

Innovation and Utilization of FABA Bean Waste as Briquette Material: A Study on Combustion Characteristics

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doi.10.21063/jtm.2025.v15.i1.15-22

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Article Information

Received:

January 25, 2025

Revised:

March 16, 2025

Accepted:

April 16, 2025

Published:

April 30, 2025

Abstract

This study aims to investigate the innovation and utilization of fly ash bottom ash (FABA) waste from PLTU Ombilin as a briquette material, focusing on its combustion characteristics. FABA, a by-product of coal combustion, poses environmental challenges if not properly managed. In this research, FABA was blended with pyrolyzed pecan shells and starch as a binding agent, then compacted into briquettes with varying compositions. The combustion characteristics, including ignition time, combustion temperature, and calorific value, were evaluated using standard testing methods. The results indicate that variations in raw material composition significantly influence briquette performance. Briquettes containing 70% FABA, 20% pecan shell, and 10% starch exhibited the longest ignition time of 4 minutes and 3 seconds, with an average combustion temperature of 243°C. Meanwhile, briquettes composed of 60% FABA, 30% pecan shell, and 10% starch achieved the highest average combustion temperature of 376°C, with a flame duration of 3 minutes and 34 seconds. The highest calorific value, 8,714 cal/g, was obtained from briquettes containing 40% FABA, 10% pecan shell, and 40% starch. These findings demonstrate the potential of FABA waste as an alternative fuel source and contribute to sustainable industrial waste management and the development of environmentally friendly energy materials.

Keywords: Fly Ash Bottom Ash (FABA); Biomass Briquette; Combustion Performance; Alternative Fuel; Industrial Waste Utilization

1. Introduction

Coal-fired power plants remain one of the dominant sources of electricity generation in many developing countries, including Indonesia. Despite the global transition toward renewable energy, coal continues to play a critical role in ensuring energy security and grid stability due to its abundance and established infrastructure. However, coal combustion generates substantial quantities of solid residues, primarily fly ash and bottom ash (FABA), which present significant environmental and management challenges if not properly utilized [1].

Fly ash consists of fine particles captured from flue gas streams using electrostatic precipitators or other filtration systems, while bottom ash refers to the coarser fraction that settles at the bottom of the combustion chamber. Both materials are rich in silica (SiO₂), alumina (Al₂O₃), iron oxides (Fe₂O₃), and other trace minerals, making them potentially valuable secondary resources [1], [2]. Globally, hundreds of millions of tons of coal ash are generated annually, and a significant portion remains underutilized, leading to land occupation, groundwater contamination risks, and dust pollution [2].

In Indonesia, the rapid growth of electricity demand has contributed to increased coal consumption and consequently higher production of FABA. According to national energy statistics, coal-fired power plants contribute more than 60% of Indonesia's electricity mix, resulting in millions of tons of FABA annually. The PLTU Ombilin, located in Sawahlunto, West Sumatra, is one such facility generating significant quantities of FABA each year. The plant operates two generating units with substantial installed capacities, contributing to regional electricity supply while simultaneously producing considerable solid combustion residues.

Historically, coal ash residues in Indonesia were classified as hazardous and toxic waste (B3), limiting their reuse potential. However, the issuance of Government Regulation No. 22 of 2021 reclassified FABA from coal-fired power plants as non-hazardous under certain conditions, thereby opening broader opportunities for its utilization in construction materials, soil stabilization, and alternative energy applications. This regulatory shift aligns with global trends promoting circular economy principles and industrial waste valorization [3]. Waste valorization aims to transform industrial by-products into value-added products, thereby reducing environmental burdens and promoting sustainable resource management.

Among various valorization pathways, the conversion of FABA into briquettes represents a promising waste-to-energy strategy. Briquetting is a densification process that converts loose biomass or particulate materials into compact solid fuels with improved handling, transport, and combustion properties. Biomass briquettes have gained considerable attention as renewable solid fuels because they exhibit higher energy density, uniform shape, and improved combustion performance compared to raw biomass [4]. Additionally, briquetting can reduce open burning practices and mitigate greenhouse gas emissions associated with unmanaged biomass disposal.

Numerous studies have examined biomass briquettes derived from agricultural residues such as rice husk, sawdust, coconut shell, and corn cob. These studies demonstrate that fuel performance is strongly influenced by raw material composition, binder content, moisture level, and compaction pressure [5]. Critical combustion parameters—including ignition time, combustion temperature, calorific value, burning rate, and ash content—determine the feasibility of briquettes as alternative fuels. For instance, briquettes produced from agricultural biomass typically exhibit calorific values ranging from 15 to 20 MJ/kg, depending on composition and processing conditions [4], [5].

However, research focusing on briquettes incorporating coal combustion residues such as FABA remains relatively limited. The integration of FABA into briquette formulations introduces unique challenges and opportunities. On one hand, the high ash content of FABA may reduce calorific value and affect combustion stability. On the other hand, FABA contains mineral components that may enhance structural integrity and influence heat transfer behavior during combustion. Previous investigations into coal ash utilization suggest that ash-rich briquettes can still exhibit acceptable combustion performance when properly blended with biomass and suitable binders [6].

Furthermore, combining FABA with biomass residues may create synergistic effects. Biomass components contribute volatile matter and fixed carbon necessary for sustained combustion, while FABA may act as a filler that modifies porosity and thermal behavior. The optimization of such mixtures requires systematic experimental evaluation of combustion characteristics. Parameters such as ignition delay, peak combustion temperature, flame duration, calorific value, and residual ash fraction must be carefully analyzed to determine fuel suitability for domestic or small-scale industrial applications [5], [6].

From an environmental perspective, utilizing FABA as briquette material offers multiple benefits. First, it reduces the volume of industrial waste requiring disposal. Second, it contributes to carbon emission mitigation by partially substituting conventional fossil fuels. Third, it supports the development of decentralized alternative energy sources, particularly in regions where access to clean energy remains limited. Such initiatives are consistent with sustainable development goals emphasizing responsible consumption, waste reduction, and affordable clean energy [3].

Despite the substantial amount of FABA generated by PLTU Ombilin, its utilization has primarily been limited to internal applications such as concrete additives and masonry products, as well as external uses like mine acid neutralization. To date, limited scientific studies have investigated its application as a briquette fuel, particularly in terms of detailed combustion characterization. Therefore, there exists a research gap concerning the technical feasibility and combustion performance of FABA-based briquettes derived specifically from Ombilin power plant residues.

Understanding combustion characteristics is essential for determining whether FABA-based briquettes can meet established fuel standards. Combustion performance affects thermal efficiency, emission profiles, user safety, and overall economic

viability. High calorific value, stable flame behavior, moderate ignition time, and controlled ash formation are key indicators of quality solid fuel [4], [5]. Consequently, systematic evaluation under controlled experimental conditions is required to assess the influence of varying FABAs–biomass compositions.

Based on these considerations, this study aims to develop and evaluate briquettes produced from FABAs waste generated by PLTU Ombilin by analyzing their combustion characteristics. By investigating ignition time, combustion temperature, flame duration, and calorific value across different compositions, this research seeks to determine the feasibility of FABAs as a partial substitute in briquette fuel formulations. The outcomes are expected to contribute to sustainable waste management practices, promote circular economy principles in the energy sector, and provide an alternative fuel solution that is both environmentally friendly and economically viable.

2. Materials and Methods

A. Research Design

This study employed a non-factorial Completely Randomized Design (CRD) to evaluate the combustion characteristics of briquettes produced from Fly Ash Bottom Ash (FABA) and pyrolyzed pecan shell. The primary factor investigated was the variation in raw material composition. Each treatment was replicated three times to ensure statistical reliability and reproducibility of results. Four formulation treatments were prepared as shown in Table 1.

Table 1. Composition of Briquette Formulations

Treatment	FABA (%)	Pecan Shell (%)	Starch (%)	Water (%)
T1	60	20	10	10
T2	70	10	10	10
T3	50	30	10	10
T4	40	40	10	10

B. Materials

1) Fly Ash Bottom Ash (FABA)

FABA was obtained from PLTU Ombilin. The material consisted of a mixture of fly ash and bottom ash with an average particle size of approximately 1 mm prior to processing. The FABA was oven-dried to remove excess moisture and sieved using a 70-mesh sieve to obtain uniform particle distribution and eliminate impurities (Figure 1).

2) Pecan Shell

Pecan shell waste was used as the primary combustible biomass component to enhance

the calorific value of the briquettes. The raw shells were subjected to pyrolysis at controlled temperatures between 300–500 °C for 4 hours under limited oxygen conditions to produce char with improved brittleness and fixed carbon content. After pyrolysis, the material was ground using a blender and sieved through a 60-mesh screen to ensure homogeneity (Figure 2).

3) Starch Binder

Commercial starch flour was used as a binding agent. The starch was dissolved in hot water and heated until a viscous gel-like solution was formed, ensuring optimal adhesive properties during briquette molding (Figure 3).



Figure 1. Fly Ash Bottom Ash (FABA)



Figure 2. Pecan Shell



Figure 3. Starch Binder

C. Briquette Production Process

1) Raw Material Preparation

The preparation stage consisted of:

- Pyrolysis of pecan shells at 300–500 °C for 4 hours
- Sieving of FABA (70 mesh)
- Sieving of pyrolyzed pecan shell (60 mesh)
- reparation of starch binder solution

All materials were weighed using a calibrated digital balance with ± 0.01 g precision according to the composition specified in Table 1.

2) Mixing Process

The weighed FABA, pecan shell char, and starch binder were mixed using a low-speed blender for 30–60 seconds until a homogeneous mixture with uniform color distribution was obtained. Controlled mixing time was applied to prevent segregation of particles and ensure even binder distribution.

3) Briquette Molding

The homogeneous mixture was placed into a cylindrical mold with:

- Diameter: 5 cm
- Height: 0.8 cm

Compaction was performed using a modified hydraulic press equipped with a pressure gauge. A constant pressure of 30 MPa was applied for 2 minutes to achieve optimal density and mechanical strength. Although the press had a maximum capacity of 50 MPa, the pressure was limited to 30 MPa to prevent structural cracking.

4) Drying Process

The molded briquettes were dried under either:

- Direct sunlight exposure, or
- Oven drying at 80 °C

for a minimum duration of 3 hours. The objective of this stage was to reduce moisture content, improve structural integrity, and enhance combustion performance.

Initial and final masses of each briquette were recorded to evaluate moisture reduction.

D. Equipment

The main equipment used in this study included:

- 60 and 70 mesh sieves (particle size control)
- Manual briquette mold with pressure gauge (max. 50 MPa)
- Hydraulic jack (30 MPa operating pressure)
- Digital balance (± 0.01 g accuracy)

- Bomb calorimeter (calorific value determination)
- Infrared thermogun (temperature range 50–500 °C)
- Stopwatch (flame duration measurement)
- Blender (material grinding and mixing)

Briquette Production Process and Equipment used are shown in Figure 4.

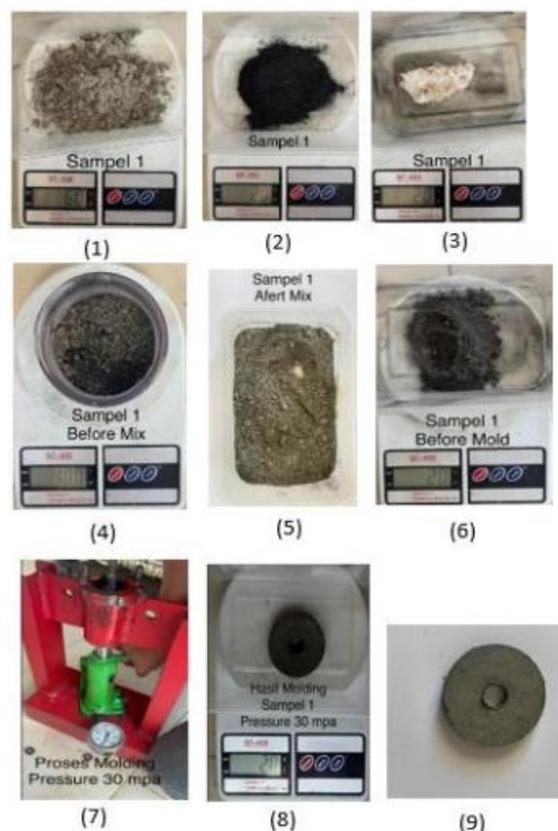


Figure 4. Briquette Production Process and Equipment used

E. Combustion Characterization

Combustion performance was evaluated through calorific value testing and flame duration analysis.

1) Calorific Value Test

The higher heating value (HHV) of briquette samples was determined using a bomb calorimeter. Approximately 1 gram of dried briquette sample was combusted in an oxygen-rich sealed chamber. The calorific value was calculated based on the temperature rise of the surrounding water jacket according to standard calorimetric principles.

The calorific value (CV) was calculated as:

$$CV = \frac{(C \times \Delta T)}{m} \quad (1)$$

where:

C = calorimeter constant (cal/°C)

ΔT = temperature increase (°C)

m = mass of sample (g)

2) Flame Duration and Combustion Temperature Test

Each briquette sample was weighed before ignition. The briquette was then ignited under controlled conditions, and:

- Flame duration was measured using a stopwatch
- Surface temperature was recorded using an infrared thermogun

Temperature measurements were taken periodically to determine the average combustion temperature. After complete combustion, the remaining ash mass was weighed to estimate combustion efficiency and residual ash fraction.

F. Data Analysis

All experimental data were analyzed using descriptive statistical methods, including mean and standard deviation calculations for each treatment group. Comparisons between treatments were performed to identify the composition that yielded the optimal combustion characteristics.

If significant performance differences were observed, further comparative analysis was conducted to determine the most effective formulation in terms of:

- Highest calorific value
- Stable combustion temperature
- Adequate flame duration
- Acceptable ash residue

3. Results and Discussion

A. Physical Characteristics of Briquettes

All briquette samples were successfully produced using a compaction pressure of 30 MPa, resulting in cylindrical specimens with a uniform diameter of 5 cm and height of 0.8 cm. The initial mass of each briquette prior to drying was approximately 20 g. After drying, mass reduction ranged between 15–16 g depending on composition, indicating moisture evaporation during the drying stage.

The relatively consistent dimensional stability across treatments suggests that the starch binder concentration (10%) was sufficient to maintain structural integrity during compaction and drying. No visible macro-cracks were observed, indicating that the selected molding pressure and drying conditions were appropriate to prevent internal stress failure. This confirms that the briquetting parameters were adequate for producing mechanically stable FABA-based briquettes.

B. Combustion Performance Analysis

1) Flame Duration and Combustion Temperature

Flame duration and average combustion temperature were measured to evaluate burning stability and thermal intensity. The results are summarized below (Figure 5):

Composition (FABA:Starch:Pecan:Water)	Flame Duration (min)	Average Temperature (°C)
60:10:20:10	3.34	375
70:10:10:10	4.03	243
50:30:10:10	3.05	160
40:40:10:10	1.33	124

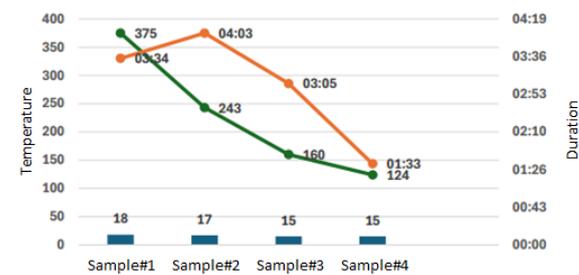


Figure 5. Flame Test Graph

Effect of FABA Content

The briquette containing 70% FABA exhibited the longest flame duration (4 min 3 s) but a moderate average combustion temperature (243 °C). This behavior indicates slower and more controlled combustion. The prolonged burning time can be attributed to the relatively high ash and mineral content in FABA, which reduces volatile matter and slows down oxidation reactions. The mineral matrix likely acts as a thermal buffer, moderating heat release rates and stabilizing combustion.

In contrast, the briquette containing 60% FABA and 20% pecan shell achieved the highest average combustion temperature (375 °C) while maintaining a relatively long flame duration (3 min 34 s). This composition represents an optimal balance between combustible biomass fraction and inert ash material. The increased proportion of biomass char provides higher volatile matter and fixed carbon, enhancing exothermic reactions and peak temperature.

Effect of Biomass (Pecan Shell) Content

Increasing pecan shell content to 40% significantly reduced flame duration (1 min 33 s) and average temperature (124 °C). Although biomass generally increases reactivity due to higher volatile matter, excessive biomass combined with reduced structural mineral content may accelerate combustion kinetics, leading to rapid burnout and unstable flame

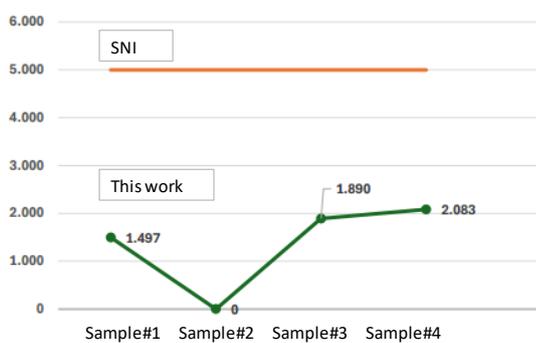
behavior. The reduced FABA fraction may also decrease heat retention capacity, causing faster temperature drop during combustion.

These findings demonstrate a trade-off between combustion stability and thermal intensity. Higher FABA content enhances burning duration but reduces peak temperature, whereas higher biomass content increases reactivity but shortens burning time.

2) Calorific Value Analysis

The calorific value (CV) results obtained using bomb calorimetry are presented below (Figure 6):

Composition	Calorific Value (cal/g)
60:10:20:10	1497
70:10:10:10	–
50:30:10:10	1890
40:40:10:10	2083



The highest calorific value (2,083 cal/g) was obtained from the composition containing 40% FABA and 40% pecan shell. The increased biomass fraction contributed additional fixed carbon and volatile matter, which enhanced total heat release during complete combustion. Biomass-derived char contains lignocellulosic carbon structures that generate higher heating values compared to mineral-rich ash residues.

Conversely, the lowest calorific value (1,497 cal/g) was observed in the 60% FABA formulation. The high inorganic fraction in FABA reduces the combustible portion of the briquette, thereby lowering the total energy density per unit mass.

However, it is important to note that none of the briquette samples met the Indonesian National Standard (SNI $\geq 5,000$ cal/g) or the Japanese briquette standard (6,000–7,000 cal/g). The relatively low calorific values indicate that the high ash content in FABA significantly limits energy density. This result is consistent with the intrinsic properties of coal

combustion residues, which contain limited fixed carbon compared to raw biomass or coal.

C. Relationship Between Calorific Value and Combustion Duration

An inverse relationship was observed between calorific value and flame duration. The composition with the highest calorific value (40% biomass) exhibited the shortest burning time, whereas the composition with the longest burning time (70% FABA) did not achieve the highest calorific value.

This phenomenon suggests that combustion rate plays a crucial role in determining flame duration. Higher calorific value corresponds to higher reactivity and faster heat release, leading to shorter burning time. In contrast, higher ash content slows reaction kinetics, extending combustion duration but reducing peak heat output.

Therefore, briquette formulation must be tailored according to intended application:

- Long-duration heating applications benefit from higher FABA content.
- High-intensity, short-duration heating applications benefit from higher biomass content.

D. Combustion Efficiency and Residual Ash

Post-combustion mass measurements indicated residual ash fractions between 15–16 g depending on formulation. The relatively high residual mass confirms that FABA significantly contributes to ash formation. While high ash content reduces energy density, it may improve structural stability during combustion and reduce deformation.

However, excessive ash formation may lead to clinker formation and reduced combustion chamber efficiency in practical applications. Therefore, further optimization—such as reducing FABA percentage or introducing supplementary high-carbon biomass—may improve energy performance without eliminating waste valorization benefits.

E. Practical Implications and Application Potential

Despite not meeting SNI calorific standards, FABA-based briquettes demonstrate potential as:

- Supplementary fuel in small-scale industrial furnaces
- Low-intensity domestic heating applications
- Waste-to-energy pilot programs near coal power plants

The 70% FABA composition is recommended for applications requiring longer, stable combustion with moderate heat output. Meanwhile, the 40% FABA formulation is suitable for applications demanding higher heat intensity within shorter durations.

From a sustainability perspective, the integration of FABA into briquette production contributes to:

- Reduction of industrial waste disposal
- Partial substitution of conventional fossil fuels
- Promotion of circular economy practices
- Mitigation of environmental risks associated with ash accumulation

However, for commercial viability, improvements in calorific value are necessary. Potential enhancement strategies include:

- Increasing pyrolysis temperature to raise fixed carbon content
- Adding high-energy biomass such as coconut shell char
- Optimizing compaction pressure to improve density

This study provides experimental evidence that FABA from coal-fired power plants can be incorporated into briquette fuel formulations, influencing combustion stability, temperature behavior, and energy density. The results clarify the trade-off between ash fraction and thermal performance, contributing to the understanding of mineral-rich briquette combustion dynamics.

The research also fills a gap regarding FABA utilization specifically from PLTU Ombilin, demonstrating its feasibility in solid fuel applications.

The results confirm that raw material composition significantly affects combustion characteristics. Increasing FABA content enhances flame duration but lowers calorific value, while increasing biomass fraction improves energy density but shortens burning time. Therefore, optimization depends on the intended thermal application.

Although calorific performance remains below international standards, the environmental and waste management benefits position FABA briquettes as a promising transitional alternative fuel, particularly in regions with abundant coal combustion residues.

4. Conclusion

This study investigated the feasibility of utilizing Fly Ash Bottom Ash (FABA) waste

from PLTU Ombilin as a raw material for briquette production, focusing on combustion characteristics. The results confirm that variations in material composition significantly influence flame duration, combustion temperature, and calorific value.

Briquettes with higher FABA content (70%) exhibited the longest flame duration (4 min 3 s) and relatively stable combustion behavior, indicating improved burning stability due to the mineral-rich composition. However, the average combustion temperature was moderate (243 °C), reflecting the lower reactive carbon fraction in FABA. Conversely, briquettes containing higher proportions of pecan shell biomass (40%) achieved the highest calorific value (2,083 cal/g), but displayed shorter combustion duration (1 min 33 s), indicating faster burnout and higher combustion reactivity.

The findings reveal a trade-off between combustion stability and energy density. Increasing biomass content enhances calorific value but reduces burning duration, while increasing FABA content prolongs combustion but lowers heat intensity. None of the formulations met the Indonesian National Standard (SNI \geq 5,000 cal/g) or Japanese briquette standards, primarily due to the high ash fraction in FABA. Nevertheless, the results demonstrate that FABA can be incorporated into briquette formulations without compromising structural integrity and basic combustion functionality.

From a sustainability perspective, the utilization of FABA as a briquette material contributes to industrial waste reduction, supports circular economy principles, and provides an alternative solid fuel option with potential applications in low- to moderate-heat demand sectors. The formulation containing 70% FABA is recommended for applications requiring longer and stable combustion, whereas the 40% FABA formulation is more suitable for short-duration, higher-intensity heat applications.

Future research should focus on optimizing biomass proportion, increasing fixed carbon content through controlled pyrolysis conditions, and incorporating higher-energy biomass materials to improve calorific value. Additionally, comprehensive proximate and ultimate analyses, emission characterization, and mechanical strength testing are recommended to further assess commercial viability.

Overall, this study demonstrates that FABA-based briquettes represent a promising pathway

for coal ash valorization, bridging industrial waste management and alternative energy development.

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