JURNAL REKAYASA PROSES
VOLUME 19, NUMBER 2, 2025, xx–xx

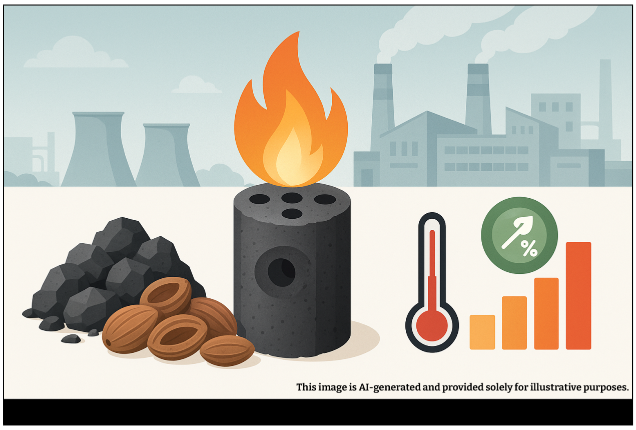
RESEARCH ARTICLE TYPE

Optimization of co-firing briquette fuel from coal waste and palm kernel shells: Enhancing energy efficiency and waste valorization

Salomo Pranata Aji[1], Dian Ayu Afifah[1], Fadian Farisan Silmi[1], Devy Cendekia[1], Yeni Ria Wulandari[1], Adityas Agung Ramandani[2], Shintawati[1,*]

[1]Department of Industrial Chemical Engineering Technology, Lampung State Polytechnic, No.10, Soekarno Hatta Rd, Rajabasa, Bandar Lampung City, 35141, Indonesia
[2]Department of Chemical Engineering and Materials Science, Yuan Ze University, No. 135, Yuandong Rd, Zhongli District, Taoyuan City, 320, China

Received 13 September 2024; revised 10 May 2025; accepted 19 May 2025



OBJECTIVES The low-rank coal is increasing every year but still slightly exploited by the industry, due to it being caused by the low-calorie value of the low-rank coal waste. Therefore, the mixture of other biomass is expected to raise the calorie value. This approach could potentially make the low-rank coal more economically viable for use in various industries, especially as a source of energy. Additionally, further research and development in this area could lead to more efficient and sustainable energy production methods. METHODS The study uses the Central Composite Design (CCD) with ratio of low-rank coal waste and palm kernel shells of 40:60 %(w/w), 60:40 %(w/w), and 80:20 %(w/w), and variations of the glue starch (5 to 7%), which have been optimized and validated using the Response Surface Method (RSM) approach. RESULTS The results of the study showed volatile matter, fixed carbon, and calorie values of 61.43% to 71.69%, 16.56% to 26.98%, and 5190.44 to 6330.40 Kcal/g, respectively. The results also demonstrated that the glue with 6% variation showed the highest fixed carbon content and calorie value in comparison to the other variations. The optimum of concentration of low-rank coal and palm kernel shell for co-firing of 80: 20%(w/w) with 5% glue addition resulting in a volatile matter, fixed carbon, calorie value, burn ability, of 61.44%, 26.79%, 6251.16 Kcal/g, and 0.05 g/min, respectively. The validation process also met the requirements for SNI 01-6235-2000 and SNI 8675-2018. CONCLUSIONS Overall, the study concluded that the co-firing of low-rank coal waste and palm kernel shell with glue starch can result in an optimized fuel mixture with high performance characteristics. These findings are significant for industries looking to improve their energy efficiency and reduce emissions.

KEYWORDS co-firing briquet, energy efficiency, low-rank coal, palm kernel shell, validation process

1. INTRODUCTION

Indonesia is experiencing significant growth and improvements across various sectors, including the electrical industry, milling industry, and palm oil production. This industrial development necessitates a constant and reliable supply of energy to sustain production levels. Coal, due to its relatively low cost compared to other fossil fuels like oil and natural gas, remains a primary energy source for the country's burgeoning industrial activities. According to ISO standards, coal is classified based on its calorific value into Low-Rank (<5,100 Kcal/kg), Medium-Rank (5,100 Kcal/kg – 6,100 Kcal/kg), and High-Rank (6,100 Kcal/kg – 7,100 Kcal/kg) categories. Since coal has varying heat content, it is preferable to use coal with a higher heat content for the same volume because it enhances combustion efficiency and reduces transportation costs (Kamal Baharin et al. 2022; Sattasathuchana et al. 2023; Vershinina et al. 2022). Consequently, Low-Rank Coal is often underutilized due to its lower heat content (Sardi et al. 2023). However, the reliance on higher-grade coal poses several challenges, including increased costs and potential supply constraints. Additionally, the environmental impact of coal combustion, particularly from higher sulfur and nitrogen content, raises concerns about air quality and greenhouse gas emissions (Ke et al. 2023; Larki et al. 2023; Nelson 2023). To address these issues, Indonesia is exploring alternative strategies to optimize its coal utilization while mitigating environmental impacts (Aguirre-Villegas and Benson 2017; Friederich and van Leeuwen 2017; Rahman and Raphael 2025). One such strategy involves the co-firing of Low-Rank

*Correspondence: shintawati@polinela.ac.id

 DOI 10.22146/jrekpros.16419

Coal with biomass materials, such as palm kernel shells, which are abundant byproducts of the palm oil industry. This approach not only leverages the existing low-cost energy resource but also provides a sustainable solution by incorporating renewable biomass into the energy mix. Through innovative practices and technologies, Indonesia aims to balance its energy needs with environmental sustainability, ensuring a more resilient and eco-friendly industrial growth trajectory.

In addition to its reliance on coal, Indonesia is one of the world's largest producers of palm oil. In 2018, the country produced 48.68 million tons of palm oil and palm kernels, including 40.57 million tons of crude palm oil (CPO) and 8.11 million tons of kernels (Yenny and Darajati 2023). The processing of one ton of fresh palm fruit (TBS) yields various byproducts, including 230 kg of empty fruit bunches, 65 kg of shell waste, 40 kg of wet solid decanter, 130 kg of fiber, and 500 kg of liquid waste. While researchers have extensively studied the valorization of byproducts such as empty fruit bunches (EFB) and palm fiber for bio-oil production (Wulandari et al. 2024; Ria Wulandari et al. 2025), this study will focus on exploring alternative uses, particularly bio-briquettes. This is due to the fact that palm kernel shell contains a calorific value of 3,500 Kcal/kg to 4,100 Kcal/kg (Kurniawan et al. 2024). This significant production results in large quantities of waste, including palm kernel shells, which are not suitable for oil production but possess good fuel properties. Given the magnitude of palm oil production, the effective management and utilization of these byproducts are critical. Palm kernel shells present an opportunity to be repurposed as a renewable energy source. Their high calorific value makes them a viable candidate for co-firing with coal, thus providing a dual benefit of waste reduction and energy production. By integrating palm kernel shells into the energy supply chain, Indonesia can enhance the sustainability of its palm oil industry while simultaneously addressing the environmental challenges associated with coal combustion. This approach not only supports waste valorization but also contributes to the diversification of energy resources, promoting a circular economy within the industrial sector.

The co-firing process, or co-combustion, involves burning two different types of fuels simultaneously in the same incineration device, often in steam-generating boilers. Co-firing coal with biomass can be integrated into existing coal-fired boiler systems (Kurniawan et al. 2024; Szufa et al. 2023; Wang 2023). This process reduces emissions of COx, SOx, and NOx gases, making it appealing for coal-fired steam power plants (Larki et al. 2023). Biomass is often considered a low-carbon fuel because it absorbs CO_2 during growth, which can partially offset emissions released during combustion; however, the actual carbon balance depends on factors such as land use changes, biomass sourcing, and regrowth practices. Additionally, biomass generally contains lower sulfur and nitrogen content than coal, which can further reduce NOx and SOx emissions. Implementing co-firing with biomass such as palm kernel shells can enhance the sustainability of power generation and help meet environmental regulations aimed at reducing greenhouse gas emissions. Furthermore, the utilization of agricultural waste like palm kernel shells in energy production supports waste management strategies, turning potential environmental liabilities into valuable resources. This synergy between waste reduction and energy production exemplifies a sustainable approach to industrial growth, aligning with global trends toward cleaner and more efficient energy systems. By adopting co-firing technologies, Indonesia can leverage its abundant biomass resources, reduce dependence on high-rank coal, and promote a more sustainable energy future. Although numerous studies have examined biomass utilization and coal co-firing independently, limited research has focused on the integration of low-rank coal waste with agricultural residues like palm kernel shells in optimized briquette form. Furthermore, previous work often overlooks the detailed influence of adhesive concentration and material ratios on key combustion and performance metrics. There remains a lack of comprehensive analysis using statistical optimization to determine the ideal composition that balances energy content, combustibility, and environmental performance.

The combination of low-rank coal and palm kernel shells aims to create a co-firing fuel that not only utilizes low-quality coal but also converts agricultural waste into a valuable energy resource. This study will evaluate the potential of this co-firing fuel by determining the optimum mixing ratio of low-rank coal and palm kernel shells, along with the appropriate adhesive composition. The quality of the resulting briquettes will be assessed based on several key properties, including calorific value, moisture content, ash content, volatile matter content, fixed carbon content, flame capacity, and combustibility. Ultimately, the findings are expected to provide insights into creating sustainable and efficient co-firing fuel, addressing both energy and waste management challenges.

2. MATERIALS AND METHOD

2.1 Preparation and production of briquet co-firing with coal and palm kernel shell waste

The physical pretreatment process involved washing and drying the palm kernel shell to remove small particles, followed by size reduction using a disk mill (Fritsch, Germany) to achieve a 60-mesh size. In the production of co-firing fuels, the experimental materials include low-rank coal and palm kernel shell, with varying concentrations relative to the total weight of the briquette. Coal waste and palm kernel shell were collected from PT. Bukit Asam Tbk.Unit Port of Tarahan and PT. Anaktuha Sawit Mandiri, respectively. Coal and palm kernel shells were blended at %(w/w) ratios of 40:60, 60:40, and 80:20, respectively. Kanji flour is used to produce glue starch, which serves as the adhesive component in the briquette mixture. Glue starch, serving as the adhesive component, is added to the mixture at concentrations of 5%, 6%, and 7% to ensure proper binding during briquette formation. The procedure begins with the preparation of the fuel mixture, where coal and palm kernel shell are blended according to the predetermined ratios, as shown in Table 1. Glue starch is then thoroughly mixed into the blend to achieve homogeneity. Subsequently, the mixed material is fed into a briquetting machine, where it undergoes compaction under controlled conditions: 10 tons of pressure applied for 20 mins at a temperature of 25°C. This process forms the mixture into dense, uniform briquettes suitable for combustion applications. Following briquette formation, the next step involves a drying process to remove excess moisture and volatile compounds,

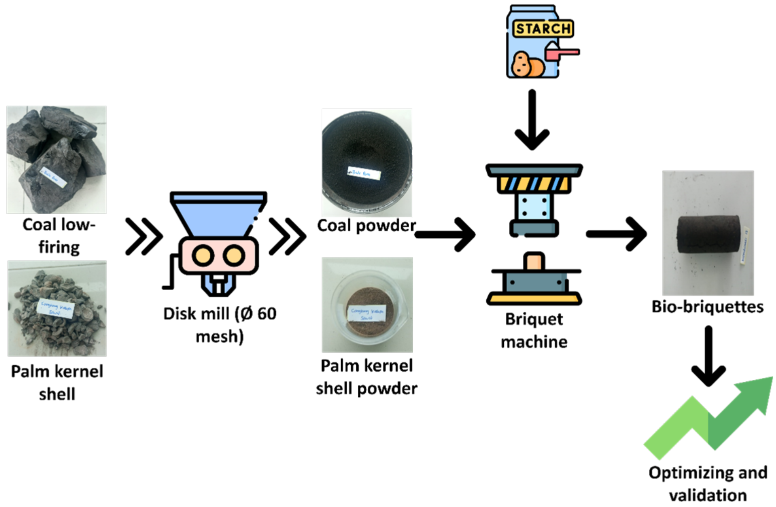


FIGURE 1. Preparation of bio-briquettes from combination of palm kernel shell and coal-low firing.

enhancing the briquettes' calorific value and stability. Drying typically occurs in a controlled environment such as a drying chamber or oven (Memmert, Germany), ensuring optimal moisture reduction without compromising the integrity of the briquettes, as shown in Figure 1.

To optimize the formulation parameters, Response Surface Methodology (RSM) is employed. RSM facilitates systematic experimentation to explore interactions between coal concentration, palm kernel shell concentration, and glue starch concentration, as shown in Table 1. Statistical analysis of experimental results enables researchers to identify the optimal combination of these factors that maximize the briquettes' performance characteristics, including calorific value, mechanical strength, and combustion efficiency. Finally, the optimized briquettes undergo evaluation for their performance metrics through rigorous testing procedures. These evaluations include calorific value measurements, mechanical strength assessments, and combustion trials to ensure compliance with industry standards and performance criteria. Briquettes meeting these criteria are then stored under appropriate conditions, ready for deployment in co-firing applications across various industrial sectors.

The co-firing fuel quality analysis of coal and palm kernel shells in the form of bricks has several test parameters slightly modified by Elisa et al. (2024); Fernando et al. (2024); Herlambang et al. (2023).

2.2 Moisture content

To determine the moisture content, a 1-gram sample is weighed (Mettler Toledo, Switzerland) and recorded as the initial weight (W_1). Calibration of the balance is performed according to the manufacturer guidelines to ensure accurate measurements. The sample is then placed in an oven set at a temperature of 104-110°C and allowed to dry for 1 hour until it reaches a constant weight. After drying, the sample is removed from the oven and cooled in a desiccator to prevent moisture absorption. Once cooled, the sample is weighed again and recorded as the final weight (W_2). The moisture content is then calculated using Equation 1.

$$\text{Moisture (\%)} = \left(\frac{W_1 - W_2}{W_2}\right) X\ 100 \tag{1}$$

TABLE 1. Experimental design using design expert version 13 with 3 variables, such as glue-starch and ratio raw materials (i.e. coal low-firing and palm kernel shell).

Combination	Concentration Glue starch (%)	Ratio of raw materials in (% w/w)	
		Coal low-firing	Palm kernel shell
1	5	40	60
2	7	40	60
3	5	80	20
4	7	80	20
5	5	60	40
6	7	60	40
7	6	40	60
8	6	80	20
9	6	60	40
10	6	60	40
11	6	60	40
12	6	60	40
13	6	60	40

2.3 Ash content

A 1-gram sample of the coal briquette is placed into a crucible, which is then placed in a furnace. The sample is initially heated to 450-500°C for 1 hour, followed by an increase in temperature to 700-750°C for an additional 2 hours. The final heating step is conducted at 900-950°C for another 2 hours. After the heating process is complete, the crucible is removed from the furnace and allowed to cool in a desiccator. Once cooled, the crucible is immediately weighed to determine the ash weight. The ash ratio is then calculated using Equation 2.

$$Ash\,(\%) = \frac{\text{Weigh of ash}}{\text{Initial weigh of sample}} \times 100 \tag{2}$$

2.4 Volatile matter and fixed carbon

To determine the level of evaporated substances, a crucible cup with a lid is first weighed, and the cup is filled with specimens obtained from the moisture content calculations. The crucible is then placed in a furnace and heated to a temperature of 950 ± 20°C for 7 mins. After heating, the crucible is cooled in a desiccator to prevent moisture absorption and then weighed again. The levels of volatile substances are calculated based on Equation 3.

$$\text{Volatile matter}\,(\%) = \frac{B-C}{A} \times 100\% \tag{3}$$

Where A, B, and C stand for the sample weight, the weight of the cup and sample after drying, and the weight of the cup and sample prior to drying, respectively.

The bound carbon content (Fixed Carbon) is determined based on Equation 4.

$$FC(\%) = 100 - (Ash + VM + Moisture) \tag{4}$$

Where, FC is fixed carbon and VM is volatile matter. These calculations are essential for evaluating the combustion properties of the fuel samples, providing insights into their efficiency and suitability for energy production.

2.5 Burn ability test

The burn rate testing is a process that involves burning briquettes to determine the duration of combustion of fuel, followed by weighing the mass of the burnt briquettes. The burning time is measured using a stopwatch, and the mass of the briquettes is weighed with a digital scale. Equation 5 was used to determine the burn rate.

$$\text{Burn ability (g/min)} = \frac{m_1 - m_2}{t} \tag{5}$$

Where, m_1, m_2, and t indicated mass before burning (g), after burning (g), and time (min), respectively.

2.6 Calorific value

After completing the calibration steps and ensuring that the W value is within the allowable limits, the experiment can proceed. To determine the calorific value of the fuel, the following formula is used. The calculation of the heating value contained in the sample is expressed in Equation 6.

$$H_g = \frac{\Delta t \times W - e_3}{m} \tag{6}$$

Where, H_g, W, m, Δt, and e_3 represent the calorific value, equivalent energy from calibration results (Cal/°C), mass of the fuel (g), the temperature difference before and after ignition, and the correction factor for heat formation in the fuse fire, respectively.

2.7 Statistical analysis

In this study, statistical analysis was performed to evaluate the significance of the effects of different parameters on the briquette properties. The analysis was conducted using one-way Analysis of Variance (ANOVA) and two-tailed t-tests, with a significance level set at $p \leq 0.05$. One-way ANOVA was applied to compare the means of multiple groups (e.g., different ratios of low-rank coal and palm kernel shell or varying glue starch concentrations) to assess whether there were statistically significant differences among the groups. ANOVA helps to identify whether any of the independent variables significantly affect dependent variables such as calorific value, volatile matter, and other briquette properties. Subsequently, two-tailed t-tests were used to compare the differences between two specific groups or experimental conditions. This test checks for significant differences in means between pairs of groups, which can help in confirming the specific combinations of raw materials and glue starch concentrations that lead to the best performance. The significance level for both ANOVA and t-tests was set at $p \leq 0.05$, meaning that differences with p-values less than or equal to 0.05 were considered statistically significant. All statistical analyses were conducted using Design Expert software version 13, which allowed for efficient model building, optimization, and interpretation of the experimental results.

3. RESULTS AND DISCUSSION

3.1 Analysis of raw materials between palm kernel shell and coal low-firing

Table 2 summarizes the characteristics of palm kernel shell and low-firing coal, highlighting key parameters such as moisture content, ash content, volatile matter, fixed carbon, and calorific value.

The moisture content of palm kernel shell of 7.09%, which is significantly lower than the 14.73% found in low-rank coal. This lower moisture content indicates that palm kernel shell may require less energy for combustion, potentially resulting in a higher effective calorific value when burned. Reducing moisture content is essential for enhancing fuel efficiency, as fuels with high moisture levels can lead to incomplete combustion and reduced energy output. In terms of ash content, palm kernel shell exhibits a value of 3.12%, compared to 4.92% for low-rank coal. The lower ash content in palm kernel shell is advantageous, as it results in less residue after combustion, facilitating easier handling and reducing the need for extensive ash disposal methods. This can lead to cost savings and improved operational efficiency in combustion systems. The volatile matter content in palm kernel shell is notably high at 72.45%, while low-rank coal has a

TABLE 2. Characteristic raw materials between palm kernel shell and coal low-firing.

Parameter	Palm kernel shell	Coal low-firing
Moisture content (%)	7.0900	14.7256
Ash content (%)	3.1181	4.9195
Volatile matter (%)	72.4510	39.7435
Fixed carbon (%)	17.3408	40.6114
Calorific (Kcal)	n.d.	4958

n.d. indicated not displayed

lower volatile matter content of 39.74%. The high volatile matter in palm kernel shell suggests that it can ignite more readily and sustain a more vigorous combustion process, making it suitable for applications that require rapid energy release. Conversely, the lower volatile matter in coal may provide a steadier and prolonged combustion, which is beneficial for applications needing consistent heat output over extended periods. The fixed carbon content in palm kernel shell is measured at 17.34%, in contrast to 40.61% for low-rank coal. The higher fixed carbon content in coal correlates with greater energy density, indicating that coal can produce more energy per unit mass compared to palm kernel shell. As compared with other materials (i.e., coconut shell) have moisture content, ash content, volatile matter, and fixed carbon of 10.5%, 0.80%, 71.1%, and 17.6%, respectively (Hazman et al. 2024). This characteristic makes low-rank coal more suitable for applications requiring high energy output, such as in industrial processes or electricity generation. The calorific value for low-rank coal is reported at 4958 Kcal. Understanding the calorific value of palm kernel shell is crucial for evaluating its potential as a viable fuel alternative.

3.2 The influence of glue-starch percentage and raw material ratio on characteristics and analysis variance analysis for improving bio-briquette quality

The analysis investigated the effects of varying glue-starch percentages and raw material ratios on the quality of bio-briquettes, with particular focus on moisture content, ash content, volatile matter, fixed carbon, burn ability, and calorific value, as shown in Table 3. In this study, the specific values of 5%, 6%, and 7% were deliberately chosen to observe the progressive influence of small incremental changes in binder concentration on briquette characteristics such as calorific value, burn ability, and fixed carbon. A previous study conducted by Saifurrizal (2013) has reported that glue-starch concentrations ranging from 5% to 25% were used in bio-briquette formulations. The findings indicated that higher binder levels, specifically at 15% glue-starch, resulted in a reduction of the calorific value by 159 cal/gram. Lower concentrations may result in insufficient bonding, while higher levels can negatively impact burn efficiency and calorific value. The results indicate that a higher glue-starch percentage generally increases moisture content and slightly affects ash content, volatile matter, and fixed carbon levels, ultimately influencing the calorific value and burn ability of the bio-briquettes.

Overall, the variance analysis shows that the combination of 5% glue-starch, 40% low-rank coal, and 5% palm kernel shell yielded the highest calorific value of 6330.4 Kcal/g, with a balanced burn ability of 0.093 g/min. Meanwhile, increasing the glue-starch percentage to 7% resulted in lower calorific values and altered combustion characteristics, indicating that the optimal glue-starch percentage for bio-briquette quality improvement may lie closer to 5%. This result suggests that a lower percentage of glue-starch is more favorable for maximizing energy output. Glue-starch, derived from kanji flour, is primarily composed of carbohydrates with relatively low calorific content compared to coal and palm kernel shell. As the binder concentration increases beyond 5%, the proportion of low-energy-density material in the briquette also increases, which in turn reduces the overall calorific value. Moreover, excessive binder may hinder combustion efficiency by reducing the availability of combustible solid particles and increasing moisture retention, leading to incomplete combustion (Chavda and Mahanwar 2018; Chirchir, D. K ., Nyaanga , D. M., Githeko, J. M.

TABLE 3. Characteristics of bio-briquettes from coal low firing and palm kernel shell based on moisture, ash, volatile meter, fixed carbon, burn ability, and calorific value.

Glue-starch (%)	Coal low firing (%)	Palm kernel shell (%)	Moisture content (%)	Ash content (%)	Volatile meter (%)	Fixed carbon (%)	Burn ability (g/min)	Calorific value (Kcal/g)
5	40	5	6.38	3.67	70.81	19.13	0.093	6330.4
7	40	7	7.67	3.8	71.96	16.56	0.093	5284.52
5	80	5	6.38	5.2	61.43	26.98	0.054	6300.3
7	80	7	7.59	5.29	63.59	23.51	0.058	5289.83
5	60	5	6.65	4.31	65.77	23.25	0.071	6138.07
7	60	7	7.8	4.63	67.4	20.15	0.074	5190.44
6	40	6	6.77	3.75	71.22	18.25	0.092	5693.9
6	80	6	6.99	5.82	62.58	24.59	0.054	5601.84
6	60	6	6.97	4.89	66.92	21.2	0.076	5647.72
6	60	6	6.93	4.73	65.95	22.78	0.078	5670.22
6	60	6	6.94	4.54	65.95	22.56	0.076	5604.08
6	60	6	6.85	4.25	66.8	22.09	0.074	5614.31
6	60	6	6.96	4.52	66.95	21.56	0.079	5668.61

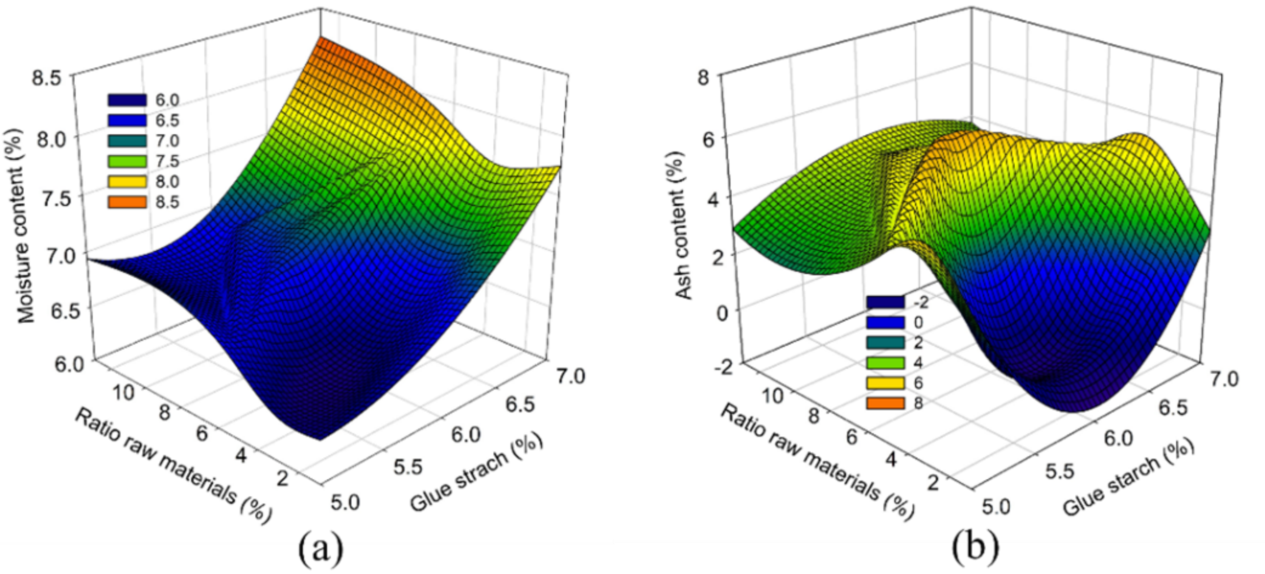


FIGURE 2. Characteristics of co-firing briquettes for (a) moisture content, (b) ash content.

2013). Therefore, maintaining a lower glue-starch content enhances the briquette's fuel quality by optimizing the balance between binding strength and energy density.

3.3 Moisture content and ash content

Figure 2 provides a detailed comparison of the compositional variations across different experimental conditions (RSM combinations), focusing on key material properties: water content, ash content, volatile matter, and fixed carbon.

In Figure 2 (a), the 7% starch glue, 60% coal low-firing, and 40% palm kernel shell exhibited the highest water content at 7.8084%, highlighting the influence of higher binder levels on moisture absorption. Conversely, the 5% starch glue, 40% coal low-firing, and 60% palm kernel shell had the lowest water content at 6.3887%, suggesting that the starch component may reduce water retention. This lower water content is generally preferred for materials where reduced moisture absorption is advantageous. Regarding ash content, the 6% starch glue, 80% coal low-firing, and 20% palm kernel shell showed the highest level at 5.8271%, indicating a greater amount of mineral residue after combustion. Conversely, the 5% starch glue, 40% coal low-firing, and 60% palm kernel recorded the lowest ash content at 3.6774%, which might be due to either more efficient combustion of organic components or lower mineral content in the raw materials. Lower ash content is usually preferable as it signifies cleaner combustion and less residue.

The ANOVA (Table 4) shows that the model is highly significant for both water content (F-value = 60.27, $p < 0.0001$) and ash content (F-value = 44.42, $p < 0.0001$), indicating that the factors considered significantly influence these quality parameters in co-firing briquettes. Factor A (Glue starch) has a highly significant effect on water content (F-value = 283.64, $p < 0.0001$), suggesting that varying the concentration of glue starch significantly impacts moisture retention in the briquettes. In contrast, Factor B (Coal Composition) does not significantly affect water content (F-value = 0.4173, $p = 0.5389$), indicating that the composition of coal used in the briquettes has minimal influence on moisture levels. For ash content, Factor B (Coal Composition) shows a highly significant effect (F-value = 87.86, $p < 0.0001$), indicating that the type of coal used strongly influences the residual ash content after combustion. The interaction term AB, and quadratic terms A^2 and B^2, do not significantly contribute to water or ash content variability.

TABLE 4. ANOVA summary for moisture content (%) and ash content (%).

Source	Sum of Squares	df	Mean Square	F-value	p-value	Sum of Squares	df	Mean Square	F-value	p-value
	Moisture content (%)					Ash content (%)				
Model	2.36	5	0.4718	60.27	<0.0001	4.37	2	2.18	44.42	<0.0001
A	2.22	1	2.22	283.64	<0.0001	0.0486	1	0.0486	0.9889	0.3435
B	0.0033	1	0.0033	0.4173	0.5389	4.32	1	4.32	87.86	<0.0001
Residual	0.0548	7	0.0078			0.4915	10	0.0491		
Lack of Fit	0.0458	3	0.0153	6.78	0.0477	0.2590	6	0.0432	0.7425	0.6461
Pure Error	0.0090	4	0.0023			0.2325	4	0.0581		
Cor Total	2.41	12				4.86	12			
Std. Dev.	0.0885					0.2217				
R^2	0.9773					0.8988				
Equations	$6.95 + 0.6083*A + 0.2129*A^2 - 0.1321*B^2$					$4.57 + 0.8483*B$				

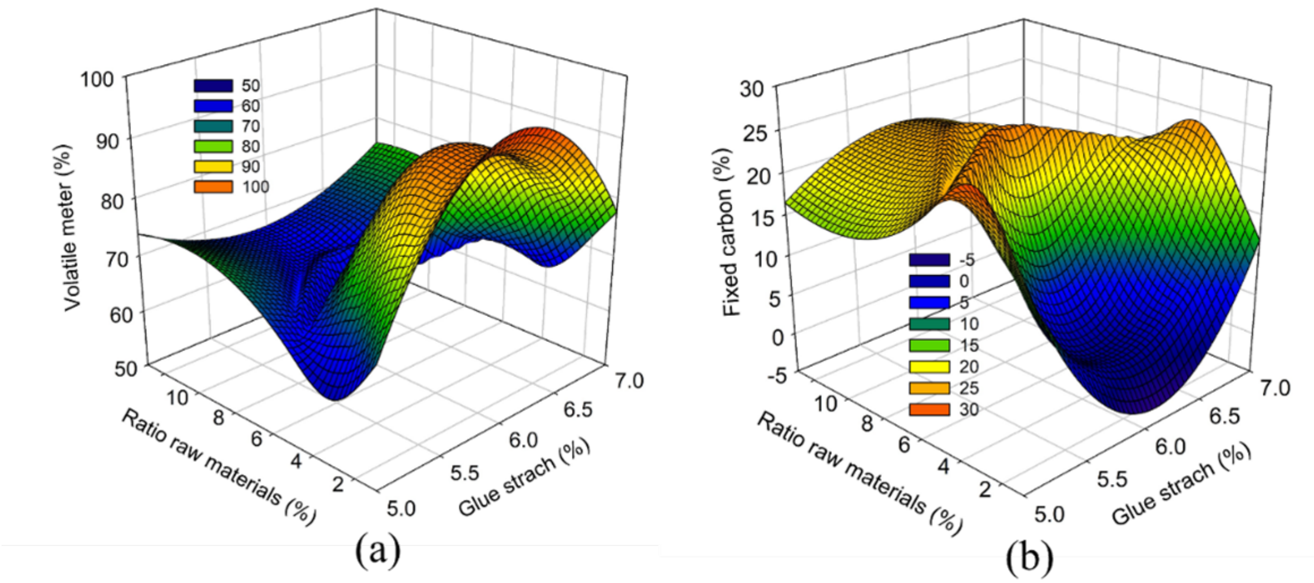


FIGURE 3. Characteristics of co-firing briquettes for (a) volatile meter, (b) fixed carbon.

3.4 Volatile matter and fixed carbon

In Figure 3b, the 7% starch glue, 40% coal low-firing, and 60% palm kernel shell had the highest volatile matter at 71.958%, indicating greater potential for rapid ignition and combustion efficiency. This highly volatile matter is beneficial for applications requiring quick and efficient burning. On the other hand, the 5% starch glue, 80% coal low-firing, and 20% palm kernel shell had the lowest volatile matter at 61.4267%, which might be due to variations in material composition affecting the release of volatile gases during combustion.

Regarding fixed carbon, the 5% starch glue, 80% coal low-firing, and 20% palm kernel shell exhibited the highest content at 26.9776%, suggesting higher carbonization efficiency or a denser structure that supports slower combustion rates and greater energy output. This high fixed carbon content is advantageous for applications where sustained energy release and efficiency are desired. In contrast, the 7% starch glue, 40% coal low-firing, and 60% palm kernel shell showed the lowest fixed carbon content at 16.6662%, potentially due to lower carbonization temperatures or less effective conversion of organic matter into fixed carbon. The 5% starch glue, 40% coal low-firing, and 60% palm kernel shell are generally preferable for applications where reduced water absorption and low ash content are desired, indicating a cleaner and more efficient combustion process. However, the 5% starch glue, 80% coal low-firing, and 20% palm kernel shell are better suited for scenarios requiring high energy output and sustained combustion due to its higher fixed carbon content. The choice of the best combination depends on the specific application requirements for moisture control, combustion efficiency, and energy output.

Similarly, the ANOVA table reveals significant effects on volatile matter (F-value = 295.65, $p < 0.0001$) and fixed carbon (F-value = 140.79, $p < 0.0001$). Factor A (glue-starch) significantly affects both volatile matter (F-value = 20.85, $p = 0.0010$) and fixed carbon (F-value = 44.35, $p < 0.0001$), indicating that the concentration of glue starch influences the combustible gases released and the carbon content in the briquettes. Factor B (ratio raw material) also shows significant effects on volatile matter (F-value = 570.45, $p < 0.0001$) and fixed carbon (F-value = 237.23, $p < 0.0001$), highlighting its strong influence on the combustion characteristics and carbonization process of the briquettes. The residual analysis shows adequate model fit for all parameters, with lack of fit tests in-

TABLE 5. ANOVA summary for volatile matter (%) and fixed carbon (%).

Source	Sum of Squares	df	Mean Square	F-value	p-value	Sum of Squares	df	Mean Square	F-value	p-value
	Volatile matter (%)					Fixed carbon (%)				
Model	121.5	2	60.75	295.65	<0.0001	88.41	2	44.2	140.79	<0.0001
A	4.28	1	4.28	20.85	0.001	13.92	1	13.92	44.35	<0.0001
B	117.22	1	117.22	570.45	<0.0001	74.48	1	74.48	237.23	<0.0001
Residual	2.05	10	0.2055			3.14	10	0.314		
Lack of Fit	0.8611	6	0.1435	0.4809	0.7981	1.38	6	0.2305	0.525	0.771
Pure Error	1.19	4	0.2984			1.76	4	0.4391		
Cor Total	123.56	12				91.55	12			
Std. Dev.	0.4533					0.5603				
R^2	0.9834					0.9657				
Equations	66.90 + 0.8450*A – 4.42*B					21.74 - 1.52*A + 3.52*B				

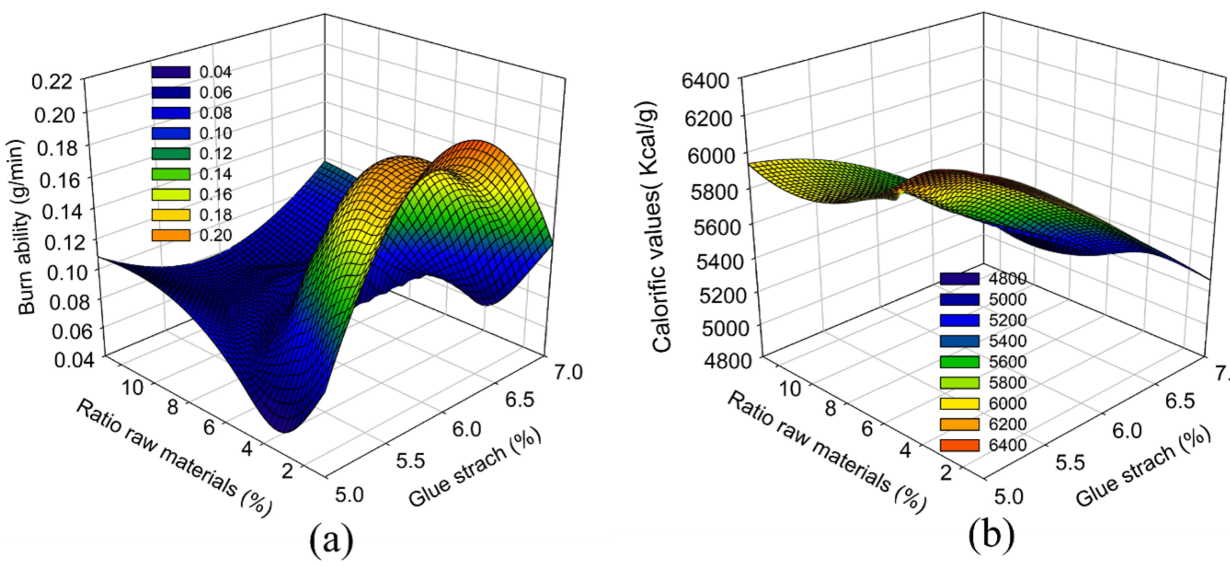


FIGURE 4. Characteristics of co-firing briquettes for (a) burn ability, (b) calorific value.

dicating no significant deviations (p-values > 0.05). Overall, the high R^2 values (0.9773 for water content, 0.8988 for ash content, 0.9834 for volatile matter, and 0.9657 for fixed carbon) suggest that the models explain a substantial proportion of the variability in each quality parameter. The provided equations allow for the prediction of water content, ash content, volatile matter, and fixed carbon based on different concentrations and combinations of glue starch and coal composition, providing valuable insights for optimizing the production of co-firing briquettes for enhanced energy efficiency and environmental sustainability. These findings underscore the importance of carefully selecting and balancing adhesive and coal components to achieve desired briquette qualities.

3.5 Burn ability and calorific value

Figure 4 illustrates comparisons among combinations regarding burnability and calorific value. These parameters are critical for assessing the overall performance and suitability of the briquettes as a renewable energy source. The data support the hypothesis that varying adhesive content and material composition significantly influence combustion characteristics, ash formation, and energy yield of co-firing briquettes. The combustion behavior and calorific values of the briquettes were investigated across various combinations, each differing in adhesive content and material composition. The 5% starch glue, 40% coal low-firing, and 60% palm kernel shell exhibited the highest combustion speed at 0.093052 g/min, indicating a rapid burn rate. In contrast, the 5% starch glue, 80% coal low-firing, and 20% palm kernel shell showed a longer combustion duration with a slower rate of 0.054533 g/min. The slower combustion rate observed in the 5% starch glue, 80% coal low-firing, and 20% palm kernel shell is desirable as it extends the briquette's burning time, contributing to increased fuel efficiency and reduced frequency of refueling. While both parameters are essential, calorific value is generally more critical, as it directly reflects the energy content of the fuel and determines its overall effectiveness in energy production (Chavda and Mahanwar 2018). Burnability, which influences how quickly and steadily the fuel combusts, is also important for practical applications requiring sustained heat output (Utami et al. 2024). However, a high calorific value ensures that more energy is released per unit of fuel, making it the key factor in evaluating fuel quality.

The 5% starch glue, 40% coal low-firing, and 60% palm kernel shell also demonstrated the highest calorific value

TABLE 6. ANOVA summary for burn ability (g/min) and calorific value (%).

Source	Sum of Squares	df	Mean Square	F-value	p-value	Sum of Squares	df	Mean Square	F-value	p-value
	Burn ability (g/min)					Calorific value (cal/g)				
Model	0.0021	2	0.001	196.25	<0.0001	1.56E+06	5	3.12E+05	110.98	<0.0001
A	8.17E-06	1	8.17E-06	1.53	0.2448	1.50E+06	1	1.50E+06	534.64	<0.0001
B	0.0021	1	0.0021	390.97	<0.0001	2275.93	1	2275.93	0.809	0.3983
Residual	0.0001	10	5.35E-06			19691.68	7	2813.1		
Lack of Fit	0	6	6.38E-06	1.68	0.3206	15954.81	3	5318.27	5.69	0.0631
Pure Error	0	4	3.80E-06			3736.86	4	934.22		
Cor Total	0.0022	12				1.58E+06	12			
Std. Dev.	0.0023					53.04				
R^2	0.9572					0.9875				
Equations			$0.0748 - 0.0187*B$					$5623.04 - 500.66*A + 86.09*A^2$		

recorded at 6330.40 Kcal/gram. This superior energy content was achieved with only 5% adhesive and an 80:20 ratio of raw material to binder, indicating that effective energy performance can be achieved even with lower binder content when the composition is optimized. In contrast, the formulation containing 7% starch glue, 60% coal low-firing, and 40% palm kernel shell yielded the lowest calorific value at 5190.44 Kcal/gram, despite a higher adhesive content. Additionally, the 7% starch glue, 60% coal low-firing, and 40% palm kernel shell exhibited the lowest calorific value at 5190.44 Kcal/gram, utilizing 7% adhesive and a composition ratio of 60% raw material to 40% binder. This inverse relationship suggests that increasing binder content beyond an optimal point may dilute the energy-rich components, leading to reduced calorific performance. These findings align with those of (Olugbade et al. 2019)Olugbade et al. (2019), who reported that excess binder can decrease calorific value due to its lower energy density compared to lignocellulosic biomass. Similarly, studies by Zou and Manthiram (2020) have shown that optimal binder ratios are necessary to balance mechanical strength with energy yield.

These results underscore a critical trade-off between calorific value and burnability. While higher adhesive content can improve structural integrity and combustion uniformity, it may reduce the proportion of combustible raw materials, thus lowering net energy output. Conversely, a lower binder content if complemented by high-energy constituents like palm kernel shell can maintain both high calorific values and effective burnability. The 5% starch glue formulation exemplifies this balance, achieving both strong briquette integrity and superior energy release.

Furthermore, palm kernel shells are known for their high lignin content, which contributes to higher calorific values (Chang et al. 2016; Ma et al. 2018). This supports the observation that increasing the proportion of palm kernel shell in the mixture directly enhances energy output, especially when not offset by excessive binder. To comprehensively evaluate the performance of these briquettes, future studies should assess additional properties such as ash content, mechanical durability, emissions, and ignition characteristics. Such multidimensional analysis is crucial for optimizing briquette design for specific energy applications, whether for household heating or industrial fuel substitution.

The ANOVA (Table 6) provided offers a comprehensive analysis of how different factors influence the burn ability and calorific value of co-firing briquettes. For burn ability (g/min), the model shows significant overall influence (F-value = 196.25, $p < 0.0001$), indicating that the combined effects of Glue starch (Factor A) and ratio raw materials (Factor B) significantly impact how quickly the briquettes burn. Specifically, glue starch alone does not show a significant effect (F-value = 1.53, p = 0.2448). Combination demonstrates a highly significant impact (F-value = 390.97, $p < 0.0001$). This suggests that the choice and proportion of raw materials used in the briquettes play a crucial role in their burn efficiency. The interaction term (AB) and quadratic terms (A^2 and B^2) do not significantly contribute to burn ability, indicating that their effects are not pronounced in this context.

Similarly, for calorific value (%), the ANOVA model is highly significant (F-value = 110.98, $p < 0.0001$), indicating that the factors considered explain a significant portion of the variability in calorific value. Glue starch (Factor A) shows a strong influence (F-value = 534.64, $p < 0.0001$), indicating that varying the concentration of adhesive significantly affects the energy content of the briquettes. In contrast, ratio raw materials (Factor B) does not significantly affect calorific value (F-value = 0.8090, p = 0.3983), suggesting that while it impacts burn ability, it does not alter the energy content per unit mass. The quadratic terms (A^2 and B^2) show marginal significance, suggesting a potential nonlinear relationship that warrants further investigation. Overall, the high R^2 values (0.9572 for burn ability and 0.9875 for calorific value) indicate that the model effectively predicts the variability in these quality parameters based on the concentrations and combinations of Glue starch and raw materials used in the briquettes.

3.6 Optimizing and validation using response surface method (RSM) approach

The optimization of this study using the Response Surface Method to find the optimal point of comparison of concentration of coal and palm shell mixtures and glue starch concentration in the production of co-firing briquet with the goal in range studied in Table 7, the optimum point obtained is at the concentration addition of starch glue 5% with comparison concentration mixture of coals and palm coals 80:20 %(w/w), which will result in water content 6.47%, ash content 5.33%, volatile matter 61.44%, fixed carbon 26.79%, ignition time 14.274 mins, burn ability 0.054g/min and calorific value 6251.16 Kcal/gram.

After validation, the results are shown in Table 7. But there is a difference between the results projected by the Response Surface Method and the validation that has been done. On the water level, there was a difference of 0.19% with a larger validation result. For ash levels, the validation is 0.19% higher than the projections. For volatile matters the projection result is larger than 1.28%. At a fixed carbon rate, the validation is 0.88%. The projection's flame capacity is 0.15 mins greater than the validation. The burn ability of the projection is greater than 0.2 g/min. For calorific values, the projections are larger than 119.037 Kcal/gram. These differences may be due to real-world variations in material quality, environmental conditions, or minor inconsistencies during the briquette production process that are not captured in

TABLE 7. Optimizing and validating process to produce bio-briquettes from coal low firing and palm kernel shell.

Parameter	Glue starch (%)	Ratio of raw materials (% w/w)		Moisture content (%)	Ash content (%)	VM (%)	FC (%)	Burn ability (g/min)	Calorific value (Kcal/g)
		Coal low-firing	Palm kernel shell						
Optimizing	5	80	20	6.47	5.33	61.44	26.79	0.05	6251.16
Validation	5	80	20	6.67	5.52	62.72	27.67	0.05	6192.12
Gap				0.19	0.19	1.28	0.88	0.00	119.037

TABLE 8. Comparison study of bio-briquettes production within 2023 to 2024.

Raw materials	Bio-briquettes production	Calorific value	References
Palm mesocarp fiber	135-gram sample; 20 g cassava flour	25.92MJ/kg	(Salaudeen et al. 2024)
Coconut shell, and husk charcoal	Ratio raw materials of 10%: 90%; 20%: 80%; 30%: 70%; and 40%: 60%	5950 cal/g	(Yulia et al. 2024)
Palm kernel shell and sawdust	200 g raw materials; 150°C, 15 min	20005kJ/kg	(Oyelami et al. 2024)
Palm-midrib	2 g sample; Size of <500 m; 22 MPa; 190°C; 4.5 mins	19.08 MJ/kg	(Gani et al. 2024)
Coconut shell	100 g; cassava ratio (10:1); 150 to 160°C; 30 mins	Yield of 78%	(Rahman et al. 2023)
Rice husk and palm kernel shell	Ratio 90:10, 80:20, 70:30, 60:40, 50:50, 100:0, and 0:100; 110 bars; 25% starch	16.92 to 19.19 MJ/kg	(Jume et al. 2024)
Coal waste and palm kernel shell	50% glue starch; ratio raw materials (80:20)	6192.12 Kcal/g	This study

the RSM model. Although the differences are relatively small, they show the importance of validating projection models like RSM to ensure the accuracy and reliability of the results. Additionally, to produce 1 ton of co-firing briquettes using the optimal composition of the coal mixture (80:20 % w/w low-rank coal to palm kernel shell with a 5% starch glue concentration), the required materials are 800 kg of low-rank coal and 200 kg of palm kernel shell. To prepare the glue starch, 50 kg of kanji flour and 450 liters of water are needed. Table 8 compares the production methods, raw materials, and calorific values of various bio-briquettes.

Despite the promising results, this study has several limitations that should be acknowledged. Firstly, the experimental design was limited to specific ratios of coal, palm kernel shell, and glue-starch concentrations, which may not encompass all optimal combinations for broader industrial applications. Secondly, the calorific value of palm kernel shell was not measured directly in this study due to equipment limitations, leading to incomplete data for direct comparison. Additionally, while the study utilized one-way ANOVA and t-tests for statistical analysis, multivariate or regression-based modeling could provide deeper insights into interaction effects among variables. Furthermore, the combustion experiments were conducted under controlled laboratory conditions, which may differ from actual operational environments such as industrial boilers. Future work should consider pilot-scale trials and a comprehensive life cycle assessment (LCA) to evaluate environmental impacts and economic feasibility.

4. CONCLUSION

The co-firing briquette developed in this study is composed of a comparative mixture of low-rank coal and palm kernel shell, processed to a 60-mesh particle size, blended with tapioca starch glue, molded into briquettes, and subsequently dried. The optimal composition was found to be 80% low-rank coal and 20% palm kernel shell, with a glue starch concentration of 5%, which produced the best performance in terms of calorific and physical properties. The validation of briquette made from this composition yielded a calorific value of 6192.12 Kcal/g, moisture content of 6.67%, ash content of 5.52%, volatile matter content of 62.72%, and fixed carbon content of 27.67%. In terms of combustion performance, it showed a burning time of 14.12 mins and burn rate of 0.05 g/min, meeting the criteria set by SNI 01-6235-2000 and SNI 8675-2018. This study demonstrates that palm kernel shell, an abundant biomass waste, can be effectively utilized as a co-firing material with low-rank coal to produce briquettes with competitive energy and combustion properties. The findings offer a sustainable solution for improving the utilization of coal-biomass briquettes in industrial heating applications, reducing dependency on fossil fuels, and minimizing environmental impact. Moreover, the optimized briquette composition has potential for scalable production and commercial use in sectors such as small-scale power generation, manufacturing industries, and rural energy systems.

5. ACKNOWLEDGEMENT

Not applicable

6. CONFLICT OF INTEREST

Authors declare that there is no conflict of interest regarding the publication of the paper.

7. AUTHOR CONTRIBUTION

Salomo Pranata Aji: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Validation. Dian Ayu Afifah: Writing – review & editing, Visualization, Validation, Investigation. Fadian Farisan Silmi: Writing – review & editing, Visualization, Validation, Investigation. Devy Cendekia: Writing – review & editing, Visualization, Validation, Investigation. Shintawati: Writing – review & editing, Validation, Investigation, Supervision, Project administration, Conceptualization. Adityas Agung Ramandani: Writing – review & editing, Visualization, Investigation. Yeni Ria Wulandari: Writing – review & editing, Visualization, Investigation.

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