# Exploring Binder Efficacy in the Fabrication of Charcoal Briquettes from Palmyra Palm and Oil Palm Shells: A Comprehensive Analysis

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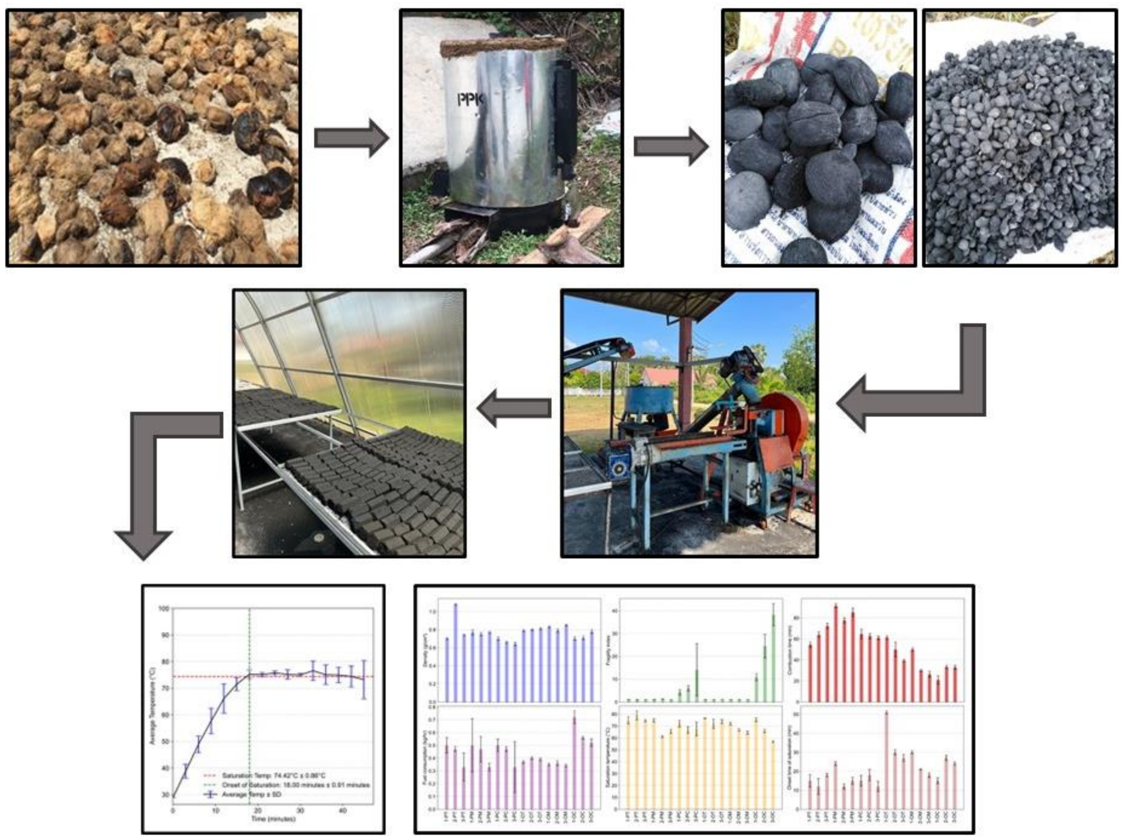
## GRAPHICAL ABSTRACT



# Exploring Binder Efficacy in the Fabrication of Charcoal Briquettes from Palmyra Palm and Oil Palm Shells: A Comprehensive Analysis

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The fabrication of charcoal briquettes was considered using two distinct bases: palmyra palm and oil palm shells. The critical role of binders – namely tapioca starch, molasses, and termite mound clay (TMC) – were emphasized in influencing the properties of the briquettes. ANOVA results revealed that both the type of binder and charcoal significantly impacted various characteristics, such as proximate components like volatile matter content, and physical properties including combustion time. Briquettes made from palmyra palm shells notably demonstrated superior performance in terms of combustion time and onset time of saturation (OTS). Among the binders, tapioca starch was distinguished for contributing to the lowest ash content and the highest fixed carbon in the briquettes. Conversely, briquettes bound with TMC, despite having the lowest volatile matter percentage, also exhibited the highest ash content and fragility, in addition to the shortest combustion time. These findings highlight the importance of selecting appropriate binders to enhance the efficiency and sustainability of charcoal briquettes, aligning with the increasing demand for environmentally conscious energy solutions in the face of escalating global energy needs.

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*Keywords: Charcoal briquette; Palmyra palm; Oil palm; Cassava starch; Molasses; Termite soil; Carbohydrate binder; Clay binder; Biomass; Proximate analysis*

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## INTRODUCTION

Energy, an indispensable catalyst for human progress, deeply influences socio-economic growth, individual livelihoods, and national security. Countries globally grapple with the challenge of meeting escalating energy demands. In this context, pivoting towards alternative energy sources has emerged as a strategic imperative. Renewable energy sources, such as biomass, hydropower, solar, and wind energy, offer a sustainable solution (Parobek *et al.* 2015). Renewable energy sources, in contrast to traditional fossil fuels, offer cleaner, more abundant, and environmentally friendly alternatives, substantially reducing anthropogenic environmental impacts (Otieno and Otieno 2020). Charcoal-based fuels, derived from renewable raw materials, present a viable energy alternative (Tambunan *et al.* 2023). Diversifying energy sources enhances national energy security and diminishes dependence on foreign energy imports (Ranjan and Hughes 2014).

Charcoal briquettes, often overlooked, emerge as a significant renewable energy source (Safana *et al.* 2018). Offering a sustainable alternative to natural forest-derived charcoal, these briquettes aid in conservation efforts and help reduce deforestation (Otieno and Otieno 2020). This is particularly relevant as wood charcoal, including that from mangrove trees, remains a popular household fuel (Tambunan *et al.* 2023). Briquettes can be produced from various biomasses, often agricultural by-products such as sesame stalks (Gebresas *et al.* 2015) or mango seed covers (Katimbo *et al.* 2014), utilizing diverse methods such as manual hydraulic presses (Adu-Poku *et al.* 2022; Mohd Faizal *et al.* 2018) or automatic briquette extruding machines (Chumsang and Upan 2014). The production of charcoal briquettes strategically employs agricultural residues, turning underused resources into valuable energy commodities (Wu *et al.* 2018). Furthermore, the desirable qualities of charcoal briquettes, including high calorific value, smokeless combustion, extended burn time, and cost efficiency compared to conventional wood charcoal (Shiferaw *et al.* 2017), have attracted considerable research interest.

Palmyra (Chumsang and Upan 2014) and oil palm shells (Safana *et al.* 2018) are recognized as abundant agro-wastes in local communities such as Thailand, with its 1.6 billion square meters of oil palm agricultural area in 2021 (Yaseen *et al.* 2023). However, there are limited sources detailing the exact agricultural areas of palmyra palm. It is known to be widely cultivated in South Asia and Southeast Asia. For example, in Indonesia's Jeneponto district, approximately 363 hectares of palmyra palm were reported in 2012 (Sirajuddin *et al.* 2016). Utilizing local resources, including tapioca starch and molasses as carbohydrate-based binders (Adu-Poku *et al.* 2022; Chumsang and Upan 2014), and termite mound clay (TMC) as a clay-based binder (Otieno and Otieno 2020), the studies explore optimal binders for briquette production.

This study aims to utilize these binders along with charcoal derived from palmyra and oil palms for briquette production. It endeavors to conduct a comprehensive evaluation of the briquettes' proximate compositions and physical properties, ensuring adherence to quality and efficiency standards. Additionally, the study seeks to maximize the use of local resources in developing a sustainable energy framework. Through detailed experiments and analyses, it aims to create community-driven, environmentally sustainable, and economically feasible energy solutions. By using agricultural leftovers as fuel sources, this method enhances the value of these by-products, promoting a commitment to a sustainable and self-reliant future.

## EXPERIMENTAL

### Preparation of Charcoal Briquette

The production of palmyra palm-based and oil palm-based charcoal briquettes necessitates a thorough and systematic approach to ensure optimal results. The foundational step in this quest is to determine the most effective ratio for producing these briquettes. To this end, an experimental design was conceptualized, focusing on three principal binders: tapioca starch, molasses, and termite mound clay (TMC). These binders play a pivotal role in ensuring the cohesiveness and structure al integrity of the charcoal briquettes. The specific mixing ratios adopted for the binders with the palm shells are detailed in Table 1. During the charcoal making process, palm shells underwent a sun-drying phase that lasted for a week, with outdoor daytime temperatures averaging around 35 °C as shown in Fig.1(a). This step is pivotal in removing residual moisture, thus reducing the duration required for the subsequent furnace drying process (Cabrales *et al.* 2020). The 30 kg of dried palm shells were carbonized in a 200-liter smokeless metallic kiln, equipped with a condensation tube for fume capture, as depicted in Fig.1(b). The kiln, heated by wood scraps at a rate of about 5 kg/hr, initiated the carbonization (pyrolysis) process upon the appearance of the first brownish liquid drop in the condenser (Ouattara *et al.* 2023) , typically within 60 minutes. This process continued until the final drop of brown liquid, marking approximately 2 hours, signifying the end of carbonization. Subsequently, the wood scrap feed was ceased. The kiln was then allowed to cool, and the charcoal remained inside for a minimum of 8 hours before opening the lid. The resulting charcoal yield from both palm shell types was approximately 60 ± 5%.

After converting the raw material into charcoal, as shown in Fig. 1(c), the charcoal was finely ground using an electric grinder operating at 28,000 rpm with a 2000-watt power rating, depicted in Fig. 1(d). The ground charcoal was then sieved to attain a consistent particle size of approximately 0.85 mm. This charcoal powder was mixed with water and a selected binder (tapioca starch, molasses, or TMC) following the mixing ratios in Table 1. The homogeneous mixture was then processed in a charcoal briquette-making machine. The briquette production, utilizing a screwing extrusion machine with a pressing speed of 400 cm/min and a nozzle temperature of 80 °C, resulted in hexagonal hollow prism briquettes, as illustrated in Fig. 1(e) and (f). This machine, essential for shaping the briquettes, was innovatively designed and built by the Ban Khlong Ri community in Songkhla, Thailand. The machine's operation requires varying water amounts for extruding stable wet briquettes, depending on the binder and components used. Table 1 specifies the necessary water quantities for each sample to produce stable wet briquettes.

The final phase in the material preparation involved drying the freshly molded charcoal briquettes. To ensure effective moisture removal and preserve the structural integrity of the briquettes, a greenhouse solar drying system was employed. As depicted in Fig. 1(g), the wet briquettes were solar-dried in a greenhouse, which reached a peak temperature of 65 °C and an average relative humidity of 80%, over a duration of two days.


**Fig. 1.** a) Dried palm shells, b) smokeless metallic charcoal kiln, c) palm shell charcoal, d) charcoal after grinding e) briquette-making machine, f) wet briquette extruded from the machine, and g) briquettes solar-dried in the greenhouse

## Proximate Analysis and Physical Property Tests

The proximate analysis followed standardized procedures consistent with prior studies (Gebresas *et al.* 2015; Mohd Faizal *et al.* 2018; Adu-Poku *et al.* 2022). Moisture content (%MC) was determined using the ASTM D 3173 method: 1 g of briquette powder was placed in a crucible and heated at approximately 105 °C for 1 hours in a box furnace (Carbolite RHF 1400, Carbolite Gero, UK), as shown in Fig. 2(a). After heating, the sample was cooled in a desiccator and then weighed. The loss in weight represents the moisture content, reported on a percentage basis. The quantification of volatile matter content (%VC) was conducted in accordance with the ASTM D 3175 standard. Samples, free of moisture from the previous step, were placed in a lidded crucible and heated at 750 °C for 7 minutes in a box furnace. Following this, the samples were allowed to cool in a desiccator before being weighed. The weight loss after heating denotes the volatile matter content, also reported on a percentage basis. Ash content (%AC) followed ASTM D 3174, starting by placing the volatile-free sample from the previous step in an open crucible and heating it at 950 °C for 30 minutes. The sample was then cooled in a desiccator and reheated until a constant weight was achieved. The remaining residue is reported as the ash content, on a percentage basis.

The percentage of fixed carbon content (%FC) was determined using the ASTM D 3172 protocol, calculated as %FC = 100 - (%MC + %VC +%AC)

**Table 1.** Mixing Ratio of Each Charcoal Briquette Treatment

| Sample | Charcoal (g) | Binder (g) | Water (mL) |
|---|---|---|---|
| 1-PT, 2-PT, 3-PT | palmyra Palm (3000) | tapioca starch (150, 210, 270) | 1200 |
| 1-PM, 2-PM, 3-PM | palmyra Palm (3000) | molasses (400, 500, 600) | 500 |
| 1-PC, 2-PC, 3-PC | palmyra Palm (3000) | TMC (150, 210, 270) | 700 |
| 1-OT, 2-OT, 3-OT | oil palm (3000) | tapioca starch (150, 210, 270) | 700 |
| 1-OM, 2-OM, 3-OM | oil palm (3000) | molasses (400, 500, 600) | 300 |
| 1-OC, 2-OC, 3-OC | oil palm (3000) | TMC (150, 210, 270) | 700 |

The physical attributes of the briquettes were a key focus of this research. Briquette density was measured and expressed in g/cm³. To evaluate their durability and resistance to fragmentation, a drop shatter test from a height of 2 meters was conducted (Gebresas *et al.* 2015), as shown in Fig. 2(b). The fragility index was calculated by determining the ratio of the weight difference (before and after the drop shatter test) to the initial weight before the test and is expressed as a percentage. Combustion time was assessed by the duration (in minutes) that it took 500 g of briquette to completely burn from ignition to being fully reduced to ash. Fuel consumption was calculated by measuring the weight difference between the briquette before burning and the residual ash after burning, divided by the combustion time, and is expressed in kilograms per hour (kg/hr).

The water boiling test is a practical evaluation where water is boiled using briquettes. This test facilitates an understanding of the correlation between the temperature of the water and the time required for heating, thereby indicating the heating efficiency of the briquettes. In this study, 500 g of briquette was used to boil 1000 mL of water inside aluminum pot placed on the clay brazier. The rise in water temperature was continuously monitored using a thermal imaging camera (FLIR E60, FLIR system Inc), with temperature recordings taken at three-minute intervals, as shown in Fig. 2(c). Furthermore, the time required to reach saturation was logged. The key parameters derived from the temperature-time graph of each sample include the saturation temperature and the onset time of saturation (OTS). The saturation temperature represents the highest temperature at which the briquette operates, marking its thermal capacity. Similarly, OTS refers to the moment when the temperature reaches its saturation. This metric is crucial; a shorter OTS is desirable, denoting the briquette's ability to rapidly generate and transfer heat (Adu-Poku *et al.* 2022). To accurately identify these parameters, the smooth derivative method was applied to the temperature-time data, pinpointing the precise moments where both temperature and time achieved saturation as shown in Fig. 2(d). Proximate components and physical properties were measured in three repetitions each.

An analysis of variance (ANOVA) was conducted on all parameters using Python. This analysis encompassed both proximate component and physical property parameters (Adu-Poku *et al.* 2022) to determine the significant differences in briquette samples with varying binders (tapioca starch, molasses, and TMC) and charcoal bases (palmyra and oil palm), as well as the interaction between binder and charcoal type on these parameters. ANOVA results are presented in Table 2. If its p-value is equal or lower than 0.05, the difference in such parameter is considered significant.


**Fig. 2**. a) Analysis of proximate components conducted in a box furnace, b) drop shatter test employed for assessing fragility Index, c) utilization of thermal imaging camera in water boiling test, and d) smooth derivation analysis to determine the saturation time and onset time of saturation

## RESULTS AND DISCUSSION

### Proximate Analysis

This study conducted a proximate composition analysis of charcoal briquettes made from palmyra palm and oil palm shells using various binders to explore their compositional properties. The analysis focused on key components, such as moisture, ash, volatile matters, and fixed carbon, which collectively constitute 100% of the composition, as illustrated in Fig. 3. The average moisture content across samples was 5.2 ± 1.6 percent. Table 2 presents the ANOVA results, examining the effects of binder and charcoal types, as well as their interactions, on moisture. Only the binder type had a significant ($p \leq 0.05$) impact on the briquettes' moisture content. Samples with termite mould clay (TMC) exhibited the lowest average moisture content at 3.8%, lower than the findings in a prior study (Mohd Faizal *et al.* 2018). Lower moisture content indicates more efficient burning and reduced smoke emissions (Agyei *et al.* 2018). Similarly, only the binder type significantly influenced ash content, as indicated by a p-value ≤ 0.05. Higher ash levels can lead to air pollution and negatively impact combustion quality (Katimbo *et al.* 2014). Figure 3 and Table 3 demonstrate that samples with termite mound clay (TMC) had the highest ash percentage at 25.8% among all binder types, comparable to clay-based briquettes reported in a previous study (Gebresas *et al.* 2015). In contrast, samples with tapioca starch displayed the lowest average ash content at 6.6%, which is still notably higher than values reported in a prior study (Mohd Faizal *et al.* 2018). Ash, a byproduct of briquette combustion, originates from the inorganic components within the briquette (Adu-Poku *et al.* 2022). Thus, higher ash content in TMC samples implies a greater proportion of inorganic materials compared to other binders.

The ANOVA results indicated that both binder and charcoal types significantly influenced ($p \leq 0.05$) the volatile matter and fixed carbon content in the proximate components. Samples with higher volatile substance content ignite and burn out more rapidly (Kurnia *et al.* 2016). Regarding binder effects, samples with molasses as a binder exhibited the highest average volatile matter content at 62.5%, and those with palmyra palm as the charcoal base showed an average volatile matter content of 59.3%, both lower than values observed in previous studies (Adu-Poku *et al.* 2022; Osei Bonsu *et al.* 2020). Fixed carbon correlates with heating value and onset time of saturation (Osei Bonsu *et al.* 2020). ANOVA results demonstrated that the type of binder, charcoal, and their interaction significantly affected the fixed carbon content of the briquettes. As per Table 3, samples with tapioca starch as a binder and those using oil palm as a charcoal base had fixed carbon contents of 35.2% and 33.0%, respectively. These values were higher than those reported in previous studies (Adu-Poku *et al.* 2022; Osei Bonsu *et al.* 2020).

While the proximate composition offers valuable insights into the potential efficiency and utility of the briquettes, it represents only a part of the overall picture. The subsequent sections will explore the physical properties, combustion characteristics, and water heating performance of these charcoal briquettes. This comprehensive evaluation aims to thoroughly assess their applicability and efficiency.

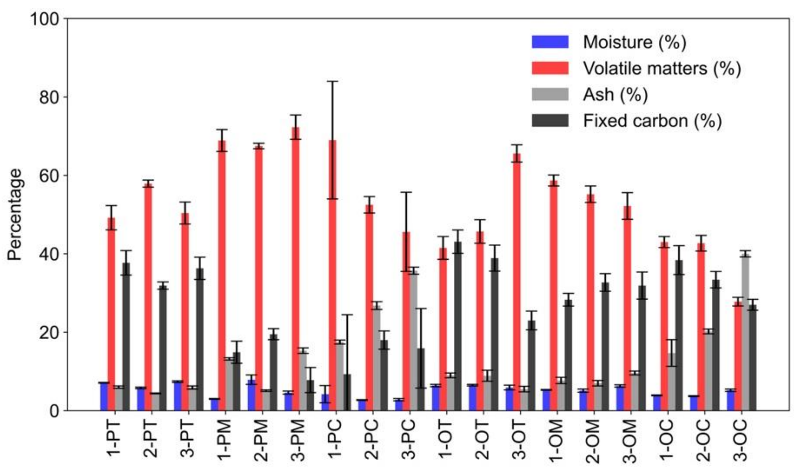


**Fig. 3.** a) The percentage of the proximate compositions of the charcoal briquette samples.

## Physical Property Analysis

The calorific value of the charcoal fine grain was measured using an oxygen bomb calorimeter (C 6000 Global Standard Package 1/10, IKA Works, Bangkok, Thailand), providing insights into its energy content. The calorific values of palmyra palm charcoal and oil palm charcoal were determined to be 26,600 and 25,300 kJ/kg, respectively. These values are comparable to those reported in previous studies for charcoal made from oil palm shells and mesocarp (Adu-Poku *et al.* 2022; Mohd Faizal *et al.* 2018; Osei Bonsu *et al.* 2020).

The physical properties of charcoal briquettes are crucial for their efficiency and suitability in various applications. Starting with the briquette density, ANOVA results indicated that neither the type of binder nor the charcoal base significantly affected density. The average density for all samples was measured at $0.77 \pm 0.09$ g/cm³. As shown in Fig.4 (a), the notable exception was sample 2-PT, with a density of 1.08 g/cm³. This can be considered an extreme outlier, as it exceeds the upper limit (z-score > 2) of the density distribution.

Regarding the fragility index, binders significantly influence it, as indicated by an ANOVA p-value lower than 0.05. Samples using tapioca starch and molasses as binders exhibited average fragility indexes of 1.1%. In contrast, samples with TMC exhibited a significantly higher average fragility index of 16.3%, a contrast that can be graphically observed in Fig. 4(b). Their high fragility index is comparable to that of a previous study using sesame stalk and clay for briquette production (Gebresas *et al.* 2015), where the fragility index was approximately 14.8%.

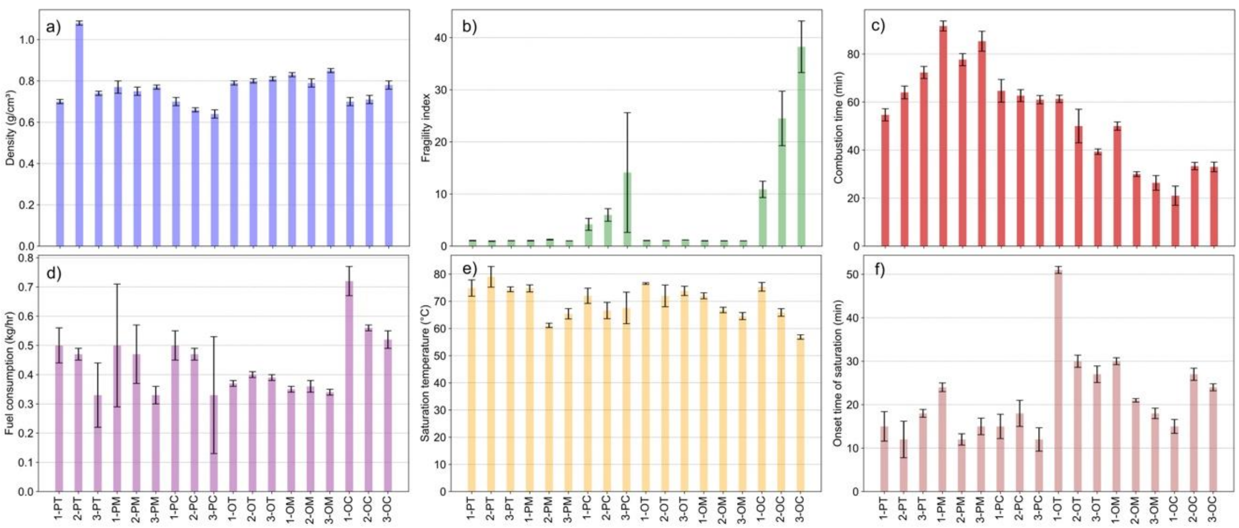


**Fig. 4.** a) density, b) fragility index, c) combustion time, and d) fuel consumption results of the charcoal briquette sample, e) saturation temperature and f) onset time of saturation

Regarding combustion time, the ANOVA results in Table 2 indicate that binder, charcoal, and their interaction significantly influenced this parameter. A longer combustion time implies that the briquettes burn slower. Considering binder effects, samples with molasses exhibited the highest average combustion time of 60.2 minutes. For charcoal effects, samples with palmyra palm showed a significantly higher average combustion time of 70.4 minutes, compared to an average of 38.3 minutes for oil palm when combusting 500 g of briquette samples, which can be graphically observed in Fig. 4(c). This value of 70.4 minutes for 500 g of samples is roughly equivalent to 0.007 kg/min heating rate, which is higher than the majority of values reported by Adu-Poku *et al.* (2022). The next parameter is fuel consumption, where the value of each sample is shown in Fig. 4(d). ANOVA results indicate that the binder and its interaction with charcoal significantly affected this aspect. Since fuel consumption is calculated from the difference in mass of the briquette before combustion minus the ash mass after combustion, lower fuel consumption indicates higher heating efficiency of the briquette. In this study, charcoal with molasses as a binder had the lowest average fuel consumption at 0.39 kg/hr. However, this is still higher than the value reported in a previous study as 0.17 kg/h (2.84 g/min) (Osei Bonsu *et al.* 2020).

**Table 2.** ANOVA for Proximate and Physical Parameters of Briquette Samples

| Factor | Moisture | Volatile matter | Ash | Fixed Carbon | Density | Fragility Index | Combustion time | Fuel consumption | Saturation temperature | Onset time of saturation |
|---|---|---|---|---|---|---|---|---|---|---|
| Binder | 0.007* | 0.021* | 0.001* | 0.006* | 0.083 | 0.001* | 0.038* | 0.034* | 0.041* | 0.242 |
| Charcoal | 0.597 | 0.015* | 0.810 | 0.001* | 0.521 | 0.076 | <0.001* | 0.744 | 0.602 | 0.006* |
| Binder · Charcoal | 0.563 | 0.252 | 0.786 | 0.034* | 0.539 | 0.054 | 0.013* | 0.034* | 0.847 | 0.169 |
| R-Square (adjusted) | 41.8% | 50.0% | 55.9% | 68.9% | 14.7% | 65.5% | 81.9% | 43.7% | 19.4% | 44.6% |

*Significant factor at $p \leq 0.05$.

**Table 3.** Means of Samples with Different Binders and Charcoal Bases

| Factor | Moisture | Volatile matter | Ash | Fixed Carbon | Density | Fragility Index | Combustion time | Fuel consumption | Saturation temperature | Onset time of saturation |
|---|---|---|---|---|---|---|---|---|---|---|
| Unit | % | % | % | % | g/cm$^3$ | % | min | kg/hr | °C | min |
| Binder | | | | | | | | | | |
| Tapioca starch | 6.5$^a$ (0.6) | 51.7$^b$ (8.7) | 6.6$^c$ (1.9) | 35.2$^a$ (7.0) | 0.82$^a$ (0.13) | 1.1$^b$ (0.1) | 56.9$^b$ (11.6) | 0.41$^b$ (0.06) | 75.1$^a$ (2.4) | 25.5$^a$ (14.3) |
| Molasses | 5.6$^b$ (1.6) | 62.5$^a$ (8.2) | 9.7$^b$ (3.9) | 22.5$^c$ (10.1) | 0.79$^a$ (0.04) | 1.1$^b$ (0.1) | 60.2$^a$ (28.6) | 0.39$^c$ (0.07) | 67.5$^b$ (5.0) | 20.0$^a$ (6.5) |
| TMC | 3.8$^c$ (0.9) | 46.8$^c$ (13.6) | 25.8$^a$ (10.2) | 23.7$^b$ (11.2) | 0.70$^a$ (0.05) | 16.3$^a$ (12.9) | 45.9$^c$ (19.0) | 0.52$^a$ (0.13) | 67.4$^c$ (6.3) | 18.5$^a$ (5.8) |
| Charcoal | | | | | | | | | | |
| Palmyra palm | 5.1$^a$ (2.1) | 59.3$^a$ (10.2) | 14.4$^a$ (10.9) | 21.3$^b$ (11.3) | 0.76$^a$ (0.13) | 8.4$^a$ (4.4) | 70.4$^a$ (12.3) | 0.43$^a$ (0.08) | 70.7$^a$ (5.7) | 15.7$^b$ (3.9) |
| Oil palm | 5.4$^a$ (1.0) | 48.0$^b$ (11.2) | 13.6$^a$ (10.9) | 33.0$^a$ (6.4) | 0.78$^a$ (0.05) | 8.9$^a$ (13.6) | 38.3$^b$ (13.1) | 0.45$^a$ (0.13) | 69.3$^a$ (6.3) | 27.0$^a$ (10.4) |

*Means marked with distinct letters differ significantly at $\alpha = 0.05$.
**Numbers in the parentheses signifying the standard derivations.

In the water boiling test, saturation temperature results are displayed in Fig. 4(e). ANOVA results presented in Table 2 indicate that the type of binder was the only factor significantly affecting the saturation temperature ($p \leq 0.05$). Samples with tapioca starch as a binder exhibited the highest average saturation temperature of 75.1°C. However, regarding the onset time of saturation (OTS) shown in Fig.4(f), which represents the speed at which water reaches its saturation temperature, a lower OTS indicates a faster heating rate of the briquette (Osei Bonsu *et al.* 2020; Adu-Poku *et al.* 2022). Charcoal type plays a significant role in determining this value, as indicated by the ANOVA results. As shown in Table 3, samples with palmyra palm as the base demonstrated a significantly lower average OTS (15.7 minutes) compared to those with oil palm (27.0 minutes), suggesting that briquettes made from palmyra palm charcoal has a higher heating rate.

From Table 2, the adjusted R-square of ANOVA test was highest in the case of combustion time where it was 81.9%, suggesting that the independent variables (binder, charcoal, and their interaction) explain approximately 81.9% of the variance in combustion time. On the other hand, only 14.7% of the variance in the dependent variable 'density' can be explained by the independent variables.

The findings of this research underscore the crucial role of binders, charcoal, and their interactions in developing efficient charcoal briquettes. The specific advantages of each binder and charcoal base become apparent through their proximate components and performance, guiding sustainable energy solutions and opening further opportunities for optimization. As the global focus shifts toward greener energy alternatives, this study serves as a testament to the potential of sustainable briquette solutions, suggesting vast possibilities for future exploration, whether in refining binder compositions or investigating the broader impacts of these sustainable choices on socio-economic landscapes.

## CONCLUSIONS

In this analysis of palmyra palm-based and oil palm-based charcoal briquettes, the efficacy of binders—tapioca starch, molasses, and termite mold clay (TMC) —was critically evaluated.

1. ANOVA results indicated that the type of binder influenced most dependent parameters except for density and onset time of saturation (OTS). Similarly, charcoal type affected volatile matter content, fixed carbon content, combustion time, and OTS.
2. Briquettes with a palmyra palm shell base had a significantly higher average combustion time and lower OTS (indicating a higher heating rate), which are key parameters related to heating efficiency. In terms of calorific values, charcoal made from palmyra palm shell had a calorific value of 26,600 kJ/kg, compared to 25,300 kJ/kg for oil palm charcoal.
3. Among the three binders, briquettes with tapioca starch exhibited favorable properties, such as the lowest ash content, highest fixed carbon, and highest saturation temperature. Conversely, samples with TMC, despite possessing less desirable properties like the highest ash content, highest fragility index, and lowest combustion time, had the lowest percentage of volatile matter among the three binders.
4. Future research could delve deeper into optimizing binder formulations, such as exploring combinations of carbohydrate-based binders like tapioca starch and molasses with trace amounts of clay-based materials such as TMC. Additionally, a socio-economic analysis might assess the feasibility of large-scale production.

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