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Effect of Binder Ratio and Carbonization Temperature on the Calorific and Mechanical Characteristics of Biocoke from Oil Palm Fronds

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Abstract. *This study investigates the production and characterization of biocoke derived from oil palm fronds, using carbonized durian seed powder as a binder under varied carbonization temperatures and binder ratios. The experiment was done in laboratory-scale to determine the optimal process conditions. Oil palm fronds were carbonized at temperatures of 400°C, 450°C, and 500°C, then mixed with durian seeds at ratios of 5%, 10%, and 15%. The mixture was molded and compacted at temperatures of 150–200°C under a pressure of 10–20 MPa. Data biocoke produced were assessed based on moisture content, ash content, calorific value, and mechanical strength. Result showed that by increasing carbonization temperature from 400 °C to 500 °C, could enhanced the fixed carbon, reduced ash content, and improved calorific value of biocoke. By adjusting the binder ratio from 5% to 15% increased water content and calorific value. Meanwhile, the excessive binder ratio (15%) lowered mechanical strength, likely due to higher residual moisture. The best characteristics energy performance and mechanical integrity was achieved at 500 °C with a 10% binder ratio. In conclusion, oil palm fronds waste and durian seeds can be processed into an environmentally friendly and sustainable biocokes. These findings demonstrate a practical pathway to valorise agricultural biomass residues and locally available biogenic binders into biocokes serves as a sustainable, lower-CO2, and coal-reducing alternative to traditional coke in thermal combustions.*

Keywords: *Biocoke; Oil palm fronds; Durian seed binder; Carbonization; Calorific value.*

1. Introduction

Indonesia is one of the world's leading producers of palm oil, generating substantial quantities of lignocellulosic biomass across cultivation and processing stages. Oil palm fronds are an abundant residue with significant potential for conversion into solid biofuels, aligning with national goals for sustainable resource utilization and waste minimization. Data from the Central Statistics Agency (2023) shows that approximately 43 million tons of oil palm fronds are produced annually, much of which is not properly managed. In Aceh province, oil palm plantations cover 1.4 million hectares, demonstrating the significant potential for converting waste into valuable products.

Processing palm oil frond waste into bio-coke, an environmentally friendly alternative solid fuel. Furthermore, durian seeds, a waste product from durian plantations, also have the potential to be used as a natural binder in bio-coke production. Using durian seeds as an adhesive binder is considered more environmentally friendly than synthetic, chemical-based binder. The innovation of utilizing oil palm frond waste with durian seed adhesive to make bio-coke is expected to reduce dependence on coal while reducing waste problems in the surrounding environment.

Previous studies that support this potential innovation were done by Ahmad et al. (2023) which showed that high-quality bio-coke can be produced from agricultural residues such as oil palm fronds under appropriate pyrolysis conditions. Meanwhile, Kongto et al. (2022) confirmed that oil palm fronds have physical and chemical properties suitable as biomass fuel with high calorific value. Furthermore, Chaichanawong and Ida (2019) in their research in Thailand highlighted the significant potential of biomass such as oil palm fronds in the development of bio-coke technology as a cleaner and more sustainable alternative energy source.

Despite the recognized potential of oil palm fronds as a biomass fuel, existing studies largely focus on single-material biochar production and pyrolysis optimization, with limited exploration of composite bio-coke formulations using environmentally friendly natural binders. The utilization of durian seed waste as a biodegradable adhesive in bio-coke production remains underexplored, particularly in relation to its influence on mechanical strength, densification characteristics, and fuel performance. Furthermore, integrated analysis of carbonization temperature, binder ratio, and compaction parameters has not been comprehensively examined. Therefore, this study aims to address these gaps by investigating the combined effect of oil palm frond carbonization temperature and durian seed binder ratio on the properties of bio-coke, contributing to sustainable biomass waste valorization in Aceh Province.

Based on the vast untapped potential of palm oil waste and durian seeds, this research aims to examine and utilize these wastes to create environmentally friendly bio-coke products. The research will focus on the use of palm oil fronds as the main ingredient and durian seeds as the binder, through a carbonization process at various temperatures. Experiments will be conducted on a laboratory scale, with limited analysis of the moisture content, ash content, calorific value, and mechanical strength of the resulting bio-coke.

This research aims to determine the best process parameters and evaluate the effect of carbonization temperature and ratio of durian seed binders on the characteristics of bio-coke from oil palm fronds. The results are expected to benefit industry in reducing waste, providing more environmentally friendly alternative fuels, and serve as an important reference for students and researchers interested in waste management and renewable energy. Furthermore, the resulting bio-coke is expected to be an efficient and sustainable energy solution, supporting carbon gas emission reduction.

2. Method

2.1 Materials

The main materials used were wet oil palm fronds and dried durian seeds. The equipment used included a chopper, drying oven, mixer, muffle furnace, molds, hydraulic press, bomb calorimeter, and hardness and density testers.

2.2 Research Procedure

The experiment was conducted at a laboratory scale. The particle size of both oil palm frond biochar and durian seed biochar was fixed at 100 mesh to ensure uniformity in the briquetting process. Bio-coke specimens were molded into cylindrical forms with dimensions of 20 mm × 20 mm.

The study evaluated two independent variables:

(1) the mass ratio of durian seed biochar to oil palm frond biochar (5:95%, 10:90%, and 15:85%), and

(2) the carbonization temperature, varied within the range of 400–500 °C.

Figure 1 describes the steps of material palm fronds and durian seed binder preparation for biocoke production. The research procedure began with tools and materials preparation, including cleaning, chopping, and drying the oil palm fronds, and processing the durian seeds into a fine powder. The oil palm fronds were then carbonized in a furnace at low oxygen temperatures. The resulting charcoal was analyzed for its initial characteristics, then mixed with durian seed powder, molded, and compacted into biocoke (Baharin et al, 2020). The resulting biocoke was further tested for moisture content, ash content, calorific value, and mechanical strength. (Gani et al, 2023)

Figure 1. Research procedure of biocoke production

Data analysis was conducted quantitatively and descriptively, with calculations of moisture content, ash content, calorific value, and mechanical strength using appropriate formulas of Indonesian national standard SNI 01-6235-2000 for commercial cokes. The data obtained will be compared with solid fuel standards and presented in tables and graphs.

3. Results and Discussions

3.1 Characteristics of carbon from oil palm fronds at varied carbonization temperature

From Table 1, it showed a comparison of moisture and ash content at carbonization temperatures of 400°C and 500°C of mixed carbon (oil palm fronds and durian seed binder) produce. At 400°C, the moisture content was recorded at 5% and the ash content at 11.4%. At 500°C, the moisture content increased slightly to 5.3%, while the ash content decreased to 8.2%. These temperature changes significantly impact moisture and ash content, which needs to be considered in optimizing the bio-coke production process. The higher carbonization temperature of carbon materials was able resulting in the calorific value of carbon.

Table 1. Characteristics of moisture and ash content of carbon produced, at temperatures of 400°C and 500°C

Sample type	Carbonization temperature (^{0}C)	Moisture content (%)	Ash content (%)	Calorific value (kcal/kg)	SNI
Oil palm fronds + Durian seed char	400	5.0	11.4	5513.144	Moisture: 8% Ash: 10% Calorific: >5000 kcal/kg
Oil palm fronds + Durian seed char	500	5.30	8.2	6182.907	

Source: Research findings, 2025

The moisture content slightly increased from 5.0% at 400°C to 5.3% at 500°C. Generally, increasing carbonization temperature reduces inherent moisture due to enhanced thermal decomposition and volatile matter removal (Demirbaş, 2004; Bridgwater, 2012). However, the slight increase observed in this study may be attributed to post-carbonization moisture reabsorption during cooling and storage, as biochar is hygroscopic in nature (Ahmad et al., 2014). Despite this minor increase, both values remain relatively low (<6%), indicating good fuel quality, as lower moisture content improves ignition stability and combustion efficiency. Compared to typical biomass briquettes, which often exhibit moisture contents between 6–12% (Grover & Mishra, 1996), the values obtained in this study fall within an acceptable and competitive range for solid biofuels.

Ash content decreased significantly from 11.4% at 400°C to 8.2% at 500°C. This reduction suggests that higher carbonization temperatures promote more complete devolatilization and improved carbon concentration, thereby reducing the relative proportion of inorganic residues in the final product. According to Klass (1998) and Basu (2010), ash content in biomass fuels typically ranges from 1–20%, depending on feedstock composition and thermal treatment conditions. Oil palm residues are known to contain moderate ash levels due to their mineral composition (Kongto et al., 2022). The ash reduction observed at 500°C indicates improved fuel quality, as lower ash content reduces slagging, fouling, and combustion residue during utilization. The value of 8.2% at 500°C approaches the acceptable range for commercial biomass briquettes (<10%), suggesting that higher carbonization temperature enhances the physicochemical properties of the bio-coke.

The calorific value of biocoke increases at 500°C, particularly at 10% and 15% adhesive, in line with more optimal degradation of volatile compounds. However, the mechanical strength of biocoke decreases at higher binder ratios, although it increases at 5% binder. This is due to increased porosity, which weakens the mechanical structure of the biocoke. The findings align with study done by Purwandari (2023), who found that heating affects the pore structure and density of bio-coke, thus affecting combustion efficiency. Low temperatures (400°C) cause more volatile compounds to be retained, reducing the calorific value. Fadilah (2018) also showed that high temperatures (≥500°C) increase fixed carbon, reduce volatile compounds, and increase energy density. These findings align with research findings that temperatures of 500°C increase the calorific value, while low temperatures result in incomplete carbonization and reduce bio-coke efficiency.

The increase in calorific value with temperature is consistent with the thermochemical behavior of biomass. Higher carbonization temperatures promote greater fixed carbon formation, reduction of volatile matter, decrease in oxygen and hydrogen content, increase in carbon concentration. This trend aligns with findings by Demirbaş (2004) and Chaichanawong & Ida (2019), who reported that higher pyrolysis temperatures improve the energy density of biochar and bio-coke products. Carbonization temperature affects biocoke characteristics in a complex manner, where increasing temperature improves energy quality but can reduce mechanical strength at higher adhesive levels. Furthermore, monitoring heavy metals in biocoke is crucial to ensure safety and environmental sustainability.

3.2 Characteristics of biocoke at various binder ratio and mechanical strength

Figure 2 depicted that the increasing ratio of durian seed binder tends to increase the moisture content and calorific value of biocoke but inconsistently affects the mechanical strength. At a ratio of 5%, bio-coke has a moisture content of 12.7%, ash content of 6.3%, a calorific value of 5097.81 kcal/kg and a mechanical strength of 4.78 MPa. At a ratio of 10%, the moisture content and calorific value increase, with the mechanical strength reaching 5.10 MPa. However, at a ratio of 15%, despite the highest calorific value (5311.68 kcal/kg), the mechanical strength decreases back to 4.78 MPa, likely due to the increase in moisture weakening the structure of the bio-coke.

The results of the bio-coke mechanical strength test at carbonization temperatures of 400°C and 500°C with durian seed binder variations of 5%, 10% and 15% showed that the addition of adhesive increased the mechanical strength up to the optimal concentration. At 400°C, the highest mechanical strength was achieved at 10% binder (6.05 MPa), while at 15% binder there was a decrease to 5.41 MPa. A similar pattern occurred at 500°C, where the highest mechanical strength was also at 10% binder (5.10 MPa), and decreased at 15% adhesive (4.78 MPa). In general, increasing the carbonization temperature increased the mechanical strength at low binder content. These results emphasize the importance of selecting the right binder ratio, with 10% being the optimal composition to produce bio-coke with maximum strength and efficiency.

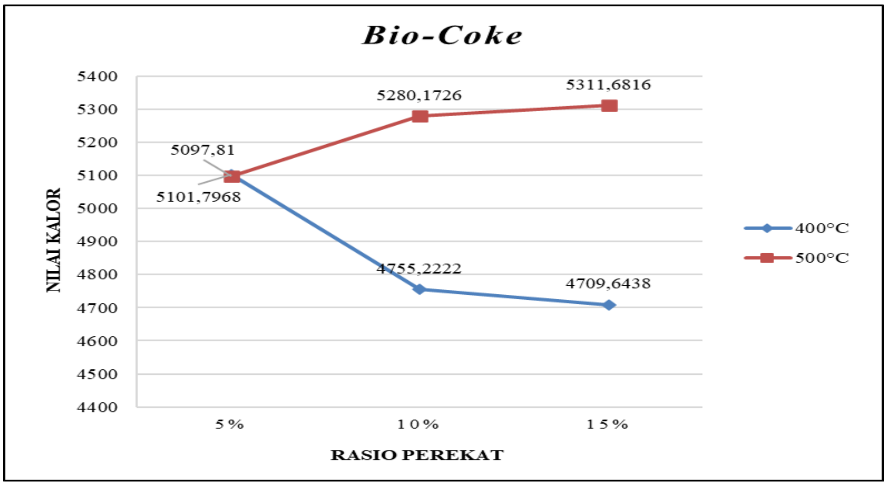

Figure 2. Effect of binder ratio on calorific values of biocoke produced

The improvements observed at 500 °C are consistent with thermochemical expectations: higher carbonization temperatures typically promote the removal of volatiles and increase fixed carbon, thereby elevating energy density while reducing ash formation. This enhances combustion efficiency and lowers slagging potential. Within the binder spectrum, moderate addition (10%) appears sufficient to enhance particle bridging and heat value without introducing excessive moisture. At 15%, residual moisture likely hinders consolidation and increases susceptibility to mechanical failure during handling, which is reflected in reduced compressive strength. These outcomes collectively support adopting 500 °C + 10% binder for practical biocoke manufacture from oil palm fronds.

The results above in parallel with study done by Nasution & Arifah (2022), which shows that starch-based binder can increase the calorific value of biocoke by adding fixed carbon and reducing volatile gases. This study also found that the increasing binder percentage at 500°C increases the calorific value. Research by Erdiwansyah (2024) also supports these findings, emphasizing that heating and pressure can reduce moisture, ash, and volatile matter content, thereby increasing combustion efficiency. Therefore, optimal carbonization temperature and binder percentage are crucial for producing high-quality biocoke. Other research by Muchlisha et al. (2023) shows that biocoke carbonized at high temperatures has lower porosity and a higher fixed carbon content, resulting in more efficient combustion.

From a resource perspective, utilizing oil palm fronds and durian seed carbon leverages two locally abundant residues, aligning with circular economy principles and potentially reducing costs associated with imported binders. The approach could be scaled through improved process control (e.g., moisture management during mixing, post-molding drying protocols) and standardized testing to meet industrial specifications for solid biofuels.

4. Conclusions

This study demonstrates that the characteristics of bio-coke produced from oil palm fronds with durian seed binder are significantly influenced by both carbonization temperature and binder ratio. Increasing the carbonization temperature from 400°C to 500°C improved the fuel quality by enhancing fixed carbon content, reducing ash content, and increasing the calorific value. These improvements indicate a higher degree of carbon enrichment and better energy densification at elevated temperatures. However, higher carbonization temperatures also increased material porosity, which may promote moisture reabsorption and potentially reduce mechanical strength under certain binder compositions. Based on the overall performance evaluation, the optimal condition was achieved at a carbonization temperature of 500°C with a 10% binder ratio, which provided the most balanced combination of high calorific value and adequate mechanical strength.

For future research, further investigation is recommended to study the optimization of compaction pressure and drying techniques that may further enhance mechanical strength and moisture resistance, improving the commercial viability of the bio-coke.

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