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Combustion Characteristics of Biomass Briquettes from Bambara Groundnut Shell and *Chrysophyllum albidum* Seed as Alternative Fuel Sources

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ABSTRACT

Biomass briquettes have gained attention as sustainable alternatives to conventional fuels due to their renewable nature and relatively low environmental impact. Traditional fuels, such as charcoal, are widely used in Nigeria, particularly in rural areas. However, the environmental degradation associated with charcoal production and its limited sustainability pose challenges for long-term energy security. This study aimed to assess the combustion characteristics of briquettes made from Bambara groundnut shell (BGS) and Chrysophyllum Albidum seed (CAS), with starch gel as a binder at different proportions using the D-optimal design. The combustion characteristics of the briquette were investigated using ignition time, fuel burning rate, specific fuel combustion, water boiling time, and proximate and ultimate analyses. The optimal briquette, formulated with a 38:42:20 ratio of BGS, CAS, and starch gel respectively, exhibited superior quality at a compaction time of 121 seconds. The optimal briquette had the lowest ash yield (11%) and a higher compressive strength (0.07 MPa) among the briquettes produced from different proportions obtained from D-optimal design. The higher heating value of the optimal briquette was 16.85 MJ/kg when compared with 18.90 MJ/kg of charcoal. Additionally, its specific fuel consumption (SFC) was 20,000 kg/m³, significantly higher than charcoal (12,500 kg/m³). The high volatile matter content (80.02 ± 0.2%) for the optimal briquette facilitates easy ignition and efficient combustion. The briquette is suitable for household cooking and small-scale industrial applications. The use of BGS, CAS, and cassava starch gel offers a sustainable biofuel alternative, reducing reliance on traditional wood fuels and mitigating deforestation.

1. INTRODUCTION

The global population is increasing exponentially, driving higher energy demand and impacting the global economy. Increased fossil fuel consumption leads to resource depletion, prompting a shift toward renewable energy (Edomah, 2018). In Nigeria, commonly used cooking fuels like wood, charcoal, kerosene, and gas emit greenhouse gases such as CO_2, CH_4, N_2O, and fluorinated gases, contributing to global warming, climate change, ozone depletion, and household pollution (Chyuan et al., 2020). The environmental and supply challenges associated with fossil fuels have intensified research into renewable alternatives, with biofuels emerging as a key focus due to their sustainability (Sekar et al., 2021). In Nigeria, escalating cooking gas costs have increased the demand for cleaner and affordable fuel options. However, direct biomass combustion releases particulate matter and gaseous pollutants. Investigating waste biomass utilisation offers a viable solution to lowering emissions and providing economical cooking fuels for low-income communities.

Biomass, composed of organic matter, is a renewable and cost-efficient energy source with relatively low carbon emissions (Trubetskaya et al., 2019). Biomass is sourced from diverse plants (such as miscanthus, Bambara groundnut shell (BGS), switchgrass, hemp, corn,

and various trees), they are renewable energy resources sustained by ongoing crop production and biological waste. It is the world's fourth-largest energy source, following coal, natural gas, and crude oil (Bernard et al., 2018). Biomass consists of organic materials such as cellulose, hemicellulose, lignin, extractives, lipids, proteins, sugars, starches, hydrocarbons, ash, and trace metals (Tursi, 2019). In Nigeria, increasing agricultural residues contribute to environmental challenges, yet these residues could be converted into biofuels to provide sustainable cooking alternatives. However, direct biomass combustion produces high ash content, undermining its advantages over cooking gas (Oladosu et al., 2024).

Bambara groundnut is a legume valued for its protein-rich seeds (16–25%) and high carbohydrate (42–60%) content (Mohammed et al., 2016). Bambara groundnut shells (BGSs) are agrowastes that are underexplored and can weigh up to 1000 kg/ha depending on pod yield and shelling efficiency. They are often overlooked due to the absence of a defined worth, as they are typically regarded as agricultural waste with limited or no recognized economic or industrial value. This lack of perceived utility results in their underutilisation, despite the potential they may hold for applications such as bioenergy production, composting, or as raw material for value-added products in the agricultural and environmental sectors (Mohammed et al., 2016). Also, Chrysophyllum Albidum seeds (CASs) are deep brown, hard-shelled, and radially arranged. These non-edible seeds are traditionally discarded as waste and have recently gained economic significance. Their utilisation not only reduces environmental waste but also promotes sustainability. Despite being a carbon-rich biomass, CAS remains underutilised, with limited research on its potential applications and modifications for value-added products (Dzarma et al., 2022). Limited research exists on the utilisation of BGS and CAS, highlighting the need for innovative approaches to reduce crop waste and expand the crop's production potential.

Briquetting is a densification process that enhances biomass combustion properties while reducing transportation and storage costs (Henry, 2017). The key factors influencing briquette quality include particle size, surface area, compression parameters (temperature, pressure, rate, and time), and binder selection (Navalta et al., 2020). Biomass with higher cellulose content exhibits lower compaction ratios than lignin-rich biomass (Muazu & Stegemann, 2015). Binders used in briquette production can be organic or inorganic. The organic binders include heavy crude oil, starch, and molasses (Ugwu & Agbo, 2013). Inorganic binders consist of clay, sodium silicate, and cement. The type and quantity of binder, along with water addition, significantly influence the thermal behaviour and combustion of briquettes. The combustion characteristics are assessed through parameters such as reaction kinetics and water boiling tests such as the reaction kinetics and the water boiling tests (Aransiola et al., 2019). The choice of binder is critical, with studies identifying guar gum and cassava starch as the most effective options (Trubetskaya et al., 2019). Cassava starch is a binding material because of its relative availability and ease of processing. It is beneficial because it does not induce smoke (Akolgo et al., 2021).

Several researchers have developed different briquettes with their combustion properties examined. Sanka et al. (2024) produced faecal sludge briquettes and conducted the properties of the fuel. The study established the viability of transforming fecal sludge into combustible briquettes as a substitute energy source for cooking. Bio-coal briquettes were produced by Adeleke et al. (2021) using torrefied biomass and coal at different proportions. The ash analysis of the briquettes was conducted, and it was observed that both the use of mixed pitch and molasses as the binder ($\leq$15%) and the introduction of torrefied biomass ($\leq$10%) to coal has no effect on the ash contents of the resulting bio-coal briquette. The study conducted by Ajimotokan et al. (2019a) analyzed the combustion performance of briquettes composed of Idigbo charcoal particles, pinewood sawdust, and their agglomerates, with gelatinised cassava peels as the binding agent.

Ajimotokan et al. (2019b) examined the combustion performance of briquettes using biomass such as corn cob and rice husk with starch obtained from cassava as a binder. Rice and coconut husks were used as agricultural residues by Akolgo et al. (2021) during the production of briquettes. The combustion of the briquettes was characterized using water boiling and user acceptability tests. The effects of different binders such as cassava starch, gelatin, and corn starch were examined in the production of briquettes from carbonized corncobs by Aransiola et al. (2019). The study determined that increasing binder concentration enhances the quality of carbonized corncob briquettes, while higher compaction pressure improves their structural integrity, making them more suitable for storage and transportation. Falemara et al. (2018) investigated the physical properties and combustion performance of briquettes from the mixture of groundnut shells and corn cobs with starch as a binder at different proportions. Oladosu et al. (2023) applied a custom design methodology to optimise the formulation of fuel briquettes made from flamboyant pods and corn cobs. Cassava starch was incorporated as a binder to improve the briquettes' structural integrity and combustion efficiency.

Despite extensive research on biomass briquettes, previous studies have not explored the production of briquettes using agricultural residues from Bambara Groundnut Shell (BGS) and Chrysophyllum Albidum Seed (CAS), particularly with cassava starch as a binder. To the best of the authors' knowledge, no prior research has optimised or evaluated the combustion characteristics of such briquettes. This study addresses this critical gap by developing and characterising briquettes from BGS and CAS, assessing their combustion properties, including calorific value, burning rate, ignition time, and ash content. The novelty lies in utilising these underutilised agricultural residues to produce an alternative solid fuel, contributing to waste valorisation, clean energy production, and sustainable environmental management.

The specific objectives of this study are to formulate and produce briquette samples using the D-optimal design, optimise the compressive strength and ash yield of BGS and CAS bi-composite briquette, and compare the energy characteristics of optimised

briquette biomass and charcoal. This study advances biomass briquette research by introducing new raw materials, optimising binder composition, compaction time, and assessing combustion characteristics, making significant contributions to waste valorisation, renewable energy development, and sustainable environmental practices.

2. MATERIALS AND METHODS

2.1 Briquette Sample Preparation

The materials used for briqueting in this study include BGS, CAS, and cassava starch. BGSs (as shown in Figure 1a) were obtained from local farmers and merchants in Iseyin Oyo state, Nigeria. At the same time, the charcoal and cassava starch were purchased at the Oja Gboro market in Ilorin. The CASs (shown in Figure 1b) were collected from fruit processing industries and local markets where the fruits are consumed in Ilorin, Kwara State. The shells of Bambara groundnut were manually separated from the kernel using a hammer. The BGS and CAS were washed with clean distilled water to remove soluble impurities, and sun-dried for seven (7) days. The dried BGS and CAS were first crushed with a hammer mill, then finely ground and sieved through a 0.5 mm mesh to achieve uniform biomass (Ajimotokan et al., 2019a; Guo et al., 2020). A solution was prepared by dissolving 20 g of cassava starch in 40 ml of water. Separately, 100 ml of water was heated to its boiling point and mixed thoroughly with the starch mixture, triggering gelatinisation.



Figure 1: The biomass used for production of briquette are (a) BGS, and (b) CAS

BGS and CAS were blended with starch gel in different ratios (Table 1) to optimise the densification of starch-bonded Bambara groundnut shell-Chrysophyllum Albidum seed (BCS) briquettes (Osei Bonsu et al., 2020). The mixing ratios of BGS, CAS, and starch gel were determined using the D-optimal method in Design Expert 13 software. The homogenized mixture was introduced into the hydraulic briqueting mold, with molder plates correctly positioned prior to compression. The upper mold was pressed downward, compacting the material within a dueling time (T_c) of $30s \leq T_c \leq 150s$ (Ajimotokan et al., 2019b), resulting in the formation of a solid briquette (Figure 2). The briquetting process was conducted at FRIN, Ibadan, using a hydraulic press. After formation, the briquettes were stored in airtight ziplock bags for further material characterization.

Table 1: The mixing ratios for BGS, CAS, and starch gel at different compaction times

Run	BGS (%)	CAS (%)	Starch gel (%)	Compaction Time (s)
1	45	40	15	30
2	39	46	15	61
3	35	50	15	90
4	39	49	11	30
5	50	40	10	36
6	35	55	10	120
7	48	40	12	90
8	50	40	10	144
9	37	43	20	30
10	39	49	11	150
11	30	60	10	30
12	44	40	16	150
13	41	49	10	90

14	30	60	10	90
15	35	55	10	59
16	45	45	10	120
17	41	40	19	90
18	30	54	16	150
19	30	50	20	90
20	30	60	10	150
21	38	42	20	121
22	30	54	16	30
23	35	45	20	150



Figure 2: The produced solid briquette

2.2 Characterization of BCS Briquette

2.2.1 Compressive strength

Compressive strength tests were conducted on briquette BCS using a Universal Testing Machine (UTM) to evaluate their durability as biofuels. The tests followed ASTM 2166-85 (2008) standards, utilising a 50 kN load cell. A constant load of 100 N/min was applied until structural failure was observed, enabling a comparative assessment to identify the most optimal and durable briquette (Onukak et al., 2017). Compressive strength increases the durability of briquettes by decreasing the moisture-absorbing capacity, which in turn deteriorates the longevity of briquettes (Haba Bunga et al., 2024).

2.2.2 Proximate and Ultimate Analyses

The physicochemical properties of BCS briquette were analyzed to evaluate their suitability for bioenergy applications. Proximate analysis, conducted in accordance with ASTM D1762-84, measured moisture content, volatile matter, and ash content. Ultimate analysis was carried out using the CHNS-932 (LECO) elemental analyzer to quantify the elemental composition, including carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) according to ASTM 3174-76. Additionally, the gross calorific values of the samples were determined using an Oxygen Bomb Calorimeter to assess their energy content (Ojha et al., 2021).

2.2.3 Combustion of briquetted BCS sample

A combustion test was conducted on the optimal BCS briquette sample and charcoal using a cooking stove. Four essential parameters such as ignition time, water boiling time, fuel burning rate, and specific fuel consumption (SFC) were measured to evaluate the performance of the fuels. The results were systematically compared to determine variations in the performance of combustion between the selected fuels.

2.3 Data analysis

A design expert analytical tool was used for Analysis of Variance (ANOVA) and validation of the quality of fit of the models generated, enabling the evaluation of the statistical significance of the process parameters and their interactions on the combustion characteristics of the biomass briquettes. The tool facilitated the development of regression models to predict responses such as ash yield and compressive strength. Model adequacy was assessed using diagnostic statistics including coefficient of determination (R^2) and adjusted R^2. D-Optimal design was employed to optimise the mixture proportions of BGS, CAS, and starch gel under varying compaction times, with the goal of enhancing fuel properties and combustion performance.

3. RESULTS AND DISCUSSION

3.1 Compressive and Ash content of BCS briquette

As presented in Table 2, compressive strength values ranged from 0.03 MPa to 0.12 MPa across 23 experimental runs. Also, the ash content ranged between 11% and 38% for 23 experimental runs. Siahdashti et al. (2022) buttressed that the compressive strength of briquettes is frequently reduced as a result of a higher ash yield, as the structural integrity of the briquette is compromised by an undue amount of ash. The most inferior BCS briquette with a high ash content of 19% (with the lowest compressive strength) is Run 10 because ash is a non-combustible residue, and increasing its fraction lowers the cohesive connection between particles, resulting in brittle briquettes (Sani et al., 2020; Sola & Atis, 2012). The BCS briquette in Run 21, composed of 38% BGS, 42% CAS, and 20% starch gel, proved to be the best because it has the lowest ash yield and relatively higher compressive strength. Briquette durability and combustion efficiency are adversely affected by high ash yield because it can result in inadequate heat generation and more residue after burning (Falemara et al., 2018). Appropriate ash content is required for briquette performance in order to balance mechanical strength and combustion efficiency (Adeleke et al., 2021).

Table 2: The actual and predicted values of ash yield and compressive strength for different material compositions, analyzed under varying compaction durations

Run	Components			Factor	Responses			
	BGS (%)	CAS (%)	Starch gel (%)	Compaction time (s)	Ash yield (%)		Compressive strength (MPa)	
					Actual	Predicted	Actual	Predicted
1	45	40	15	30	24.00	24.00	0.1200	0.1200
2	39	46	15	61	20.00	20.00	0.0600	0.0600
3	35	50	15	90	16.00	15.98	0.0800	0.0799
4	39	49	11	30	15.00	15.00	0.0900	0.0900
5	50	40	10	36	20.00	19.99	0.0500	0.0500
6	35	55	10	120	18.00	18.08	0.0300	0.0303
7	48	40	12	90	17.00	17.04	0.0400	0.0402
8	50	40	10	144	15.00	15.02	0.0300	0.0301
9	37	43	20	30	18.00	18.00	0.0700	0.0700
10	39	49	11	150	19.00	19.01	0.0300	0.0300
11	30	60	10	30	25.00	25.01	0.0700	0.0700
12	44	40	16	150	23.00	22.99	0.0400	0.0400
13	41	49	10	90	15.00	15.02	0.0400	0.0401
14	30	60	10	90	17.00	16.97	0.0300	0.0299
15	35	55	10	59	18.00	18.30	0.0400	0.0589
16	45	45	10	120	16.00	15.90	0.0400	0.0396
17	41	40	19	90	17.00	16.97	0.0300	0.0299
18	30	54	16	150	12.00	12.00	0.0400	0.0400
19	30	50	20	90	19.00	19.00	0.0400	0.0400
20	30	60	10	150	17.00	16.98	0.0500	0.0499
21	38	42	20	121	11.00	11.03	0.0700	0.0701
22	30	54	16	30	12.00	12.00	0.0300	0.0300
23	35	45	20	150	13.00	12.99	0.0400	0.0400

3.1.1 Model analysis of the experimental runs

The relationships among the proportion of BGS, CAS, and starch gel and compaction time with the responses or output variables of compressive strength and ash content are presented in Equations (1-2).

$$\text{Compressive Strength} = +0.0670A + 0.0299B + 0.2786C - 0.0389AB - 0.5338AC - 0.111AD - 0.4570BC - 0.0100BD - 0.1226CD + 2.50ABC - 0.2195ABD - 0.0103ACD + 0.2395BCD - 0.0333AD^2 + 0.0301BD^2 + 0.3081CD^2 + 1.83ABCD + 0.4389ABD^2 - 0.0033ACD^2 - 0.4222BCD^2 - 6.67ABCD^2 \quad (1)$$

$$\textit{Ash content} = +7.90A + 17.11B - 128.24C + 11.04AB + 284.06AC - 8.38AD + 298.22BC - 7.46BD + 45.05CD - 638.57ABC + 72.16ABD + 2.25ACD - 42.79BCD + 17.99AD^2 + 10.42BD^2 + 90.78CD^2 - 684.21ABCD - 66.41ABD^2 - 174.28ACD^2 - 275.98BCD^2 + 956.97ABCD^2 \quad (2)$$

Where, A, B, C, and D are represented as BGS, CAS, starch gel, and compaction time respectively. The coefficient of determination (R^2) and adjusted R^2 for the compressive strength are 1.0000 and 0.9995 respectively, while the R^2 and adjusted R^2 for ash content are 0.9997 and 0.9941 respectively. These results reveal that the models are of high accuracy and the correlation between the predicted and actual values of the compressive strength and ash content are strong.

3.2 Combustion tests

The ignition time (T_i) is the time taken for the briquette to ignite with the aid of other energy such as kerosene. The highest ignition time from Table 3 was observed in run 21 at 5.05 minutes. The smallest ignition time was observed in charcoal at 4.17 minutes. The ignition time of the optimal briquette decreased by 21.1% when compared with charcoal. The ignition time is a function of the volatile matter. It was also observed that the higher the volatile matter the higher the ignition time since more time is taken to burn off the volatiles before combustion (Oladosu et al., 2023). The combustion test was carried out on the briquette samples to determine their water boiling time (Tb). An optimised briquette sample (Run 21) of 110 g was ignited in a stove, with 500 mL of water placed in a kettle for boiling assessment. Among the tested fuels, charcoal demonstrated the shortest boiling time at 10 minutes, whereas Run 21 required 30 minutes, the longest duration observed as provided in Table 3.

Table 3: Combustion tests on briquette BCS and charcoal

Sample	Mixtures	Weight of briquette (g)	Ti (min)	Tb (min)	FBR (g/s)	SFC (kgm^{-3})
Run 21	38:42:20	84	5.05	30	0.025	20000
Charcoal		100	4.17	10	0.027	12500

Also, the burning rate of the briquette, which quantifies the mass loss per unit time during combustion, was analyzed. As shown in Table 3, charcoal recorded the highest burning rate at 0.027 g/s, whereas the lowest value of 0.025 g/s was observed in run 21. The high combustion rate of charcoal implies a greater material consumption rate, which may influence fuel efficiency and economic viability. The SFC is the amount of briquette burned to the volume of water evaporated in the combustion test (Oladosu et al., 2023). It can be deduced that the SFC for the optimal sample was evaluated to be 20000 kg/m3 while the SFC for charcoal was 12500 kg/m^3.

3.3 Physiochemical properties of BCS briquette

Proximate analysis was carried out on the briquette which has the lowest compressive strength and highest ash yield and the run which has the highest compressive strength and lowest ash yield. Table 4 shows that run 10 has the lowest compressive strength and highest ash yield of 0.03MPa and 19% respectively and run 21 has a high compressive strength and lowest ash content of 0.07MPa and 11% respectively. The proximate analysis of the formed briquette is shown in Table 4. The ash content percentage indicates the amount of impurity that will not burn during and after combustion. The low ash content which is run 21 indicates that it is suitable for thermal utilisation. Moreover, the fixed carbon for run 10, run 21, and charcoal was 15.28± 0.4%, 19.60± 0.3% and 33.70± 0.4%, respectively. Run 10 has the lowest fixed content among the three samples (as shown in Table 4), and it generates less sustained heat which can prolong cooking time. A higher fixed carbon percentage generally results in longer burning time and higher heat retention, leading to greater thermal efficiency (Sanka et al., 2024).

Table 4: The proximate and ultimate analyses of BCS briquette

Sample	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash content (%)	C (%)	H (%)	N (%)	O (%)	S (%)	HHV (MJ/kg)
Run 10	7.92 ± 0.2	74.76 ±0.1	15.28 ± 0.4	2.04 ± 0.2	48.70 ± 0.1	5.99 ± 0.3	2.40 ± 0.2	44.70 ± 0.1	0.28 ± 0.1	12.98
Run 21	18.85 ± 0.1	80.02 ± 0.2	19.60 ± 0.3	0.37 ± 0.1	57.99 ± 0.3	5.92 ± 0.3	0.15 ± 0.1	33.90 ± 0.2	0.02 ± 0.3	16.85
Charcoal	4.92 ± 0.3	40.30 ± 0.5	33.70 ± 0.4	5.20 ± 0.2	60.80 ± 0.3	5.50 ± 0.3	1.55 ± 0.1	31.50 ± 0.2	0.80 ± 0.3	18.90

The elemental compositions of the samples are presented in Table 4. The percentage of carbon in run 21 is satisfactory due to its high carbon content which is variably translated to greater heating value (as presented in Figure 3) with more energy released during combustion. This makes high-carbon briquettes suitable for long-duration cooking and industrial heating applications (Oladosu et al., 2023). Run 21 which has low sulfur and nitrogen contents indicates minimal release of sulfur and nitrogen oxides into the atmosphere during combustion. This reduces the formation of nitrogen oxides (NOx) and sulfur dioxide in the atmosphere and averts environmental pollution (Guo et al., 2020).

The heating value greatly determines the quality of briquettes. The higher the calorific value of briquettes, the better the briquettes produced (Waluyo & Pratiwi, 2018). From Figure 3, Run 21 has the highest heating value of 16.85 MJ/kg which is probably due to the high carbon content (Onukak et al., 2017). Run 10 has a low calorific value of 12.98 MJ/kg when compared with charcoal with the

highest calorific value of 18.90 MJ/kg. The formed BCS briquette of run 21 with a high volatile content of 80.02±0.2% can easily be ignited during combustion. The high volatile matter content also indicates that during combustion, most of the formed briquettes will volatilize and burn as gas in combustion chambers. The high heating value of 16.85 MJ/kg calculated for briquettes produced from run 21 with a mixing ratio of 38:42:20 indicates that BCS briquettes can produce the heat required for small-scale industrial applications and household cooking. Biomass briquettes have lower compressive strength than charcoal, which will make their storage, handling, and transportation difficult. This limitation can be addressed by increasing the quantity of binder used and biomass so that the particles will be bound properly together. A briquette made from the homogenous mixture of BGS, CAS, and starch gel from cassava can be a sustainable alternative energy source.

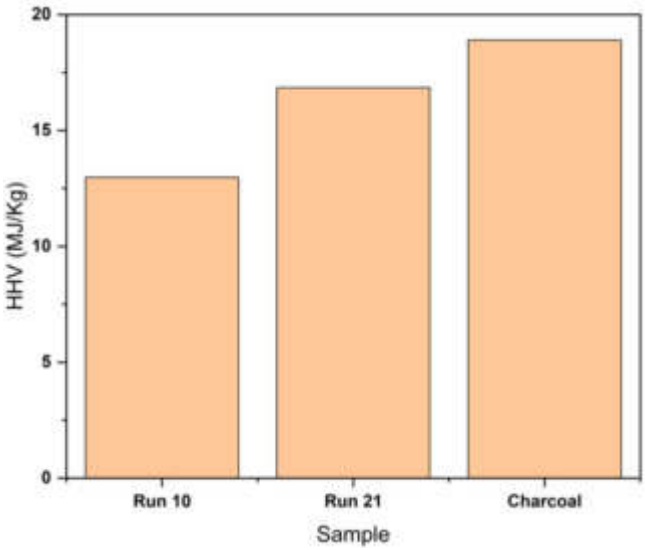


Figure 3. The higher heating value of the samples

4. CONCLUSION

This study optimised the compressive strength and ash yield of briquette from formulated samples of BGS, CAS, and starch gel using the D-optimal design. The fuel mixing ratio of 38:42:20 for BGS, CAS, and starch gel at a compaction time of 121 seconds was considered the best quality briquette. The optimal briquette has the lowest ash yield of 11% and relatively higher compressive strength of 0.07 MPa. The optimal briquette's ignition time and water boiling time decreased and increased by 21.1% and 66.7%, respectively, compared with charcoal. Also, the charcoal recorded the highest burning rate at 0.027 g/s, whereas the lowest value of 0.025 g/s was observed for the optimal BCS briquette. The SFC for the optimal sample was evaluated to be 20000 kg/m^3 while the SFC for charcoal was 12500 kg/m^3. The optimal BCS briquette with a high volatile content of 80.02±0.2% could easily be ignited during combustion. The high volatile matter content also indicated that during combustion, most of the formed briquettes would volatilise and burn as gas in combustion chambers. The high heating value of 16.85 MJ/kg for the optimal BCS briquettes with a mixing ratio of 38:42:20 indicated that the briquette could produce the heat required for small-scale industrial applications and household cooking. A briquette made from the homogenous mixture of agricultural residues such as BGS and CAS, and starch gel from cassava can be a sustainable alternative energy source, which invariably minimises the effects of deforestation.

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