameters (moisture, ash, volatile matter, and fixed carbon) and combustion characteristics (calorific value, ignition time, and burning rate) following SNI 01-6235-2000 standards. At a carbonisation time of 240 min and a concentration of 8% pine resin, the best results were obtained in terms of moisture content (3.87%), ash (3%), volatile matter (10.80%), fixed carbon (82.33%), calorific value (7,761.21 cal/g), ignition time (63 s), and burning rate (0.1093 g/min). These findings demonstrate that pine resin can effectively enhance ignition performance without compromising the combustion stability. Coconut shell biobriquettes with the addition of pine resin show high potential as an environmentally friendly alternative fuel because they produce a high calorific value, low moisture and ash content, and fixed carbon content that meets SNI 01-6235-2000 standards and ISO 17225 for solid biofuel. These characteristic indicate that bio-briquettes can be used as a renewable energy source to replace fossil fuels for household needs and small-scale industries.

Keywords: biobriquettes, carbonization, coconut shells, pine resin, tapioca

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1. Introduction

The increasing global demand for energy, coupled with growing concerns regarding the environmental consequences of fossil fuel consumption, has intensified the utilization of sustainable and renewable energy alternatives such as biofuels. A sustainable energy system should support economic growth, be competitive, and effective, ensure energy security, and protect the environment and human health (Kalak, 2023). Biomass is an optimal renewable energy resource characterized by its inherent sustainability, abundant reserves, low cost, and carbon-neutral properties (Dai *et al*., 2019). This environmentally sustainable energy source accounts for approximately 10% of the global annual energy consumption. The convergence of global demographic expansion, diminishing fossil fuel reserves, escalating environmental degradation, and volatile petroleum pricing has intensified scholarly and policy attention toward renewable energy (RE) development. Biomass energy has considerable potential as a fossil fuel substitute for mitigating greenhouse gas (GHG) emissions. It functions as a derivative of solar energy through the photosynthetic process, whereby vegetation assimilates atmospheric carbon dioxide and water as nutritional substrates and energy inputs, subsequently synthesizing various hydrocarbon compounds (Dai *et al*., 2019; Palanisamy *et al*., 2023; Slade *et al*., 2014). According to the International Energy Agency (IEA), biomass currently contributes approximately 6% to global primary energy consumption, with a substantial share in developing regions, where it remains a principal source of household and industrial energy (IEA, 2024; Junginger *et al*., 2019).

Among the various biomass resources, coconut shell is promising due to its abundance in tropical countries and favorable fuel properties, including a high calorific value in the range of 30 MJ/kg (Espina *et al*., 2022). However, the direct use of raw coconut shell biomass is hindered by its low bulk density, high moisture content, and volatile matter, which collectively lower their combustion efficiency and increase pollutant emissions (Esmar, 2011; Kumar *et al*., 2021; Sarker *et al*., 2023).

Indonesia, one of the largest coconut-producing countries, has over 3.3 million hectares of coconut plantations, generating vast quantities of coconut shell waste (Ditjenbun, 2023). Despite its energy potential, the inefficient combustion of this biomass often results in significant energy losses and contributes to indoor air pollution (Esmar, 2011; Kumar *et al*., 2021).

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Briquetting technology offers an effective pathway to valorize coconut shell waste by converting it into compact, energy-dense, and clean-burning solid fuel. The briquetting process enhances fuel handling, storage, enhanced homogeneity of blends, and combustion characteristics (Ibitoye *et al.*, 2022; Kebede *et al.*, 2022; Sarker *et* al., 2023).

Biomass briquettes can be further optimized by using adhesives to improve the bond between particles, which also affects the combustion performance *(Kpalo et al., 2020; Obi et al.*, 2022). Tapioca starch, a biodegradable and thermally stable binder, is commonly employed because of its availability and compatibility with various biomass types (Asri, 2013; Obi *et al.*, 2022; Amin *et al.*, 2017). Pine resin, derived from *Pinus merkusii*, has recently emerged as a promising additive due to its high flammability, adhesive properties, and capacity to facilitate quick ignition (Kuspradini *et al.*, 2018; Ningsih *et al.*, 2023).

Previous research has primarily focused on incorporating pine resin into briquette matrices to enhance their thermal properties. For example, (Pari *et al.*, 2023) reported improvements in calorific value and ignition time with increasing pine resin content, although excessive resin levels accelerated combustion and reduced burning time. Previous studies (Ningsih *et al.*, 2023), (Herjunata *et al.*, 2020) have reinforced the potential of pine resin, reporting significant increases in calorific value while maintaining low ash and moisture content that align with international and national fuel standards. Despite these advantages, the findings also highlight that increasing resin content may elevate volatile matter levels and lower fixed carbon, suggesting a trade-off between energy density and combustion stability. This highlights the importance of optimizing the pine resin concentration to balance ignition efficiency and sustainable performance. However, these studies have largely explored pine resin as an internal additive or binder blended into biomass mixtures.

The present study introduces a novel approach to bio-briquette optimization by evaluating the efficacy of pine resin when applied externally as an ignition-enhancing surface coating rather than as a conventional internal binder. This method aims to facilitate rapid ignition time without significantly altering the combustion rate, thereby preserving fuel consumption during the burning process. To date, no systematic investigation has been conducted to assess the effects of pine resin as an external ignition layer on the combustion behavior of bio-briquettes.

In parallel, this study addresses another critical but underexplored factor influencing briquette performance: the carbonization time. The length of the carbonization process may have a direct impact on the physicochemical characteristics of the resulting charcoal, particularly the proportions of fixed carbon and volatile matter, which in turn affect the calorific value, ignition time, and burning time of bio-briquette. Although prior studies have acknowledged the importance of carbonization, few have examined its interactions with binder compositions and surface ignition aids. By evaluating these two parameters in combination, this study aims to develop an optimized formulation for high-performance coconut shell briquettes using tapioca starch as a binder with the addition of pine resin, which can accelerate the initial ignition time of the bio-briquettes.

2. Material and Methods

2.1 Materials and Apparatus

The materials used in this study included coconut shell charcoal was obtained from UMKM Arang Batok Slamet, Malang (Indonesia), tapioca flour of the Rose Brand, pine resin derived from gondorukem (Grade Pertama (WW)) dan turpentine oil (Grade A) obtained from Jaya Mandiri Pinus, Surabaya (Indonesia), and aquadest. The equipment used included an oven, furnace, hydraulic press, cylindrical iron mold (d = 4 cm, h = 5 cm), desiccator, digital balance, 20 ml crucible cup, 60 and 80 mesh sieve screens, mortar and pestle, electric pan, grinder, moisture analyzer, drum carbonization, bomb calorimeter, torch, spatula, and stopwatch.

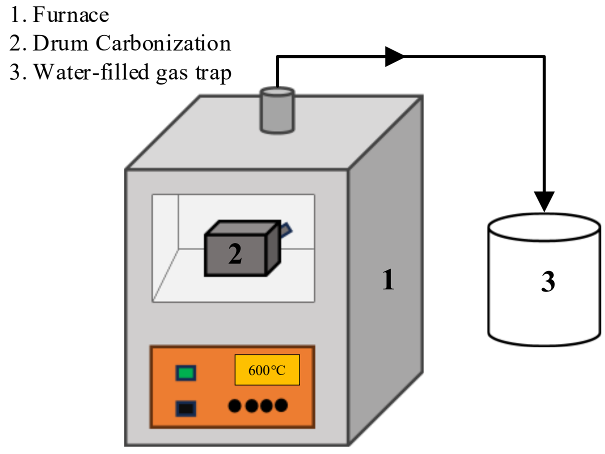


Fig. 1 Schematic diagram of carbonization reactor

2.2 Methods

2.2.1 Raw Material Charcoal Testing

This stage involved testing the characteristics of the raw material, coconut shell charcoal, including its moisture, ash, volatile matter, and fixed carbon contents. The purpose of this test was to evaluate whether the raw material complies with SNI 1683:2021 standards before proceeding to the next stage.

2.2.2 Carbonization of Raw Material Charcoal

The carbonization process was carried out by heating coconut shell charcoal in a furnace at 600°C for three different processing times: 120, 180, and 240 min. This process aims to increase the fixed carbon content and reduce the concentration of volatiles contained in the raw material. After carbonization, the resulting charcoal was reduced in size using a stone mortar, followed by a mechanical grinder to ensure a uniform particle size. The fine charcoal was then screened to obtain particles with a size of -60 +80 mesh for briquette production. Figure 1 illustrates a schematic diagram of the carbonization process apparatus.

2.2.3 Briquette Production

Briquette processing began after the preparation of coconut shell charcoal powder, tapioca adhesive, and pine resin. Tapioca adhesive was used as a binder and was prepared by mixing tapioca flour and aquadest in a ratio of 1:8. The pine resin adhesive was prepared by mixing gondorukem and turpentine oil in a 1:4 ratio. In this study, the pine resin was varied in each sample. The first layer consisted of coconut shell bio-briquettes with tapioca adhesive and without the addition of pine resin (0%), whereas the second layer was varied according to the pine concentration of 2%, 4%, 6%, 8%, and 10%. Each sample with a pine resin variation was combined with a 0% pine resin bio-briquette layer to maintain combustion quality. The pine resin

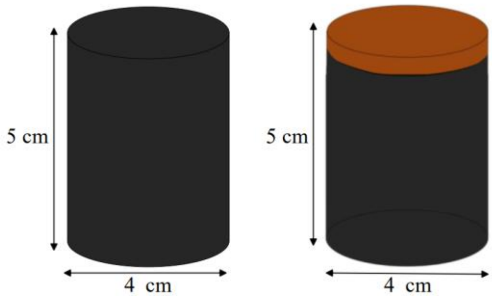


Fig. 2 Schematic representation of the briquette mold and pressing configuration

coating was only used at 5%, serving as a starter to accelerate the ignition time. The bio-briquette molding scheme is shown in Figure 2.

2.2.4 Briquette Characteristics Analysis

In this procedure, the moisture, ash, volatile matter, fixed carbon contents, calorific value, initial ignition time, and combustion rate were measured.

a. Moisture Content

Moisture content is defined as the ratio of moisture to the dry weight of the solid fuel. High water content requires energy for high water evaporation, which can reduce the calorific value (Ningsih *et al*., 2023). Moisture content testing was performed using a moisture balance by placing ± 1 g of sample on an aluminum pan and then closing it to start the moisture content analysis by heating it to a temperature of ± 115 ˚C. The test results are displayed on the display within a time range of 2 - 10 min (Rodhiyah *et al*., 2024).

b. Ash Content

Ash is the material that remains after combustion process has taken place, reaching a constant weight and no longer containing carbon (Fansyuri *et al*., 2023). Approximately 1 g of the sample was placed in a crucible and heated to 500 ˚C for 1 h. Further combustion was carried out at 750 ˚C for 2 h. The sample was weighed, and the ash content was calculated using Equation 1, based on ASTM D-3174 (2012) (Ajimotokan *et al*., 2019; Ningsih *et al*., 2023; Pari *et al*., 2023; Tomen *et al*., 2023).

$$Ash\ Content\ (\%)\ = \frac{A}{B} \qquad (1)$$

where: A is the mass of ash from combustion (g) and B is the mass of the sample before combustion (g).

c. Volatile matter (VM)

High volatile matter values cause briquettes to burn more easily and ignite, thereby increasing the combustion rate (Novalinda *et al*., 2022). Samples of ±1 g were heated in a furnace at 950 ˚C for 7 min. The percentage of volatile matter was calculated using Equation 2 and 3 of ASTM D-3175 (2018) (Ningsih *et al*., 2023; Pari *et al*., 2023; Tomen *et al*., 2023).

$$\text{Lost weight (\%)} = \frac{\text{B} - \text{C}}{\text{A}} \qquad (2)$$

$$\text{VM (\%)} = \text{lost weight} - \text{moisture content} \qquad (3)$$

where: A is the mass of the initial sample before heating, B is the mass of the cup with the lid containing the sample before heating, and C is the mass of the cup with the lid containing the sample after heating in the furnace.

d. Fixed Carbon (FC)

The fixed carbon value was determined based on proximate analysis, which includes the moisture, volatile matter, and ash content. A high carbon value optimizes the heating value *(Bot et al*., 2023). The fixed carbon value was determined using Equation 4 (Ajimotokan *et al*., 2019; Ibitoye *et al*., 2022; Kebede *et al*., 2022; Ningsih *et al*., 2023; Pari *et al*., 2023).

$$FC\ (\%) = 100 - (\%\ water + \%\ ash + \%\ VM) \qquad (4)$$

e. Calorific Value

The calorific value is the primary indicator for determining fuel quality. The calorific value is defined as the maximum energy released by a fuel per unit mass through complete combustion (Adeleke *et al*., 2023; Almu *et al*., 2014). Calorific value testing was performed according to SNI 01-6235-2000, which utilizes a bomb calorimeter.

f. Ignition Time

The ignition time describes the time required for a briquette to produce a stable flame when in contact with a fire source (Palanisamy *et al*., 2023). The measurement was started when the briquette came into contact with the fire source until a fire was evenly formed on the surface of the briquette (Agussalim *et al*., 2022).

g. Combustion Rate

The combustion rate testing was conducted to evaluate the fuel quality and efficiency (Almu *et al*., 2014; Palanisamy *et al*., 2023). The combustion rate was calculated by dividing the combustion time by the mass of the residual combustion products. The combustion rate is calculated mathematically using Equation 5 (Adam *et al*., 2021; Agussalim *et al*., 2022; Espina *et al*., 2022; Mohammed & Olugbade, 2015; Ningsih *et al*., 2023; Pratama & Praswanto, 2022).

$$Combustion\ rate\ \left(\frac{g}{min}\right) = \frac{A - B}{t} \qquad (5)$$

where A is the initial sample weight (g), B is the sample weight after combustion (g), and t is the combustion time (min).

3. Result and Discussion

3.1 Characteristics of Coconut Shell Charcoal Raw Materials

This study involves the proximate analysis of raw coconut shell material to test its suitability for solid fuel specifications. The main raw material that is the object of this research is coconut shell charcoal. **Table 1** shows the test results of the coconut shell charcoal raw material in terms of moisture, ash, volatile matter, and fixed carbon content.

According to Table 1, the coconut shell charcoal used as raw material in this study shows significant changes in its proximate characteristics after carbonization. This also indicates that an increase in carbonization time causes a decrease in the moisture content and volatile matter, as well as an increase in the fixed carbon value. The decrease in moisture content and volatile matter is mainly due to water evaporation caused by the high-temperature operation in the carbonization process. In addition, the effectiveness of carbonization can reduce volatile compounds through a limited air mechanism (Gobel & Arief, 2022; Kipngetich *et al*., 2023; Shafiyya *et al*., 2022). Although the

Table 1
Characteristics of coconut shell charcoal raw materials

Duration of Carbonization (minutes)	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)
0	6.985	2.000	28.170	62.85
120	3.967	2.000	13.700	80.33
180	3.793	2.667	11.874	81.67
240	3.228	2.667	11.439	82.67

ash content increases from 2.00% to 2.67%, all characteristic parameters are still within the range specified by the SNI 1683:2021 specifications. This indicates that the charcoal produced under these conditions is suitable as a raw material for producing high-quality bio-briquettes.

Moreover, according to Table 1, increasing the carbonization time can indeed improve the material characteristics, including a reduction in moisture content and volatile matter content. However, the ash content parameter increases, which has a negative impact on the combustion quality. The ash content in biomass that has undergone carbonization tends to be higher due to the deposition of volatile compounds during the process, as well as reactions between steam and carbon that significantly reduce the mass of the biomass. This mass reduction is accompanied by an increase in carbon content and the release of heteroatoms such as oxygen (O), nitrogen (N), hydrogen (H), and sulfur (S) (Fadlurrahman *et al.*, 2024; Hasibuan & Pardede, 2023; Junary *et al.*, 2015; Kipngetich *et al.*, 2023).

The results indicate that increasing carbonization time from 120 to 240 minutes progressively improves the fuel characteristics of the coconut shell charcoal, as reflected by reduced volatile matter and increased fixed carbon content. At 240 minutes, devolatilization has proceeded sufficiently to enhance the calorific value while maintaining combustion stability. Beyond this duration, further extension of carbonization time at a constant temperature of 600°C is unlikely to yield significant additional improvement in fixed carbon content, as most thermally labile components have already been removed. Prolonged carbonization may instead lead to reduced charcoal yield due to continued mass loss, increased ash concentration relative to remaining mass, and higher process energy consumption without proportional enhancement in fuel performance. Therefore, from the standpoint of fuel optimization and processing efficiency, a carbonization time of 240 minutes represents a practical balance between improved combustion properties and energy input.

3.2 Proximate Analysis of Bio-briquettes

This study evaluates the most important proximate characteristics of bio-briquette to determine its combustion properties. Figure 3 compiles all the proximate properties of bio-briquettes produced in this study, including the moisture content, ash content, volatile matter, and fixed carbon.

Figure 3(a) explains that an increase in the carbonization time tends to reduce the moisture content. The moisture content of bio-briquettes ranges from 3.52% to 5.35%, which is within the standard range set by SNI 01-6235-2000, specifically a maximum of 8%, and well below the ISO 17225 maximum 15% for solid biofuels (Hasibuan & Pardede, 2023). The lowest value of 3.52% is obtained at a carbonization time of 240 min with a pine resin concentration of 2%, while the highest value of 5.35% is found at a carbonization time of 120 min with a pine resin concentration of 10%. This finding aligns with the results of studies by (Handayani *et al.*, 2019) and (Siahaan *et al.*, 2013), who stated that prolonged carbonization duration causes the pores of the charcoal to open more widely, allowing water within the material to escape more easily. On the other hand, an increase in pine resin concentration tends to increase the moisture content of bio-briquettes. The highest average moisture content is recorded in bio-briquettes with a 10% pine resin concentration at 4.50%, whereas the lowest is obtained at a 2% pine resin concentration. This is consistent with the study performed by (Ningsih *et al.*, 2023), who noted that the addition of pine resin to bio-briquettes can increase the moisture content because the moisture in the binder can mix with the bio-briquettes, thereby affecting the total moisture content. Bio-briquettes with lower moisture content exhibit superior properties in terms of density, structural stability, and durability. In contrast, a high moisture content increases the risk of significant cracking (Aal *et al.*, 2023). The high moisture content in biomass negatively affects combustion efficiency, as additional energy is required to evaporate the water before optimal combustion can take place. This energy consumption decreases the net heat production, thereby reducing the overall energy efficiency of the fuel. In addition, high moisture content contributes to incomplete combustion, which is characterized by increased carbon monoxide (CO) and particulate emissions. Therefore, reducing the moisture content of biomass is an important factor for improving combustion efficiency while reducing environmental emissions (Tabasso *et al.*, 2020; Ungureanu *et al.*, 2018).

Figure 3(b) illustrates the trend of increasing ash content with increasing carbonization time. The ash content ranges from 2.67% to 5%, indicating that all samples meet the SNI 01-6235-2000 standard, which specifies a maximum of 8%, and are also compliant with the ISO 17255 standard for solid biofuels (≤ 10%) (Hasibuan & Pardede, 2023). The lowest value is observed at 240 min of carbonization with 2% pine resin, while the highest value is recorded at 240 min with 10% pine resin. This aligns with the previous study showing that increased carbonization time can raise ash content because the combustion process causes carbon to burn completely, leaving ash as the combustion residue (Junary *et al.*, 2015). An increase in the ash content is also observed with increasing concentrations of pine resin. The findings of this study are consistent with those of previous studies, indicating that the presence of impurities is associated with a high ash content. These impurities consist of minerals that cannot be burned by oxygen, such as SiO_2, CaO, and alkaline components, as carbonization occurs under oxygen-free conditions (Cholilie & Zuari, 2021). Ash content is a crucial component in bio-briquettes production since a high ash content can form a crust during the combustion process (Ningsih *et al.*, 2023). High ash content in briquettes indicates high combustion residues and generally correlates with a low heating value (Agussalim *et al.*, 2022). The ash content has a significant effect on the heat transfer efficiency as well as the oxygen diffusion process to the fuel surface during combustion (Ajimotokan *et al.*, 2019). Additionally, increased ash content may also lead to higher particulate matter emissions, which can contribute to air pollution and negatively impact the overall combustion efficiency of bio-briquettes (Cholilie & Zuari, 2021).

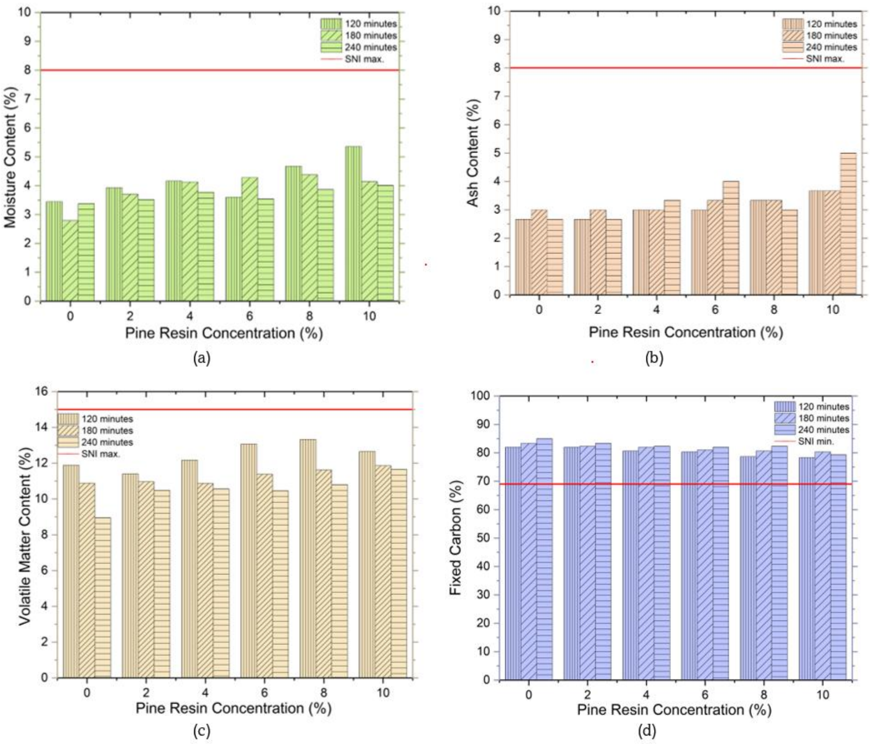


Fig. 3 Correlation of carbonization time and pine resin concentration with (a) Moisture content; (b) Ash content; (c) Volatile matter; and (d) Fixed carbon

As shown in Figure 3(c), the range of volatile matter content in bio-briquettes is 10.45%–13.33% that are within the SNI 01-6235-2000 standard of 15%. The lowest value was observed at 240 minutes of carbonization and 6% pine resin, while the highest value was recorded at 120 minutes and 8% pine resin. Volatile matter affects the combustion properties of bio-briquettes, where lower values result in cleaner and more efficient combustion, while higher values tend to increase smoke emissions (Anisa *et al*., 2025). Volatile matter is a gaseous compound produced during the heating process, consisting of combustible gases such as hydrogen, carbon monoxide (CO), and methane (CH_4), as well as non-combustible gases such as carbon dioxide (CO_2) and water vapor (H_2O) (Kongprasert *et al*., 2019). Based on Figure 3(c), the carbonization time tends to reduce the volatile matter content because volatile compounds evaporate more readily at higher temperatures and longer durations during the carbonization process (Gobel & Arief, 2022). Meanwhile, an increase in pine resin concentration caused an increase in volatile matter content, with the highest average at a pine resin concentration of 10% at 12.05% and the lowest at a pine resin concentration of 2% at 10.94%. This increase is attributed to the inherently volatile components present in pine resin, which contribute to higher measured volatile matter content (Herjunata *et al*., 2020; Ningsih, 2019).

Figure 3(d) shows the fixed carbon content of bio-briquettes ranged from 78.33% to 83.33%, with all bio-briquettes samples exceeding the minimum standard of SNI 01-6235-2000, which is 69%. Figure 3(d) also illustrates increase in fixed carbon content as the carbonization time increases, with the highest value at 240 minutes of carbonization, corresponding to 83.33%. This is consistent with the decrease in moisture content and volatile matter, which is inversely proportional to the increase in fixed carbon (Hasibuan & Pardede, 2023). Conversely, an increase in pine resin concentration tends to decrease the fixed carbon value, as the moisture content and volatile compounds in the bio-briquettes increase with the addition of pine resin concentration (Saputra *et al*., 2023). In this study, fixed carbon refers to the solid combustible residue remaining after the removal of moisture, ash, and volatile matter, calculated by difference from proximate analysis (FC = 100% - %moisture - % ash - %VM) (Pari *et al*., 2023). This differs from total carbon content, which would be determined through elemental analysis (CHN/CHNS analysis) and represents the absolute mass percentage of carbon atoms in the sample, including carbon present in volatile compounds (Jimenez & Ladha, 2008). Carbon is the primary element in charcoal, which also contains hydrogen, oxygen, sulfur, and nitrogen. Fixed carbon represents the carbon fraction in charcoal, excluding water, ash, and volatile matter (Ningsih, 2019).

To further support the interpretation of fixed carbon development with increasing carbonization time, powder X-ray diffraction (PXRD) analysis was performed on the raw and carbonized samples. While proximate analysis quantifies the increase in fixed carbon as a function of carbonization duration, PXRD provides complementary structural information regarding the evolution of carbon ordering during thermal treatment. The diffraction patterns therefore serve to verify whether the observed increase in fixed carbon corresponds to the expected transformation of lignocellulosic biomass into predominantly amorphous carbon at 600 °C. The PXRD results are presented in Figure 4.

Both samples display broad, diffuse scattering patterns with no sharp crystalline peaks, which indicates the significant characteristic of amorphous carbon materials. A broad peak centered between roughly 22–25° 2θ indicates amorphous carbon, in contrast to well-ordered graphite which would show a sharp (002) reflection at approximately 26.4° 2θ ($d_{002} \approx 3.35$ Å).

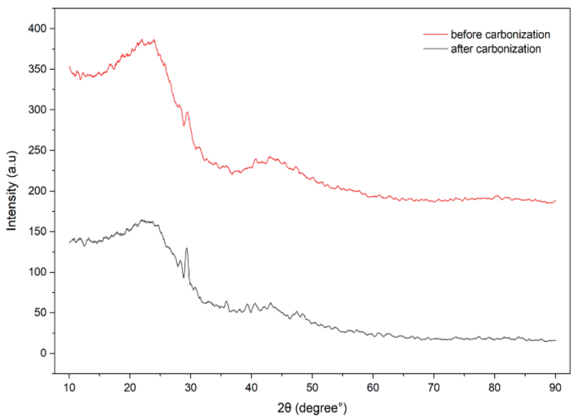


Fig. 4 PXRD patterns of briquettes before and after carbonization (600 °C, 240 min), showing the structural transition from lignocellulosic biomass to amorphous carbon.

Both patterns show the characteristic broad carbon peak in the low-angle region, but the black curve (carbonized, 600°C / 240 min) appears to have a slightly more defined and elevated broad feature near ~23–26°. The formation of broad peaks between 15° and 30° 2θ resembling amorphous carbon peaks occurs when temperatures above 500°C are sufficient to break down the lignocellulosic structure for the complete breakdown of cellulose and hemicellulose (Gale *et al.*, 2021). This confirms that carbonization performed in this study was effective.

The red curve (un-carbonized) retains features consistent with lignocellulosic raw material. The XRD pattern of biomass typically has prominent cellulosic peaks at approximately 16° 2θ (101 plane) and ~22° 2θ (220 plane), and as carbonization temperature increases, these cellulosic peaks decrease in intensity and become broad, coinciding with a decrease in the crystallite sizes of cellulose and hemicellulose (Gale *et al.*, 2021). The red curve's broader, higher-intensity profile at low angles (10–20° region) is consistent with retained lignocellulosic contribution, while the black curve's collapse in that region confirms cellulose decomposition.

3.3 Combustion Characteristics of Bio-briquettes

In addition to the proximate properties, this study also evaluated the combustion properties of the briquettes to assess their quality as a fuel. Figure 5 summarizes the results of the main combustion characteristics tests, including the calorific value, ignition time, and combustion rate. The results in Figure 5(a) show that the calorific value of bio-briquettes is in the range of 7,566.30 – 8,458.75 cal/g, and all meet the requirements of SNI 01-6235-2000 (≥5000 cal/g), also ISO 17225 standard, which specifies a minimum net calorific value of approximately 4,302.1 cal/g (Hasibuan & Pardede, 2023). The calorific value is an important parameter of fuel characteristics that describes the amount of heat energy produced through chemical reactions during the combustion process, and represents the level of energy contained in the fuel (Martins *et al.*, 2015). Carbonization time shows a tendency to increase the heating value, along with a decrease in the water and volatile matter content (Shafiyya *et al.*, 2022). The decrease in both parameters reduces the heat required to vaporize the materials during the combustion process, thereby increasing the energy efficiency (Handayani *et al.*, 2019). A high heating value indicates better fuel combustion efficiency, as it generates more heat and directly contributes to the performance of the combustion process (Ashraf: *et al.*, 2014). In contrast, increasing the pine resin concentration showed a negative correlation with the heating value. Concentrations of 2% to 6% produced relatively higher heating values than those of 8% and 10%. This decrease is influenced by the water content in pine resin and its thermoplastic properties, which tend not to burn completely, thus reducing the efficiency of energy release (Ningsih *et al.*, 2023). In addition, the heating value can be affected by other factors, such as the type of raw material, particle size, and shape (Dinesha *et al.*, 2019). In addition, a higher water content in pine resin requires more energy to vaporize during combustion, which also reduces its calorific value (Ningsih *et al.*, 2023; Shafiyya *et al.*, 2022).

Based on Figure 5 (b), the bio-briquette ignition time ranged from 56 to 115 s. This time is significantly shorter than that of briquettes without the addition of pine resin, which take 191-195 seconds to ignite. Ignition time is an indicator in assessing the ease of briquettes to burn, namely, the time required for a fire to appear on the surface of the briquette. The carbonization time tends to accelerate ignition time. This is due to the decrease in moisture content that occurs during the carbonization process, which lowers the energy required to trigger the flame (Handayani *et al.*, 2019; Pari *et al.*, 2023). Increasing the concentration of pine resin from 2% to 10% also showed a tendency to accelerate briquette ignition. This is due to the flammable content of turpentine compounds and resin acids in pine resin, as well as an increase in volatile matter that accelerates the combustion reaction (Herjunata *et al.*, 2020; Jamilatun, 2008; Kuspradini *et al.*, 2018). The low viscosity and boiling point of pine resin favor enhanced atomization and vaporization of the fuel. These characteristics speed up the ignition time of the briquettes, as the volatile compounds in the sap break down more easily and trigger combustion in the initial phase (Vallinayagam *et al.*, 2013).

Based on Figure 5(c), the combustion rate of the briquettes ranged from 0.1047 - 0.1125 g/min. The combustion rate is an

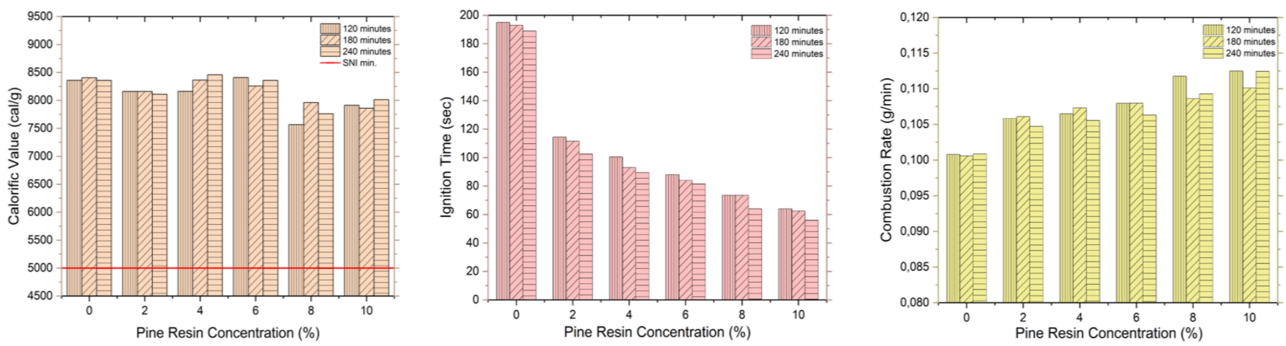


Fig. 5 Correlation of carbonization time and pine resin concentration with (a) Calorific value; (b) Ignition time; and (c) Combustion rate

important parameter for measuring the speed at which briquettes are depleted during combustion, where higher values indicate shorter combustion times (Aljarwi *et al.*, 2020; Dinesha *et al.*, 2019). Figure 4(c) shows that increasing the carbonization time tends to decrease the combustion rate. This is due to the increase in fixed carbon that occurs due to a decrease in moisture content and volatile matter during carbonization, thus extending the duration of combustion (Handayani *et al.*, 2019; Jamilatun, 2008; Junary *et al.*, 2015). A high fixed carbon content tends to extend the duration of combustion, potentially reducing the overall charcoal consumption (Jamilatun, 2008). In addition, increased ash content also inhibits heat transfer and oxygen diffusion, thus slowing down the combustion process (Ningsih *et al.*, 2023). In contrast, increasing the concentration of pine resin from 2% to 10% tends to increase the combustion rate. This is attributed to the resin and turpentine content in pine resin, which are volatile and flammable, thus increasing the volatile matter content and accelerating the combustion reaction (Hasibuan & Pardede, 2023; Kuspradini *et al.*, 2018). This is in accordance with previous studies, which found that the low viscosity of pine resin can accelerate the vaporization rate of the fuel and improve its mixing with air, thereby supporting the combustion process and contributing to an increased combustion rate (Vallinayagam *et al.*, 2013).

Biomass briquetting studies confirm that high volatile matter content tends to make the briquettes deplete faster and increase the burning rate, resulting in shorter total burning times and less stability for sustainable fuel applications (Agussalim *et al.*, 2022; Pari *et al.*, 2023; Siswati *et al.*, 2019). Although increasing the pine resin content has the potential to increase the volatile matter fraction, the application of resin as an external coating results in a different combustion mechanism compared to internal mixing. The combustion behavior observed in this study suggests that the increasing pine resin content may elevate the volatile matter fraction, which can influence burning behavior. Previous work (Pari *et al.*, 2023) reported that when pine resin was homogeneously blended throughout the briquette matrix, the overall volatile matter increased substantially, resulting in a higher burning rate and reduced combustion stability.

In contrast, the present study applies pine resin as an external surface layer rather than incorporating it uniformly within the briquette matrix. This difference in application method plays a key role in combustion behavior. The external coating primarily affects the initial ignition phase by providing readily combustible volatile components at the surface. Once ignition is established, sustained combustion is governed predominantly by the charcoal core, which retains the inherent combustion characteristics of carbonized coconut shell.

As a result, shorter ignition times can be achieved without significantly accelerating the overall combustion rate. Because the resin is applied externally and at controlled percentages, the total volatile matter content of the briquette remains within standard limits, thereby maintaining combustion stability. This behavior differs from internal additive blending, where simultaneous volatile release throughout the briquette matrix can promote accelerated combustion.

To further understand the chemical interactions responsible for the observed combustion characteristics, FTIR analysis was then conducted to identify the functional groups present in the briquette samples. In this study, FTIR analysis was conducted to identify the functional groups in biobriquettes containing 0% pine resin and biobriquettes containing 8% pine resin at a carbonization time of 240 minutes and presented in Figure 6. The FTIR characterization results for biobriquettes with a carbonization time of 240 minutes (0% variation) shown in Figure 6(b) reveal several identifiable absorption peaks. The peak at 2873.94 cm^{-1} corresponds to C–H stretching vibrations originating from the hemicellulose, cellulose, and lignin components (Heliani *et al.*, 2024). The peak at 2308.79 cm^{-1} indicates the presence of a C=O group belonging to the carbonyl group (Rampe *et al.*, 2021). Peaks at 1174.65 cm^{-1} and 1035.77 cm^{-1} indicate the presence of C-O bonds (Ikhtiarbakti & Gareso, 2018; Lazim & Hadibarata, 2015). Peaks at 877.61 cm^{-1} and 825.53 cm^{-1} represent Si-O stretching and bending vibrations, indicating the presence of silica in the sample (Heliani *et al.*, 2024). The smallest peak detected at 759.95 cm^{-1} is associated with out-of-plane C-H bending, indicating the presence of hydrocarbon compounds in the biobriquettes (Putu *et al.*, 2024). Based on the FTIR analysis, it was proven that a carbonization time of 240 minutes was capable of degrading most of the lignocellulosic components, although some residues were still detected.

The FTIR characterization results for biobriquettes containing 8% pine resin at a carbonization time of 240 minutes, shown in Figure 6(a), show several identifiable absorption peaks. FTIR characterization results for biobriquettes containing 8% pine resin at a carbonization time of 240 minutes revealed several identifiable absorption peaks. The peak at 2875.86 cm^{-1} corresponds to C–H stretching vibrations originating from the hemicellulose, cellulose, and lignin components (Heliani *et al.*, 2024). The peak at 2308.79 cm^{-1} indicates the presence of a C=O group belonging to the carbonyl group (Rampe *et al.*, 2021). The peak at 1259.52 cm^{-1}

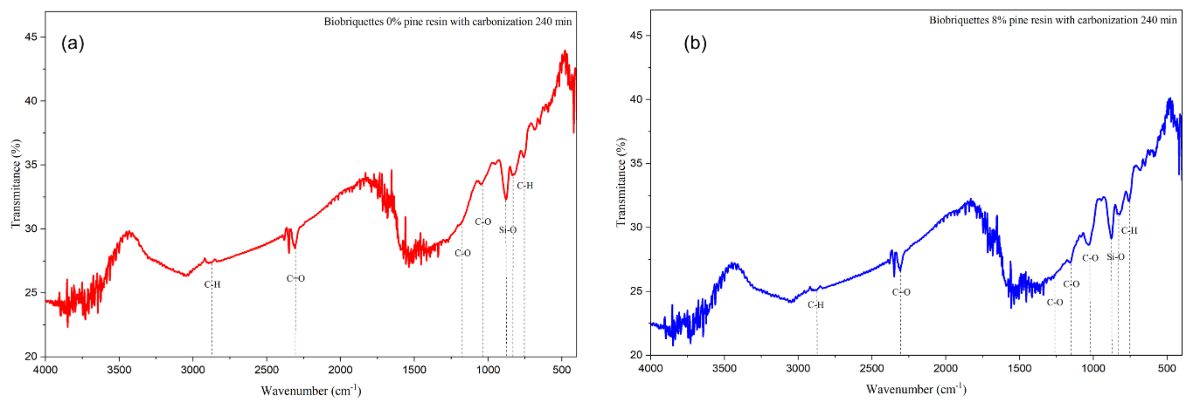


Fig. 6 FTIR spectrum of biobriquettes: (a) with pine resin (8%) carbonized for 240 minutes (b) without pine resin (0%) carbonized for 240 minutes

represents C-O stretching vibrations and suggests the presence of carboxylic acid (Angın *et al.*, 2025; Ikhtiarbakti & Gareso, 2018). Peaks at 1155.36 cm^{-1} and 1026.13 cm^{-1} indicate the presence of C-O bonds (Ikhtiarbakti & Gareso, 2018; Lazim & Hadibarata, 2015). Peaks at 877.61 cm^{-1} and 825.53 cm^{-1} represent Si-O stretching and bending vibrations, indicating the presence of silica in the sample (Heliani *et al.*, 2024). The smallest peak detected at 759.59 cm^{-1} is associated with out-of-plane C-H bending, indicating the presence of hydrocarbon compounds in the charcoal (Putu *et al.*, 2024). In this sample, the FTIR analysis results are nearly identical to those of coconut shell charcoal with a carbonization time of 240 minutes; the only distinction is the appearance of a peak at 1259.52 cm^{-1} indicating the presence of carboxylic acid groups from pine resin. This carboxyl group, primarily abietic acid, plays a role in enhancing flammability during the initial ignition phase (Sarria-Villa *et al.*, 2021).

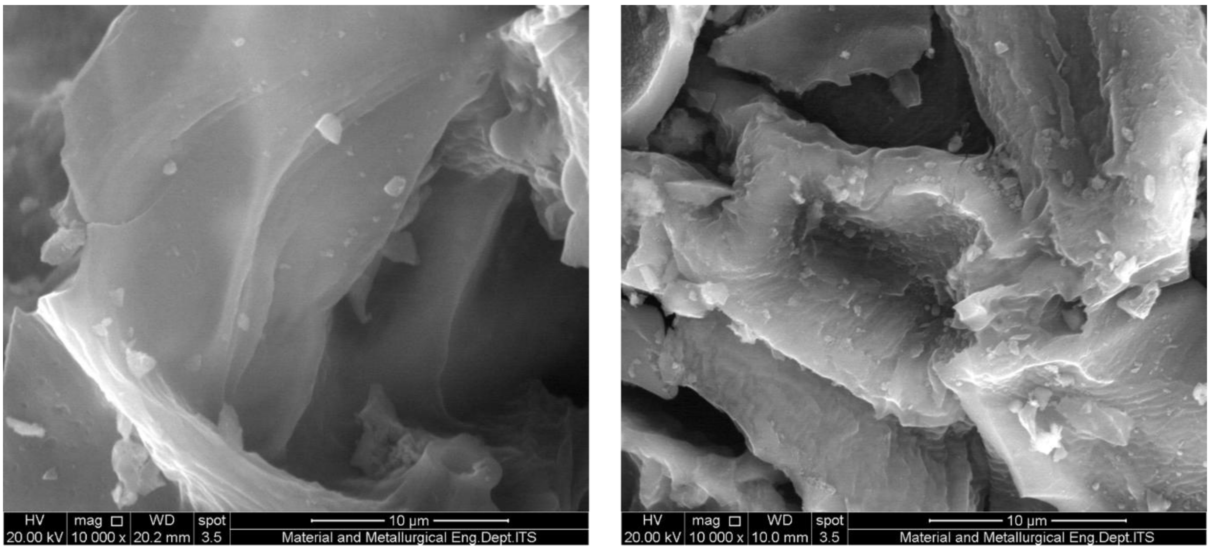
The FTIR results show that both samples have similar peaks, with the presence of C–H stretching (±2874–2876 cm^{-1}), C=O carbonyl (2308.79 cm^{-1}), C-O (±1026–1175 cm^{-1}), Si-O (877 and 825 cm^{-1}), and out-of-plane C-H bending (±760 cm^{-1}). The main difference identified is the appearance of a new peak at 1259.52 cm^{-1} in the sample containing pine resin, indicating the presence of C-O stretching bonds from carboxylic acids, components likely derived from resin acids in the pine resin (Sarria-Villa *et al.*, 2021). The resin compound content (abietic acid) in pine resin with these carboxyl groups decomposes easily due to its low flash point, 33–38°C and produces volatile compounds during initial heating (Kuspradini *et al.*, 2018). Once the volatiles are exhausted, combustion is controlled by the carbon matrix of the coconut shell, thereby maintaining combustion stability (Saputro *et al.*, 2013). Based on FTIR test results, no significant changes were found in the peaks related to carbon structural stability; in other words, no formation of new groups was detected that could accelerate thermal decomposition during carbonization. The addition of pine resin in the form of a coating does not alter the combustion characteristics of the biobriquettes. This is consistent with research findings indicating that pine resin accelerates ignition time without affecting combustion stability.

SEM images at 10,000× magnification compare pine resin–coated activated carbon (Figure 7a) with uncoated activated carbon (Figure 7b). The coated sample exhibits comparatively smoother and more continuous lamellar surfaces with partially bridged interlamellar spaces. This morphology is consistent with the presence of a surface layer attributed to pine resin deposition on the carbon framework. In contrast, the uncoated sample shows a more irregular and fragmented lamellar texture with clearly visible open interlamellar porosity, which is characteristic of coconut shell–derived activated carbon (Singla *et al.*, 2024). The observed smoothing and partial bridging of surface features in the coated sample suggest that pine resin is predominantly distributed on the external carbon surfaces rather than penetrating deeply into the internal pore structure. This observation is consistent with the intended role of pine resin as an external surface coating that enhances ignition behavior.

3.4 Economic Efficiency and Sustainability Analysis

Beyond the proximate characteristics and combustion properties, the effectiveness of biobriquettes as an alternative fuel source can be evaluated through an economic efficiency analysis compared to conventional fuels such as Liquefied Petroleum Gas (LPG). Table 2 presents the efficiency comparison between LPG and briquettes as fuels, based on data from Ditjenbun (Ditjenbun, 2023). The economic assessment reveals that biobriquettes cost Rp 2.39 per calorific unit compared to LPG at Rp 1.55 per calorific unit, indicating LPG's superior cost-effectiveness in terms of direct energy cost.

However, the decision to adopt biobriquettes over LPG should not be evaluated solely on cost-per-calorie metrics. Biobriquettes may provide advantages in contexts where local biomass resources are readily available and production can be conducted near consumption sites. In rural or remote communities where LPG distribution infrastructure is limited or unreliable, biobriquettes can reduce dependence on centralized fuel supply chains and transportation logistics (Hasibuan & Pardede, 2023). Furthermore, fluctuations in fossil fuel prices and ongoing subsidy policy adjustments may influence the relative economic competitiveness of alternative solid biofuels. In addition to economic considerations, the use of biomass-derived briquettes can contribute to resource utilization efficiency through agricultural waste valorization (Ifa *et al.*, 2020).



(a) 8% pine resin coated (b) no pine resin coated

Fig. 7 Scanning electron microscopy (SEM) images of coconut shell–derived activated carbon at 10,000× magnification: (a) pine resin–coated sample and (b) uncoated sample.

Table 2
Fuel efficiency comparison

Fuel	Price/kg (Rp)	Calorific value (cal/g)	Price/Calor (Rp)
Biobriquettes	18,556.1*	7761.2	2.39
LPG	16,833.3	11254.6	1.50

*The price of biobriquettes is the result of cost estimation calculated by researchers based on the production process carried out

Table 3
The comparison of additives in fuel efficiency

Parameters	Pine Resin (8%)	$KMnO_4$ (20%)	KNO_3 (20%)	$KClO_3$ (20%)	$NaNO_2$ (20%)	$K_2Cr_2O_7$ (20%)
Calorific value (cal/g)	7761.2	5603.26	5476.33	5582.19	5285.01	5524.77
Ignition time (sec)	63	17	24	20	28	20
Combustion rate (g/sec)	0.0018	0.0016	0.0014	0.0015	0.0012	0.0015

Source: Siswati *et al.* (2019)

Morever, biobriquettes offer significant environmental benefits. Previous researcher (Alabi *et al.*, 2023) demonstrated that biomass biobriquettes emit lower greenhouse gases compared to fossil fuels, and their production from agricultural waste helps reduce deforestation (Tesfaye *et al.*, 2022). Carbonization methods can reduce particulate emissions by 40% compared with raw biomass, thereby improving air quality (Trubetskaya *et al.*, 2019). Biobriquettes present safer transportation and handling compared to volatile LPG (Ifa *et al.*, 2020). The addition of pine resin as an additive produced higher calorific values (7,761.21 cal/gram) than chemical oxidizers, although with slightly longer ignition times. This indicates that pine resin can enhance the energy content without significantly compromising the ignition performance.

Although biobriquettes are economically less competitive than LPG, their environmental benefits, safety advantages, and sustainability aspects present compelling arguments for their adoption in sustainable energy strategies. The trade-off between economic efficiency and environmental sustainability requires careful consideration in energy policy development.

3.5 Comparison of Pine Resin and Chemical Oxidizers

This study evaluated pine resin as a natural additive for coconut shell biobriquettes, comparing results with (Siswati *et al.*, 2019). Biobriquettes with 8% pine resin achieved a calorific value of 7,761.21 cal/g, significantly higher than that of chemical oxidizers (5,285.01-5,603.26 cal/g at 20% concentration). This superior performance is attributed to the chemical oxidizers containing metal oxides, which increase the ash content and reduce the combustion quality (Herjunata *et al.*, 2020). Table 3 shows the comparison of pine resin and chemical oxidizers (Siswati *et al.*, 2019).

The ignition time for pine resin bio-briquettes was 63 s compared to 10 s for $KMnO_4$-treated samples. This difference reflects the lower concentration used (8% vs 20%) and the natural properties of pine resin. Despite its longer ignition time, pine resin offers environmental advantages, such as reduced combustion residues. Pine resin biobriquettes demonstrated superior combustion rates of 0.0018 g/s compared to 0.0012-0.0016 g/s for chemical oxidizers. This enhanced performance is due to the resin and turpentine components, which are highly volatile and flammable compounds (Kuspradini *et al.*, 2018). The results confirm that pine resin is an effective, environmentally friendly alternative to chemical oxidizers, maintaining superior combustion characteristics while reducing environmental impact through natural, renewable resource utilization.

4. Conclusion

This study systematically investigates the effect of carbonization time and the addition of pine resin on the physical and combustion characteristics of coconut shell bio-briquettes. The feasibility of the formulation for fuel applications is confirmed by the fact that every bio-briquette sample satisfy the minimum standards established by SNI 01-6235-2000 in terms of moisture content, ash content, volatile matter, and fixed carbon, and also complies with international standards ISO 17225 for solid biofuels. The optimal treatment is obtained at a carbonization time of 240 min with a pine resin concentration of 8%, producing the best characteristics in terms of proximate parameters and combustion. These findings indicate that using pine resin as a surface ignition enhancer in the form of a layer can accelerate the ignition time without reducing combustion efficiency and quality. From an economic perspective, the production of bio-briquettes is less cost-efficient than that of LPG, but offers considerable environmental and safety advantages. Utilizing locally available coconut shell waste and natural pine resin reduces the dependency on fossil fuels and promotes circular resource use. These bio-briquettes present a sustainable and cleaner alternative energy option for households and small industries in tropical regions.

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