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Comparative Analysis of Carbonized Hybrid Briquettes Produced from Cassava Peel and Sawdust for Cooking Application

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ABSTRACT

The increasing use of biomass residues in briquette forms is not just for disposal problems but provides alternatives to fossil fuel and fuelwood. This research concentrated on assessing the effectiveness of the briquettes when used for cooking. The briquettes were prepared from carbonized materials: 100% Cassava peels (CP), 100% Sawdust (SD) of *Gmelina arborea* and their hybrid (MIX_1 -75:25, MIX_2 -50:50, and MIX_3 -25:75) with starch binder in percentage (5% and 10%) by weight at varying resident time of 10, 20, and 30 minutes. ANOVA was utilized to evaluate the significance at $p<0.05$. The produced briquettes were oven-dried and subjected to mechanical, boiling test, and fuel performance tests to evaluate their suitability as domestic fuel. The result shows that shatter index ranged between 46.81%–95.54%, compressive strength ranged from 0.12–0.26 N/mm^2. Briquette's thermal efficiency with good flame was within the range of 24.27%–55.55%. However, the average burning rate of all the briquette types was between 0.39 to 0.85 kg/hr, while the average specific fuel consumption ranged from 0.08 to 0.14 kg/l. The briquette took 15 minutes to boil water from 96.9°C to 97. 9°C.The comprehensive briquette test reveals that cassava peel exhibits the highest capacity for handling, while hybrid briquettes MIX1 and MIX3 demonstrate commendable fuel performance. It was noted that the binder ratio, type of biomass material, and residence time significantly impact the properties of the briquettes.

Keywords: Briquette, carbonization, characterization, compressive test, fuel efficiency

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INTRODUCTION

Sustainable and renewable energy is essential for humanity's well-being. Biomass energy constitutes approximately 15% of the energy consumption in the world. Biomass encompasses any organic material suitable for fuel, such as wood, charcoal, animal manure, plant matter, and agricultural waste (Ferguson, 2012). Fuels commonly used in households within developing nations are referred to as 'traditional,' including wood, animal dung, and agricultural residues. In Nigeria, fuelwood and charcoal alone contribute to around 73% of cooking energy, according to the International Energy Agency (IEA, 2019).

These fuelwood collection practices lead to major environmental issues, such as air pollution caused by greenhouse gas emissions, soil erosion, land degradation, and deforestation. Shaaban and Petinrin (2014) report that around 350,000 hectares of forest and natural vegetation are lost yearly, while afforestation efforts only cover 50,000 hectares annually. Deforestation has caused the depletion of 79% of Nigeria's old-growth forests between 1990 and 2005 (Mfon, 2014). Furthermore, Bolaji (2012) observed that burning agricultural residues, fuelwood, roots, and animal dung releases a great amount of carbon monoxide, particulate matter, and hydrocarbon into the atmosphere.

Many developing nations, including Nigeria, have abundant untapped renewable energy sources that apply to various uses (Orisaleye et al., 2018). Due to their rich renewable resources, developing countries can use different energy alternatives such as wind, solar, geothermal, biomass, and hydro (Sotannde et al., 2010). Supporting this idea, Piebalgs (2017) states that developing nations naturally have the means to utilize renewable energy by making the most of their natural resource abundance. According to FAO data from 2019, Nigeria is currently the world's foremost cassava producer, surpassing countries like Thailand (31 million tons), Brazil (21 million tons), and Ghana (18 million tons). Despite this significant production, only a fraction of the cassava tubers harvested in Nigeria are utilized for consumption, with the majority discarded, often littering roadsides. Regrettably, peels and other byproducts, like chaff, are often seen as nuisances rather than valuable resources.

In Nigeria, the absence of robust and enforceable legislation governing cassava waste management challenges peasants and smallholder farmers in grasping the interplay between cost-effective waste treatment and the added value of managing cassava waste. This discrepancy is commonly termed as a knowledge gap (FAO, 2020). Using wood-based industrial waste, such as sawdust from sawmills, to produce activated carbon stands out as one of the most ecologically advantageous methods for transforming low-value residues into high-value materials. Activated carbons demonstrate exceptional performance across various industrial applications, playing a pivotal role. Because of their large specific surface area, conductivity, and structural versatility, with adjustable porosity, activated carbon materials are useful in a diverse array of critical technologies. These encompass catalysis, energy storage, energy conversion, sensors, environmental protection, and the synthesis of fine and bulk chemicals (Nahil & William, 2012).

The selection of raw materials for biomass briquettes is guided by the energy potential and availability of the chosen waste (Bot et al., 2022a). Millions of tons of waste generated from human activities, particularly agricultural activities related to food production, cause serious environmental pollution due to the challenges associated with their disposal (Ezenwa et al., 2019). Most of these agricultural wastes, produced during the cultivation and processing of crops, are often either dumped on farm sites or burned at disposal sites, posing environmental hazards such as global warming and soil degradation (Arachchige, 2021). Sawdust, a byproduct of wood processing, mainly consists of fibers and cellulose (Lubwama & Yiga, 2018). These wastes can be transformed into solid fuels through the briquetting process, which enhances their calorific value and produces high-grade solid briquettes that ensure a clean, smoke-free flame suitable for small-scale industrial and domestic applications (Bello & Onilude, 2020) and biomass briquettes promote economic development in underdeveloped nations while also conserving the environment (Bamisaye & Raphael, 2021). According to the conclusions of Bot et al. (2022b), households would gain from replacing fuelwood with briquettes. The most significant economic benefit comes from using briquettes instead of fuelwood. The plant (cassava) generating the residues selected for this study is as widespread around Oyo town (the sample collection location) as the other sources, and the waste is available in relatively large quantities. Sawdust is also readily available due to the numerous sawmills in the town.

Multiple researchers, including Waheed and Akogun (2020), Kpalo et al. (2021), Bamisaye and Raphael (2021), and Waheed et al. (2022) have explored the creation of briquettes using processed agricultural waste for energy generation. Their studies have highlighted the utility of these products for various applications. Incorporating a variety of biomass feedstocks into the briquette mixture, as proposed by Akogun et al. (2022) and Ajimotokan et al. (2019), Improves the thermal properties and physical attributes of the resulting briquettes by promoting better adhesion between the constituent particles. It is crucial to compress these processed agricultural wastes into briquettes to make them easier to manage and better suited for heating purposes, as Waheed and Akogun (2020) emphasized. Achieving optimal briquetting requires careful selection and configuration of processing variables. Navalta et al. (2020) noted that the compression strength, density, and energy potential of briquettes are significantly influenced by factors such as pressure, temperature, particle size, choice of binder, and the properties of the biomass material (carbonized or uncarbonized).

Research has shown that briquettes' combustion and mechanical characteristics are enhanced when waste is converted into biochar. Wu et al. (2018) characterized fuel briquettes produced from wood sawdust and cotton stalks using various thermochemical processes, such as hydrothermal carbonization, dry torrefaction, and pyrolysis, before briquetting. Their findings revealed that the method used to produce carbonized biomass significantly impacted the briquettes' performance, including calorific value, density, and compressive strength. Li et al. (2019) compared heat transfer efficiency and pollutant emissions between briquettes made from raw and charred biomass for household cooking. They found that briquettes from charred biomass enhanced thermal efficiency and emitted fewer pollutants.

This study aims to assess the performance of two biomasses in cooking applications as an alternative fuel source for domestic use. It investigated the physico-mechanical and combustion properties of the briquettes for use in domestic cooking. Additionally, it was hypothesized that due to their availability, a mixture of cassava peel (agricultural waste) and sawdust (forest waste) in different proportions would result in high-quality hybrid briquettes with good combustion behavior, influenced by adequate fuel properties to enhance cooking efficiency in Oyo State, Nigeria. Household cooking is a significant energy use in developing countries such as Nigeria. This need is typically met by the direct burning of wood and its byproducts. Wood energy, including firewood, wood char, sawdust, and wood chips, constitutes over 80% of Africa's energy supply for cooking and heating. The inappropriate use of wood fuel has a wide range of negative environmental and health consequences (WHO, 2011; Kpalo et al., 2020).

MATERIALS AND METHODS

Materials

Five-ton hydraulic jack briquetting machine, Hammer miller, Digital weighing balance, 2mm mesh screen, Universal strength-testing machine, Element analyzer, Muffle furnace, Bomb calorimeter, Digital Multi-Stem thermometer.

Samples Selection and Preparation

This study used Gmelina sawdust samples converted and collected at Idi igba, Oyo state, Nigeria. In contrast, cassava peels were collected from a waste dump site for garri and starch manufacturers at Ajegunle market, Oyo state, Nigeria. The cassava peel was rinsed, after which both peel and sawdust were spread out on a thick bag to prevent contamination and left to air-dry for 2 weeks to a 12% moisture content and then milled using a Hammer miller after which both samples were sieved using a 2 mm particle-size mesh screen for consistency.

Carbonization Procedures

The dried cassava peel and sawdust were charred at a temperature of 400°C for 3 hours to produce a high–carbon product char (Figure 1). Cassava peel and sawdust, which serve as a control, were mixed at different percentages (100:0, MIX_1-75:25, MIX_2-50:50, MIX_3-25:75, and 0:100) for cassava peel and sawdust mixture, respectively (Table 1). It was carried out

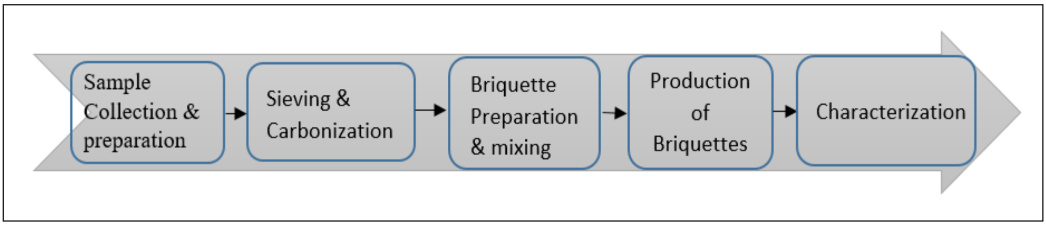

Figure 1. Elaborate schematic illustrating the briquetting process employed in this investigation

in accordance with the work of Velusamy *et al*. 2023 for mixing the proportion of *Senna auriculata and Ricinus communis*, and Palanisamy et al., 2023 for *Gloriosa superba* waste and turmeric leaves waste.

Table 1
Mixing proportion of cassava peel and sawdust

Samples	Mixing Proportion	
Cassava peel (CP)	100	0
MIX1	75	25
MIX2	50	50
MIX3	25	75
Sawdust (SD)	0	100

Binder Preparation

The binder used for this study was starch obtained from cassava. The starch binder proportion varied into 5g and 10g. The starch was measured into bowls, and 100 ml of boiling water at 98°C was added to form a gelatin paste, following the methods of Velusamy et al. (2021a), Chungcharoen and Srisang (2020), and Aransiola et al. (2019). 100 ml of boiling water to prepare the starch paste because the sample quantity was 50 g. Each 50 g portion of cassava peel and sawdust was then vigorously mixed with the prepared binder at 5 g and 10 g levels, respectively (Figure 2). Starch was selected as the binding agent due to its easy availability in the study area (Palanisamy et al., 2023).


(a) (b) (c)

Figure 2. Pictorial representation of (a) Sieved materials, (b) Carbonized samples, (c) Starch binder

Production of Briquettes

The 5-ton hydraulic jack briquetting machine was used in manufacturing the briquettes. The machine has twelve cylindrical molds that are welded onto a single frame and have

Figure 3. Produced briquettes from sawdust and cassava peel materials

dimensions of 80 cm in height by 6.5 cm in diameter. The blend was manually inserted into the briquetting machine while a pressure of 2.4 MPa or 10 kg/cm^2 was applied for the mixed paste to compact and form a briquette. The briquette molds produce twelve briquettes per batch, which are expelled at different periods (10-, 20-, and 30-minute resident time) to determine the effects of setting the time on the briquette characteristics. Each production batch was replicated for CP, MIX$_1$, MIX$_2$, MIX$_{3,}$ and SD three times. The produced briquettes were allowed to set for 3 days before oven drying. Each sample's weight, height, and diameter were duly noted after sun drying (Figure 3). Cassava starch was used due to its light quality and higher physical and mechanical attributes in accordance with the method described by Velusamy et al., 2021b.

Characterization

The mechanical properties (shattering index and compressive strength), physical properties (density), and calorific values were examined to evaluate if the briquettes were suitable for handling, transportation, and storage. The performance of the briquettes was assessed for cooking efficiency utilizing the outcomes from a water boiling experiment. These properties were tested days after the briquettes were produced and given time to dry. A straightforward random sample technique was employed to establish the characteristics of the briquettes utilized for sampling.

Physico-mechanical Characteristics

The physico-mechanical properties were determined to reflect the briquette's hardness, a significant factor in crafting new solutions for household energy sources.

Density. The compressed density of each briquette produced was determined after sun drying, using a ratio of measured mass to the volume of the briquettes. The mass of the produced briquettes (mb) was determined using a digital weighing balance. In contrast, the dimensions, including the briquettes' diameters (db) and height (hb), were measured using a Vernier caliper. The measured diameters and height were subsequently used to calculate the volumes (Vb) of the briquettes using Equation 1, while the corresponding densities (ρb) were calculated using Equation 2 (Aliyu et al., 2021).

$$\mathrm{Vb} = \pi \frac{db}{4} \mathrm{hb} \qquad [1]$$

$$P_b = \frac{m_b}{V_b} \qquad [2]$$

Shatter Index. The shattering index or durability index of the produced briquettes was measured according to the ASTM D440-86 (2002) method of drop shatter, developed for coal by Davies and Abolude (2013). The test was conducted after sun drying of the briquette samples. The weight of each sample was measured and placed in a polythene bag. The bag was dropped from a height of 2 m onto the concrete floor four times. After the dropping, the briquettes and their fractions were placed on top of a 35 cm square mesh screen and sieved. The mass of the remaining briquettes was measured, and the shatter index, expressed as the ratio of the weight of material retained on the screen (mbs) to the weight of briquettes before the dropping (mb), was determined using Equation 3 (Davies & Abolude, 2013).

$$Shatter\ index = \frac{Mbs}{Mb} \times 100 \qquad [3]$$

Compressive Strength. The briquette's axial compressive strength (N/mm^2) was measured using a Universal Testing Machine with a digital control and display unit for test control and result display. The dimension of the sample was first measured and inputted into the system, and the briquette was placed directly under the plunger to be pressed. The machine applied the load to the briquette until failure occurred. The applied force was recorded and displayed until the maximum force corresponding to the failure was recorded. The compressive strength is then calculated using Equation 4 (Davies & Abolude, 2013).

$$Compressice\ strength = \frac{Maximum\ force\ applied}{Surface\ area\ of\ the\ briquette} \qquad [4]$$

Determination of Fuel Performance in Cooking Application

The temperature at the boiling time was measured using an LCD digital Multi Stem Thermometer (Model ST9283B). The duration for igniting the briquettes and heating the water to 100°C was measured. Additionally, the thermal fuel efficiency (TFE), fuel burning rate (FBR), and specific fuel consumption (SFC) were assessed throughout the experiment.

Water Boiling Test. The outcome of a boiling water experiment was used to evaluate how well the briquettes performed in the cooking application. These characteristics were established days after the briquettes were created and given time to dry. The efficacy of the briquette for household cooking was evaluated through a water boiling assessment conducted in accordance with the Chinese Water Boiling Test Protocol 2008, as outlined by (Chen et al., 2016; Lubwama & Yiga, 2017); this was utilized for this study as it was found to be more practical in rural environments. A stopwatch was utilized to measure the duration of the briquette's combustion. The timer was set but not initiated until the fire was started. The empty pot was placed on the scale and weighed, and 1L of water was poured into the pot. The weight of the pot with the water was taken and recorded in a field activity notebook. The thermometer was placed in the pot to take the water's starting temperature, and it was captured. Two hundred grams of briquettes were put into the conventional cook stove, and a fire starter was used to ignite them.

The pot, filled with water, was positioned on the stove just as the flames ignited. Subsequently, the timer was initiated, and the water temperature was measured every 3 minutes throughout the burning process. As the water in the pot reached the boiling point (100°C), the pot lid was removed. The time it took the water to boil and the boiling temperature was recorded. Additionally, all remaining fuel samples were left in the stove chamber and allowed to continue burning till they burned out. The pot weights with hot water and the extracted ash from the stove were taken and recorded. The test concludes once the water within the pot cools to 5°C below the boiling point. The data recorded during the burning of the briquette and the boiling of water was analyzed to assess how well the briquette performs when used for cooking.

Thermal Fuel Efficiency. This measures the ratio of useful energy water receives in the pot to the energy consumed during combustion. The energy imparted to the water in the pot serves dual purposes: heating the water and facilitating evaporation. The amount of evaporated water was determined by subtracting the initial water weight in the pot from the final weight after cooling. Total useful energy (TFE) can be computed using Equation 5, provided by Davies and Davies (2013).

$$TFE = \frac{M_W C_P (T_b - T_O) + M_C L}{M_F E_F} \tag{5}$$

Where, TFE = Thermal fuel efficiency; M_W= mass of water in the pot (kg/liter); C_P=specific heat of water (kJ/kg K); T_O= initial temperature of water (K); T_b = boiling temperature of the water (K); M_C mass of water evaporated (kg); L= latent heat of evaporation (kg); M_F= mass of fuel burnt (kg); E_F=calorific value of the fuel (kJ/kg).

Fuel-burning Rate. According to Desta et al., 2024, the burning rate is when a given mass of briquette fuel burns in the air. If it is low, it indicates that the briquette has a high energy density and is of high quality. The fuel burn rate was calculated using the above test arrangement described in the ignition time of the briquette's discussion. The weight of the briquette sample before and after burning was recorded. The time it took to burn the briquette was also recorded. It was done three times for each of the briquettes. Fuel-burning rates were estimated using Equation 6.

$$FBR = \frac{M_F}{T} \qquad [6]$$

Where, FBR= Fuel Burning Rate; M_F = mass of fuel burnt (kg); T= Time taken to burn fuels (hr)

Specific Fuel Consumption. Specific fuel consumption refers to the quantity of solid fuel required to accomplish a specific task relative to the task's weight. It represents the relationship between the fuel mass (in kilograms) and the volume of water (in Liters) consumed. This computation follows Equation 7, outlined by Hakizimana and Kim (2016).

$$SFC = \frac{M_F}{M_W} \qquad [7]$$

Where, SFC= Specific Fuel Consumption; M_F = mass of fuel burnt (kg); M_w = mass of water in the pot (liter)

Experimental Design

The chosen experimental setup employs a 2 × 3 × 5 factorial design within a completely randomized design (CRD) framework with 3 replications, giving 90 samples in total. The following are the variables.

1. Material Type: 5 (CP, MIX_1, MIX_2, MIX_3 and SD)
2. Binder Level: 2 (5g and 10g)
3. Resident time: 3 (10, 20, 30 mins).

Statistical Analysis

Briquette samples were chosen through a simple random sampling technique within each of the five categories, and their characteristics were examined and duplicated three times. The data obtained from these tests underwent statistical analysis using the Statistical Package for Social Sciences. Analysis of Variance (ANOVA) was employed to identify noteworthy variations among the means of different briquette properties and their performance in a water boiling test. Throughout this study, all significant tests were conducted at a 95% confidence level ($p < 0.05$).

RESULTS AND DISCUSSION

Briquette Characterization (Mechanical Physical properties)

Density

The various p-values of physical and mechanical properties obtained from ANOVA and their interactions are presented in Table 2. The density of the produced briquettes was notably influenced by both the type of briquette and the interaction between briquette type and binder level, with statistical significance (p<0.05, while binder level, resident time, their interaction, and 3- factors interaction did not yield any noticeable impact on the briquettes. Table 3 displayed the follow-up test on the briquette type using the Duncan Multiple Range Test to show the extent of significance where the density of CP and SD show significant differences. In the meantime, Figure 4 presents the average impacts of factors on the density of briquette samples. Sawdust had the highest density of 627.79 kg/m^3 at 5% binder level and at 30 mins resident time compared to 320.18 kg/m^3 obtained at 5% binder level and at 10 mins resident time.

Table 2
P-*values for density, compressive strength and shatter index of briquettes*

Source of Variation	Degree of Freedom	Density (Kg/m^3)	Shatter index (%)	Compressive strength (N/mm^2)
Briquette Type	4	0.036248*	0.000000*	0.000000*
Binder level	1	0.092818	0.964512	0.120707
Resident time	2	0.535503	0.067867	0.411608
Briquette Type*Binder level	4	0.242672	0.002109*	0.003678
Briquette Type*Resident time	8	0.850590	0.040970*	0.528162
Binder level*Resident time	2	0.210566	0.212416	0.190859
Briquette Type*Binder level*Resident time	8	0.808155	0.464415	0.935329
Error	60			
Total	89			

*Significant at $p < 0.05$)

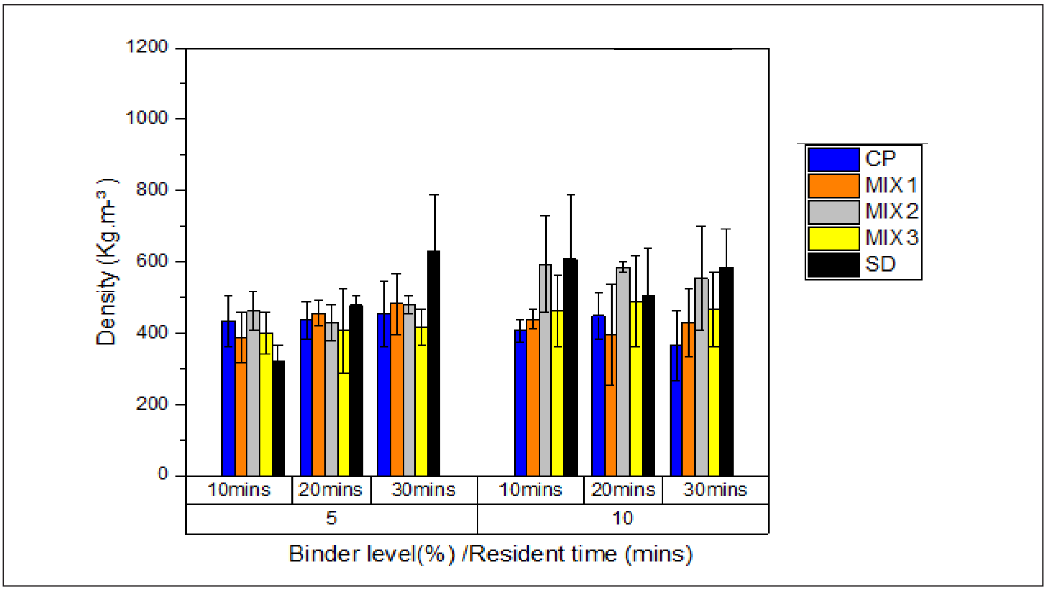

Figure 4. Mean values of density of briquettes about binder level (%) and resident time (mins)

Akogun et al. (2020) recorded a higher result of briquettes made from fresh sawdust and torrefied cassava peels. and ranged between 870 kg/m^3–1080 kg/m^3. The 147 kg/m^3 range to 1362 kg/m^3 was recorded for waste-based briquettes, as Ossei-Bremang et al. (2024) reported. The highest density of sawdust briquette (627.79 kg/m^3) was slightly lower than 660 kg/m^3 obtained in palm kernel but higher than rice husk, sawdust, and corncob with 384.3kg/m^3, 396.1 kg/m^{3,} and 443.5kg/m^3 respectively (Adu-Poku et al., 2022; Sunnu et al., 2021). This difference may be due to the porosity of the material type used for production. It has been suggested by Guo et al. (2020) and Chaisuwan et al. (2020) that briquettes made by a hydraulic piston press typically have a density of less than 1,000 kg/m^3, commonly ranging from 300 to 600 kg/m^3.

Table 3

Duncan's multiple range test for density, shatter index, and compressive test of briquettes

PARAMETERS	BRIQUETTE TYPE				
	CP	MIX$_1$	MIX$_2$	MIX$_3$	SD
Density	424.01^a	431.19^{ab}	517.26^{bc}	440.65^{abc}	520.81^d
Shatter index	67.58623^a	91.30800^d	23.19186^c	78.60582^b	73.20769^{ab}
Compressive strength	0.2592763^c	0.176556^a	0.160172^a	0.157751^a	0.070444^b

Note. Means with the same letter(s) in the row are not significantly different ($p < 0.05$)

Shatter Index

Table 2 is the Anova of shatter index, which shows that the different briquette types along with 2-factor interactions of briquette type and binder level as well as briquette type and resident time shows markedly distinct at ($p > 0.05$). 2-factor interactions of binder level and resident time and 3-factor interactions did not notably impact the shatter index of the briquettes produced. Regarding the material type, binder level, and resident time, the highest shatter index of 95.54% was recorded in the MX$_1$ briquette at a 5% binder level and 30 minutes of resident time (Figure 5). Duncan's test, presented in Table 3, shows that the shatter index of MIX$_1$ and MIX$_2$ are significantly different from each other and other briquette materials.

The average shatter index obtained for MX$_1$ in this study is in line with the work of Tembe et al. (2014), who reported similar shatter index values ranging from 83.5% to 99.1% in their study. Meanwhile, CP, MX$_{3,}$ and SD are within the lower range of 63.76% to 75.47%, as reported by Aliyu (2021). These findings align closely with the top shatter indices Ajiboye et al. (2016) achieved for sawdust and charcoal briquettes, which were 98.21% and 98.17%, respectively. Sotannde et al., 2010 obtained an average value of 98.74 for briquettes made from charcoal briquettes. In their study, Adu-Poku et al. (2022) found that palm kernel shells and sawdust achieved average rates of 95.52% and 95.02%, while rice husk and corn cob yielded 93.75% and 94.34%, respectively. Additionally, in

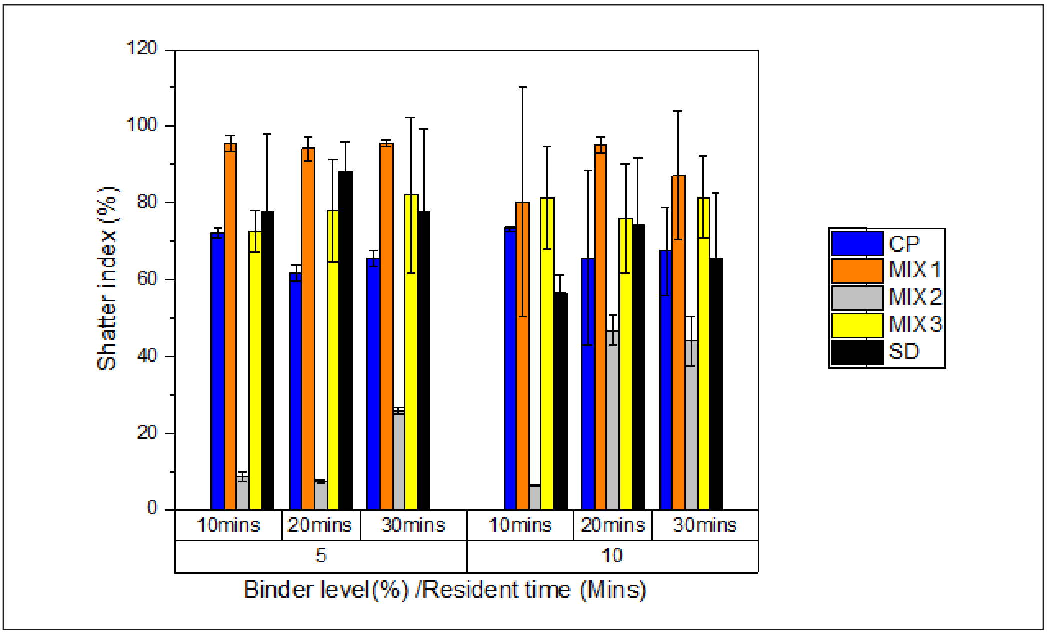

Figure 5. Mean of shatter index of briquettes about binder level (%) and resident time (mins)

accordance with the Italian briquette standard, all demonstrated an impact resistance index surpassing or equaling 97.7%, consistent with the findings of Mitchual et al. (2013). This variance might stem from differences in binder composition and the carbonization process.

Compressive Strength (N/mm^2)

Analysis of variance (ANOVA) shows that material type and 2-factor interaction of material type and binder level had a notable impact on the compressive strength of the briquette ($p<0.05$). Meanwhile, binder level, resident time, 2-factor interaction, and their 3-factor interaction did not exert any notable impact on the compressive strength of the briquettes (Table 2). The follow-up test using the Duncan Multiple Range Test in Table 3 indicates no significant variance in compressive strength among the hybrid briquettes.

The result in Figure 6 gave the highest compressive strength of the CP briquette, with a value of 0.29N/mm2 at a 10% binder level and within 10 minutes of resident time. The lowest compressive strength happens in the SD briquette, with a value of 0.04 N/mm^2 at a 5% binder level and within 10 minutes of resident time. Table 3 shows the follow-up test to observe the extent of significance of the briquette type.

The briquettes made from sawdust had finer particle sizes and were less porous due to stronger intermolecular bonds between the particles, which consequently increased the briquettes' strength. This study partially aligns with Blesa et al. (2003), who assert that an increase in residence time positively impacts the mechanical strength of briquettes. In their study, Ezenwa *et al.* 2024 recorded a higher compressive strength of 8.31 N/mm^2 for breadfruit pulp. Blesa et al. (2003) state that the two primary characteristics necessary to produce a good briquette are compression (crushing) and water resistance. Gendek *et al.* (2018) stated that other factors influencing the strength of briquettes include particle size, material type, moisture content, and compaction parameters. Compressive strength enhances the durability of briquettes by decreasing their capacity to absorb moisture (Kers et al., 2010). According to Borowski and Hycnar (2013), tests conducted on commercial fuel briquettes determined that a compressive strength of at least 1.0 MPa is acceptable. The compaction pressure enhances the strength properties by improving the intermolecular bonding among the briquette particles (Ajimotokan *et al.*, 2019). This study's compressive strength was lower than values obtained from Oladeji and Oyetunji (2013) and Oyedemi (2012), which may have resulted from the carbonization of the material. This implies that pyrolyzing the material could affect the compressive strength of the briquette.

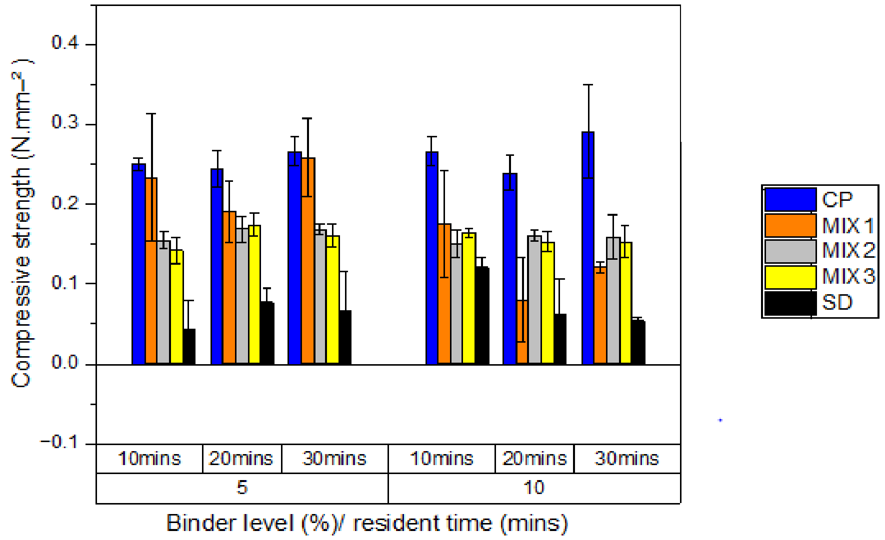

Figure 6. Mean of compressive strength of briquettes about binder level (%) and resident time (mins)

Fuel Performance in a Cooking Application

Boiling Water Test

This discussion presents and analyzes the results of the various parameters tested during the water boiling test. Traditional cookstoves were utilized because they reflect the cooking methods commonly used in most developing regions where fuel wood and charcoal are the primary energy sources. Boiling time is the duration it takes for the water in the pot to reach its boiling point. Readings of the values obtained from the boiling test were used to plot a graph showing temperature against time, as shown in Figures 7 to 11. In this study, 96^0C was set as the water boiling point based on the time the boiling temperatures were attained during the test for each briquette. At inception (0 mins), the boiling water behavior of the CP briquette in Figure 7 shows a particular temperature pattern through a significant change in temperature after 6, 9, and 12 mins of boiling water. The result in Figures 8 to 10 shows that when hybrid briquettes (MX_1, MX_2, and MX_3) at 10% binder level were used to boil 1L of water, it showed an increase in temperature after 6 and 12 minutes. The graph in Figure 11 shows that boiling water with SD briquettes, regardless of binder level and resident time, shows the same trend at intervals of time except at 12mins, where SD at 5% binder level became higher in temperature than SD at 10% binder level. The plotted graph indicates that short-term exposure to adverse weather conditions during storage and transport does not affect the briquette's performance, as Saha et al. (2014) observed. In a similar study, Lubwama and Yiga (2018) used a comparable number of briquettes made from rice and coffee husks to boil 1 liter of water. Onuegbu et al. (2011) highlighted that briquettes' burning rate and calorific value are critical factors in determining the time required to bring water to a boil.

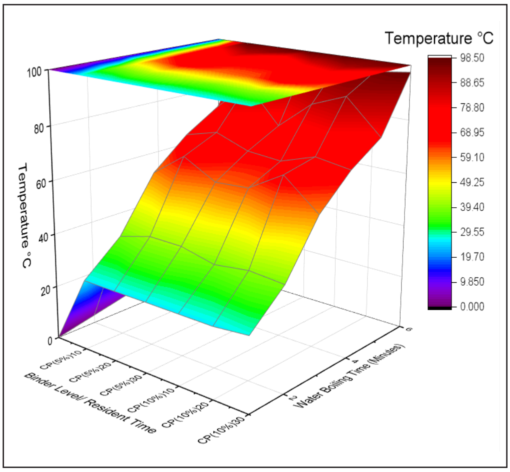

Figure 7. 3D response surface of temperature, binder level, and resident time on water boiling test of Cassava peel briquettes

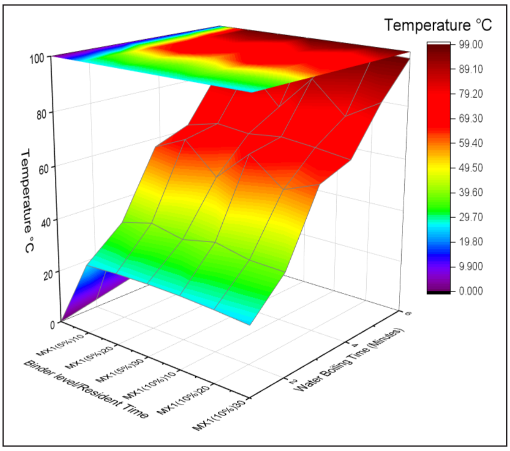

Figure 8. 3D response surface of temperature, binder level, and resident time on water boiling test of hybrid MIX1 briquettes

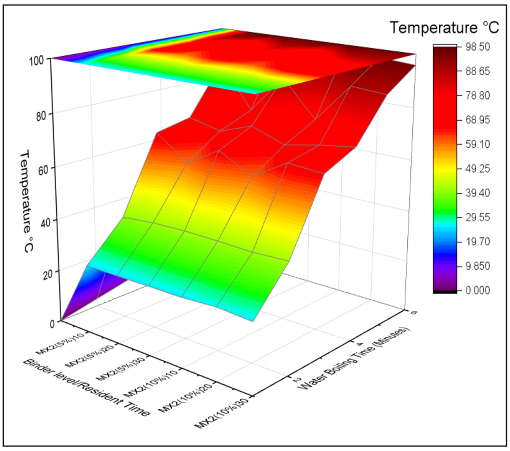

Figure 9. 3D response surface of temperature, binder level, and resident time on water boiling test of hybrid MIX2 briquettes

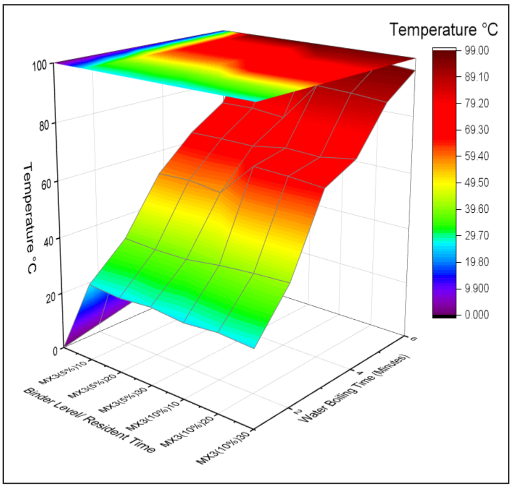

Figure 10. 3D response surface of temperature, binder level, and resident time on water boiling test of Hybrid MIX3 briquettes

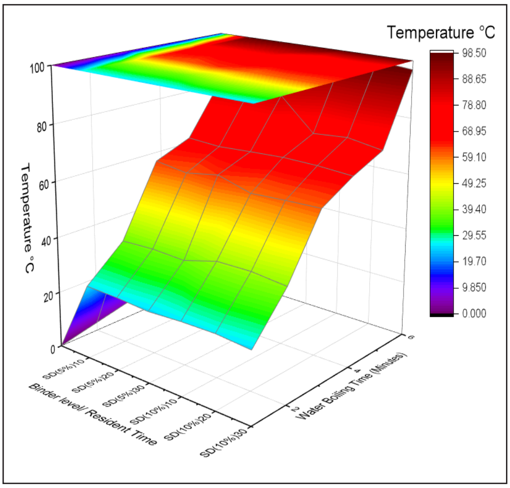

Figure 11. 3D response surface of temperature, binder level, and resident time on water boiling test of sawdust briquettes

Fuel Performance of the Briquettes

Thermal Fuel Efficiency (%)

Analysis of variance shows that material type, binder level, and 2-factor and 3-factor interactions significantly influenced the Briquettes' TFE, both at $p<0.05$, as shown in Table 4. Duncan's multiple range test in Table 5 shows that CP and MIX_2 are not significantly different. The results in Figure 12 indicated that the highest TFE of 55.55% was obtained in hybrid briquette MX_1 and MX_3 at 30 minutes of resident time and 5% and 10% binder level, respectively. The lowest TFE of 30.34% was obtained from CD at 10% binder level,

Table 4
p-values for mechanical properties and fuel performance

Source of Variation	Df	Thermal Efficiency (%)	Fuel Burning Rate (kg/h)	Specific Fuel Consumption (kg/l)
Material Type	4	0.000000*	0.000000*	0.000000*
Binder level (%)	1	0.000000*	0.009224*	0.005886*
Time (Mins)	2	0.069406	0.000001*	0.000213*
Material*binder level	4	0.000000*	0.000000*	0.000000*
Material*Time	8	0.008342*	0.004191*	0.023171*
Binder level*Time	2	0.125103	0.325107	0.320393^{ns}
Material*binder level*Time	8	0.043889*	0.622135	0.072830^{ns}
Error	60			
Total	89			

Note. * = Significant at $P < 0.05$; ns = not significant at $P < 0.05$

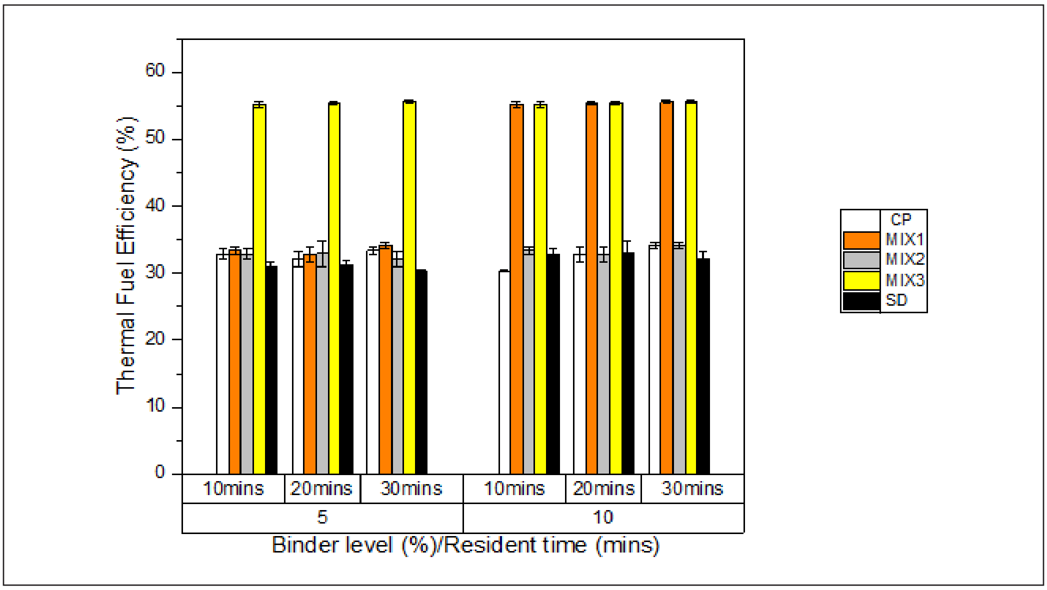

Figure 12. Mean of thermal fuel efficiency of briquettes about binder level (%) and resident time (mins)

Table 5
Duncan's multiple range test of thermal fuel efficiency, fuel burning rates, and specific fuel consumption based on material type

PARAMETERS	BRIQUETTE TYPE				
	CP	MIX_1	MIX_2	MIX_3	SD
Thermal fuel efficiency (%)	32.57389^a	44.40389^c	32.99722^a	55.38000^d	31.69556^b
Fuel-burning rates (kg/h)	0.450000^a	0.588333^c	0.437222^a	0.737778^d	0.495556^b
Specific fuel consumption (kg/l)	0.100889^a	0.110000^a	0.105389^{ab}	0.124556^b	0.100500^b

Note. Means with the same letter(s) in the row are not significantly different ($p < 0.05$)

10 minutes resident time, and SD at 5% binder level and 30 minutes resident time. It was observed that TFE tends to be higher where the ratio of CD and SD was higher.

Several factors, including the type and amount of biomass, the binder, and the cookstove, influence the Briquettes' TFE. The values obtained in this study are lower than those of Davies and Davies (2013). The efficiency of the briquettes was higher than the range obtained by Oyedemi (2012) at 15%–38%, which greatly depends on the amount of briquette burnt. The result of this study compared the fuel efficiency of groundnut shell briquette in the range of 14.47%–18.46% and for firewood, which was 10.31% (Oyelaran et al., 2015), as evidenced by the shorter time required for boiling one liter of water. This study also conforms well to Achebe *et al. (2018)* results for Gmelina arborea briquettes at 33.8% and 43.4% while performing lower than Bello et *al.* (2022) at 49.31%–57.80% using different binder types and ratios.

Fuel Burning Rates (kg/h)

Table 4 shows the analysis of variance, which shows that the material type, binder level, resident time, and their 2-factor interaction had a significant impact on the burning rate of the briquettes. Table 5 shows Duncan's multiple range test recorded based on briquette type; the fuel burning rates of CP and MIX_2 are not significantly different. On the other hand, a follow-up test based on resident time shows no significant difference between fuel burning rates at 10 and 20 mins. Figure 13 shows that FBR was highest with a value of 0.85kg/h in both MX_1 and MX_3 at 10% binder level and 20 mins resident time, while the lowest FBR of 0.39 kg/h was recorded in briquettes produced from CP, $MX_{2,}$ and SD at binder level 5%, 5% and 10% within resident time at 20, 30 and 30mins respectively.

The tested briquettes burned brightly and steadily, and they produced red-hot char. Achebe *et al.* (2018) reported a burning rate of 0.055 and 0.214kg/min, which was lower than the results obtained for this study. Rudiyanto *et al.* (2023) also reported a burning rate for cassava peel between the range of 0.021 – 0.026g/s, which appears to be lower than the results of this study. Oyedemi (2012) reported a burn rate of 0.80 kg/hr for Gmelina arborea sawdust briquettes, which conformed with this study. These variations in values may have resulted from the production procedure of the individual briquettes. Firewood, on the other hand, has a burn rate of 1.166 kg/hr (Oyelaran *et al*., 2015), indicating that the briquettes produced in this study are suitable substitutes for firewood. Navalta et al. (2020) observed that the type and composition of biomass used in briquette production affects its burning rate, along with its density, shape, and size.

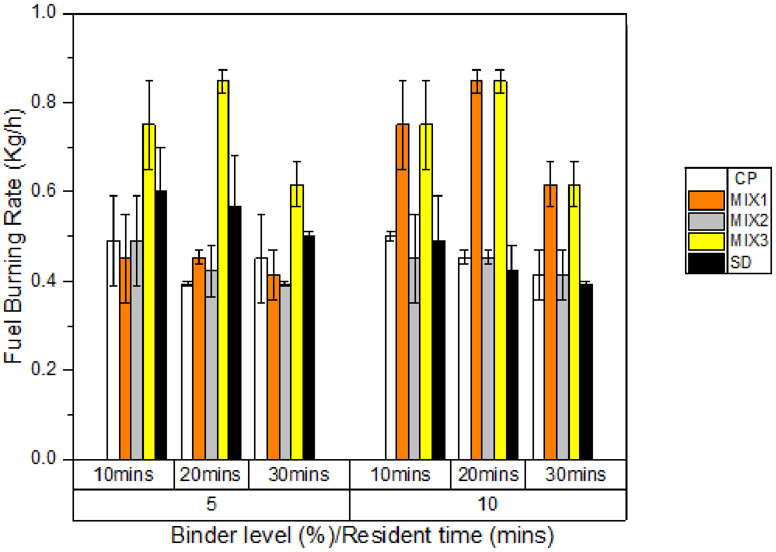

Figure 13. Mean of fuel burning rate of briquettes about binder level (%) and resident time (mins)

Specific Fuel Consumption (kg/l)

Table 4 The ANOVA test revealed a significant impact of material type, binder level, resident time, and their two-factor interactions on the specific fuel consumption of the briquette samples. However, the 3-factors interaction was not significant ($p < 0.05$). Duncan's test based on material type shows that the specific fuel consumption of MIX_2 is significantly different from (CP and MIX_1) as well as (MIX_3 and SD). On the other hand, a follow-up test based on resident times shows no significant difference between specific fuel consumption at 10 and 20 mins. Figure 14 shows that the highest SFC (0.14 kg/l) of the briquettes was recorded among the hybrid briquettes MX_1 and MX_3 at 5% and 10% binder level and 20 mins resident time while the lowest value of 0.08 was obtained in SD briquette at 5% binder level and 20 mins resident time. The follow-up test for briquette type and resident time is presented in Tables 5 and 6, respectively.

The specific fuel consumption value in this study was within the range of 0.09–0.14 kg/l, which was lesser than Oyedemi (2012) for cassava peel briquette (0.4), wood (0.6), and charcoal (0.5, Stoves and Bello et al., (2022) at a fuel consumption rate of 0.575. As

Table 6
Duncan's multiple range test of fuel burning rates and specific fuel consumption based on resident time

PARAMETERS	**RESIDENT TIME (mins)**		
	10	**20**	**30**
Fuel-burning rates (kg/h)	0.572000[a]	0.570667[a]	0.482667[b]
Specific fuel consumption (kg/l)	0.109533[a]	0.111700[a]	0.103567[b]

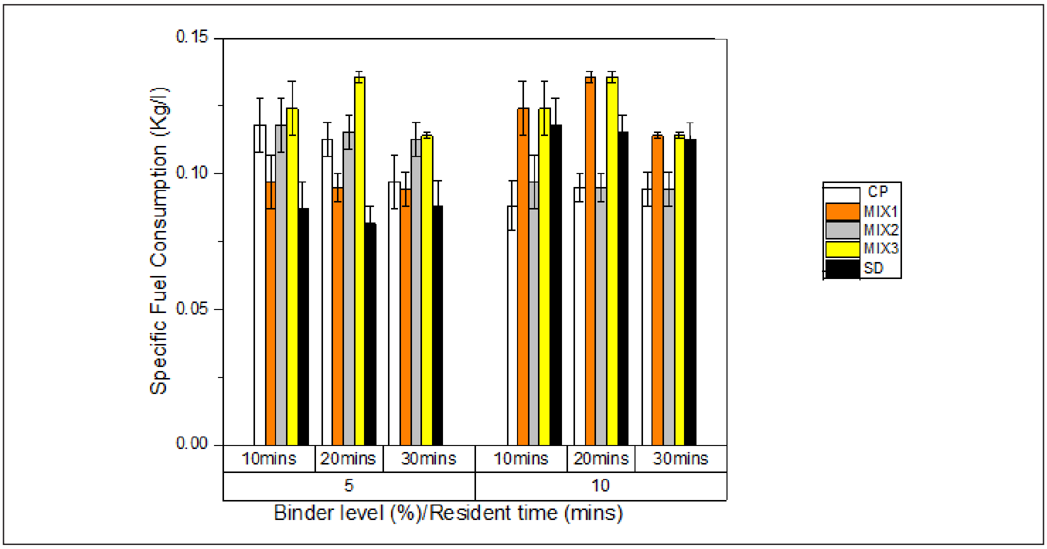

Figure 14. Mean of specific fuel consumption of briquettes about binder level (%) and resident time (mins)

comparable to firewood, Oyelaran et al. (2015) reported a fuel consumption rate of 0.332, which appeared to be higher than the value in this study. Also, a very higher SFC was reported as Rice husk showed an SFC of 4.987 kg/l, sawdust recorded 4.59 kg/l, and corn cob measured 4.036 kg/l. and 2.559 kg/l for palm kernel shells Adu-Poku et al., (2022). This result implies that lesser quantities of briquettes would be needed while taking a longer period to cook. Also, this could be due to a rise in density of the briquettes, which might reduce their porosity, thereby limiting the rate of oxidant infiltration and the outflow of combustion products during burning (Adu-Poku et al., 2022).

CONCLUSION

This study concluded that hybrid briquette MX1 demonstrated the highest durability with a shatter index of 95.54% at a 5% binder level and 30 minutes of residence time. In comparison, cassava peel briquette had the strongest compressive strength (0.29 N/mm^2) at a 10% binder level and 10 minutes of residence time. These briquettes possess adequate durability for handling, transportation, and storage. The fuel performance of hybrid briquettes MX1 and MX3 showed the highest thermal fuel efficiency (TFE) of 55.55% and a fuel burning rate (FBR) of 0.85 kg/h at specific binder levels and residence times. These briquettes also exhibited efficient cooking performance with easy ignition and minimal ash generation. Using cassava peel and sawdust in briquette production presents significant environmental and socio-economic benefits for rural communities in Oyo State and Nigeria by addressing waste management, energy deficits, and air pollution. Overall, the study affirms these briquettes' high quality and potential as a viable alternative to fuel wood.

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