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Evaluation of Thermal and Emission Performances of Briquettes Produced from Carbonized Corn Cob and Corn Husk

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ABSTRACT

The Mozambican agro-industrial sector relies heavily on various crops, with maize being the most significant. During processing, substantial waste is generated, which is often discarded as organic matter or burned, contributing to environmental pollution and the loss of potential energy resources. This study evaluated the thermal and emission performance of briquettes made from carbonized corn cob (CCC) and carbonized corn husk (CCH), using cashew nut skin as a binder for clean cooking applications. The briquettes were assessed against firewood and charcoal as control fuels, focusing on several energy performance parameters: water boiling time (WBT), combustion index (CI), thermal efficiency (TE), and emissions (E). Testing was conducted using an improved combustion stove (burn-jikokoa). Results indicated a CI of 1.06±0.04 for carbonized corn cob briquettes (BCCCNS) and 1.14±0.03 for carbonized corn husk briquettes (BCHCNS). The WBTs (in minutes) were 17 for BCCCNS, 29 for BCHCNS, and 45 for both firewood and charcoal. Thermal efficiency was notably higher for BCCCNS (45%) and BCHCNS (42%) compared to charcoal (24.13%) and firewood (21.55%), suggesting that the selected waste materials are excellent for producing high-energy briquettes. In terms of emissions, particulate matter (PM2.5) levels were measured at 80 µg/m^3 for both BCCCNS and BCHCNS, while firewood produced 190 µg/m^3 and charcoal 120 µg/m^3. Carbon monoxide (CO) levels were all below 200 ppm. These findings demonstrate the potential of utilizing agro-industrial waste to create sustainable and efficient cooking fuels.

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INTRODUCTION

Corn (Zea mays L.) is the primary food crop in Mozambique. According to the Agricultural Survey by Carrilho *et al.*, (2021), approximately 80% of the country's 3.6 million farms produce maize, which occupies around 41% of the total area dedicated to staple food cultivation. Corn accounts for 83% of cereal production and it is the preferred cereal among Mozambican households.

The corn harvesting process generates significant waste in the form of cobs, straw, and husks. It is estimated that for every tonne of maize grains harvested, between 2.2 and 2.7 tonnes of cobs and straw, as well as 0.3 to 0.9 tonnes of corn husks, are produced (Blandino *et al.*, 2016). This agricultural waste presents an opportunity for energy generation.

Biomass is the fourth-largest energy source globally, contributing about 15% of primary energy consumption. Its appeal as a fuel source is growing due to its renewable nature and relatively low CO_2 emissions. With low sulphur and nitrogen content, this type of waste promotes a cleaner and safer environment by reducing greenhouse gases and other harmful emissions associated with fossil fuels (Demiral and Tümsek, 2010).

Africa’s energy needs are currently met through a combination of biomass and fossil fuels. In 2022, Africa’s primarily traditional biomass, accounted for about 39%. Oil contributes about 26%, followed by natural gas at approximately 16% and coal at 14% (IEA, 2022). As of 2023, comprehensive data on Africa’s total primary supply including biomass is limited. However, biomass continues to play a significant role in the continent’s energy consumption, especially in rural area.

Mozambique, with a population of around 20 million, has about 80% of its residents living in rural areas, where biomass serves as the primary energy source. Approximately 80% of the country's energy consumption comes from woody biomass and charcoal (IEA, 2019) with annual demand estimated at 16 million cubic meters. However, only about 19% of the population has access to electricity (Salite *et al.*, 2021; Ugembe *et al.*, 2023).

The search for alternative, renewable, and environmentally friendly energy sources has become a global imperative in light of ecological, economic, and political challenges, as well as the anticipated depletion of non-renewable resources like fossil fuels. Mozambique is actively engaged in this transition. Renewable energy sources and energy efficiency are essential for efforts aimed at reducing greenhouse gas emissions and combating global warming. The sustainable development of biomass energy plays a vital role in enhancing the national economy by improving energy security, alleviating poverty in rural areas, preserving forest resources through sustainable management practices, diversifying the energy mix, and ensuring compliance with health and safety standards.

The utilization of corn cob as a feedstock for briquette production presents a promising avenue for sustainable energy solutions. Agricultural residues, such as corn cobs, offer a renewable and cost-effective alternative to traditional fossil fuels, contributing to energy security and environmental sustainability. Several aspects must be considered when evaluating the feasibility and efficiency of corn cob briquettes, including their thermal and emission performance, briquetting techniques, and insights from previous studies (Campus, 2011; Urbanovicova and Findura, 2017).

Corn cob briquettes exhibit competitive thermal properties, making them a viable substitute for conventional solid fuels such as wood and charcoal. The calorific value of corn cob briquettes typically ranges between 14–18 MJ/kg, depending on processing conditions and densification parameters. Compared to raw biomass, briquettes enhance combustion efficiency due to their uniformity, reduced moisture content, and higher bulk density (Bharti and Singh, 2018; Biaye *et al.*, 2024; Djafar *et al.*, 2022; Medina *et al.*, 2016). Furthermore, their emission characteristics are a critical factor in assessing their environmental impact (Ahmad et al., 2022; Biaye *et al.*, 2024). Studies have shown that corn cob briquettes generate lower particulate matter and carbon monoxide emissions compared to traditional charcoal, contributing to improved indoor air quality when used for cooking and heating applications. However, variations in combustion efficiency, ash content, and the presence of volatile organic compounds necessitate further research to optimize their use.

The production of high-quality briquettes from corn cobs requires an appropriate briquetting technique to ensure durability, combustion efficiency, and ease of handling (Roman and Grzegorzewska, 2024). The two common briquetting methods include mechanical and hydraulic compaction. Mechanical briquetting, often using screw or piston presses, generates higher-density briquettes with improved structural integrity, whereas hydraulic briquetting allows for lower energy consumption but may produce lower-density briquettes (Vaish *et al*., 2022). Key parameters affecting briquette quality include particle size, moisture content, binder usage, and compaction pressure. The selection of an appropriate briquetting process is essential for optimizing both the physical properties and combustion characteristics of the final product (Grover and Mishra, 1996; Imoisili *et al*., 2014; Kpalo, *et al*., 2020; Kpalo *et al*., 2020; Roman and Grzegorzewska, 2024; Vaish *et al*., 2022).

Several studies have explored the potential of agricultural residues, including corn cobs, for briquette production. Research findings indicate that biomass briquettes derived from corn cobs, rice husks, and sawdust demonstrate comparable energy efficiency and environmental benefits.

For instance, studies conducted in sub-Saharan Africa and Southeast Asia have reported that corn cob briquettes provide a sustainable alternative to wood fuel, reducing deforestation pressures while maintaining adequate heat output for cooking and industrial applications(Dragusanu and Lunguleasa, 2022). Additionally, comparative studies highlight that corn cob briquettes perform better in terms of combustion efficiency when blended with other biomass sources such as sawdust or peanut shells. However, challenges such as feedstock availability, production scalability, and market acceptance remain key areas for further investigation (Dragusanu and Lunguleasa, 2022; Kpalo *et al*., 2020; Ofem and Odey, 2023).

Overall, corn cob briquettes represent a viable renewable energy source with the potential to mitigate deforestation and reduce reliance on fossil fuels. However, continued research into optimizing their thermal efficiency, emission performance, and production processes is necessary to enhance their adoption on a larger scale.

This study aimed to evaluate the thermal and emission performance of briquettes produced from carbonized corn cob and corn husk.

MATERIAL AND METHODS

Material Collection and Preparation

Corn cobs ((Figure 1a) and corn husks (Figure 1b) were collected from local farm, Agrimaçaroca farm, in the Vilankulos district, Inhambane province. The binder, cashew nut skin (Figure 1c), was obtained from sellers in the Macia Market, Gaza province. After collection, all samples were stored in the Automatic Control Laboratory of the Faculty of Engineering at Eduardo Mondlane University.

Initial moisture content of corn cobs, corn husks and cashew nut skin measured were 15.54%, 75.03% and 18.17% on wet basis (w.b), respectively. The corn cobs and corn husks materials were cut into small pieces and then were dried to reduce moisture content up to 11.00% (w.b.) (Figure 2). The samples of corn cob and corn husks were ground using a ultra-centrifugal grinding machine (Restch ZM 200) and then sieved with a 1 mm sieve (Tampson, VS 1000) to obtain the desired particle size of ≤1 mm. The sample of cashew nut skin was crushed manually and then sieved at same condition of corn cob and corn husks

(a) (b) (c)

Figure 1: Samples of raw biomass waste used for this study (a) corn cobs, (b) corn husks and (c) cashew nut skin.

(a) (b)

Figure 2: Samples of biomass dried (a) corn cobs and (b) corn husks.

A small galvanized iron reactor with height 10 cm and diameter 17 cm was used to carbonize the corn cobs and corn husks samples separately. The samples were placed in the reactor and covered for anaerobic combustion to take place. After that the reactor was placed in a muffle furnace (Termolab - Electric Furnace; MLM) to carbonization. The carbonization process took place at a temperature of 400 °C, with a heating rate of 3.08 °C/min and a residence time variation of 1, 2 and 3 hours.

A total of ten different samples were prepared (Table 1) in varying ratio of corn cobs to cashew nut skin and corn husks to cashew nut skin to produce briquettes. The produced briquettes were submitted to mechanical analyses to verify the shatter index and chemical analyses to verify the quality of those briquettes. After that, the briquettes with good characteristics were used to teste thermal and emission analysis.

Table 1: Material composition of corn cobs (CC), corn husks (CH) and cashew nut skin (CNS) briquettes

No	Sample Name	Corn cobs	Corn husks	Cashew nut skin
1	CC	100	0	0
2	CH	0	100	0
3	CCCNS (50%-50%)	50	0	50

4	CCCNS (60%-40%)	60	0	40
5	CCCNS (70%-30%)	70	0	30
6	CCCNS (80%-20%)	80	0	20
7	CHCNS (50%-50%)	0	50	50
8	CHCNS (60%-40%)	0	60	40
9	CHCNS (70%-30%)	0	70	30
10	CHCNS (80%-20%)	0	80	20

Material Characterization

All analyses were conducted in triplicate. Proximate analysis was performed to estimate the percentages of volatile matter, ash content, and fixed carbon in the raw materials. The volatile matter was determined according to ASTM D-3175-18, while the ash content was measured following ASTM D3174-12 standard. Fixed carbon content was calculated by subtracting the values of moisture content, volatile matter, and ash content from 100%.

Briquette Production

The briquettes were formed using a cylindrical mould with a diameter of 50 mm and a height of 70 mm. Approximately 60 g of the prepared sample was placed into the mould and densified under controlled conditions (temperature of 150 °C and pressure of 10 MPa) using a manually operated hydraulic piston press. The pressure was applied for approximately from 60 seconds to compact the raw biomass into a dense and solid form, until programmed temperature of 150 ºC was reached. Initially, around 10 briquettes from each sample were prepared and subjected to mechanical and chemical analyses. From those briquettes that exhibited favourable characteristics, an additional 54 briquettes were produced for thermal analysis and emission tests.

Briquette Characterization

Determination of Moisture Content

Moisture content was determined according to ASTM D2444-16 standard. Each produced briquette was weighted and then oven-dried at 105 ± 2 ºC to constant masses in 24 h. The moisture content was calculated by Equation (1).

$$MC = \frac{W_1 - W_2}{W_2} \quad (1)$$

Where MC = moisture content, W_1 = wet weight, W_2 = weight after drying.

Determination of Density

The density of the produced briquettes was determined according to ASTM D2395-17 standard. It was calculated by dividing the mass of each briquette by its volume, which was obtained by measuring the diameter and height. The mass was recorded using a digital weighing balance (Denver Instrument, M-310). The methodology for calculating energy density involved multiplying the useful calorific value by the apparent density of the briquettes to avoid overestimating this property.

Determination of Dimensional Stability

The dimensional stability was assessed by measuring the height of the produced briquettes with a digital calliper (Mitutoyo; CD-6"CSX) at intervals of 0, 1, 2, 24, 48, and 72 hours, as well as at 7 and 15 days. Three briquettes were selected from each sample for height analysis. Dimensional stability was calculated by using Equation (2).

$$E = \frac{h_t - h_0}{h_0} \times 100\% \quad (2)$$

Where E = Dimensional stability, h_0 = initial height, h_t = height measured in determined interval of time.

Determination of Friability

The friability test was conducted using the tumbling method. Three briquettes from each sample were weighed and then placed in a ball mill (Anand A.C Induction Motor). The briquettes were subjected to mechanical action at 40 revolutions per minute (rpm) for 5 minutes, totalling 200 revolutions for each sample. Afterward, the briquettes were removed from the mill and weighed again. Friability was calculated by using Equation (3).

$$Fr = \frac{m_i - m_f}{m_f} \times 100\% \qquad (3)$$

Where F_r = Friability, m_i = initial mass, m_f = final mass after mechanical action.

Determination of Combustion Index

To determine the Combustion Index (CI), a system similar to that developed by Quirino and Brito (1991) was constructed.

The experimental procedure began by placing a wooden base beneath the combustor to minimize heat transfer to the scale, which was a precision model (Ranger 3000 line, Ohaus brand) with a capacity of 5 g. The combustor was positioned on the scale to monitor mass loss accurately. The produced briquettes were then placed in the combustor and ignited. A thermocouple was positioned near the surface of the briquettes to measure temperature over time, as illustrated in Figure 3. Charcoal and firewood were used as comparisons.

Figure 3: Combustion Index equipment.

Temperature control and mass consumption were monitored every minute throughout the 120-minute test. The combustion index was calculated by using Equation (4).

$$CI = \frac{M_0 - M_1}{M_0} \times 100\% \qquad (4)$$

Where CI = Combustion Index, M_0 = initial mass of briquettes, M_1 = final mass of ash residues.

Water Boiling Test

For the water boiling test, a metal pot, a stopwatch for time recording, a cooking stove, and a thermometer for temperature measurement were used. Approximately 480 g of briquettes were placed in the cooking stove, and a pot containing 2.5 liters of water at room temperature was positioned on top. The time and temperature required for the water to reach its boiling point were recorded. Additionally, emissions generated during the combustion of the briquettes were measured. The concentrations of key gases (CO and CO_2) and particulate matter (PM2.5) were automatically recorded using a flue gas analyzer (LEMS: Satelite C655D).

To ensure reproducibility, three trials were conducted for each type of briquette. For comparison, the same test was performed using charcoal and firewood. From the boiling point test, it was possible to record the fuel burning rate and thermal efficiency.

Data Analysis

Analysis of variance (ANOVA) was conducted to assess the performance of each treatment. All significance tests in this study were performed using Tukey's test with a significance level of $p < 0.05$.

RESULTS AND DISCUSSIONS

Moisture Content of the Samples

The moisture content of the samples used to produce briquettes is a crucial parameter for evaluating changes that may occur during storage and transportation. Table 2 presents the moisture content results of the raw materials. The moisture content values of the original samples were 10.54% for corn cob, 10.94% for corn husk, and 10.17% for cashew nut skin.

The results show further that the mean values with the same letter(s) in a column for briquette properties are not significantly different ($p < 0.05$). Analysis of variance indicated no significant differences in the moisture content values of the studied samples ($p < 0.05$).

Table 2: Moisture of the original samples

Sample	Moisture Content (%)
Corn cob (CC)	10.54^a
Corn husk (CH)	10.94^a
Cashew nut skin (CNS)	10.17^a

For corn cob, Akintaro *et al*., (2017) and Kpalo *et al*., (2020) reported similar moisture content values. In a study evaluating the mechanical properties of wood-derived charcoal briquettes, Makgobelele *et al*., (2021), found a moisture content of 12.2%. Oliy and Muleta (2020) studied five varieties of corn cob and reported a moisture content about of 8.24%.

For corn husk, Silva *et al*. (2022) recorded moisture content of around 9%, which is slightly lower than the values found in this study. The optimal moisture content for briquette production typically ranges from 8% to 12%, depending on the nature of the feedstock (Chin and Siddiqui, 2000). Higher moisture content in biomass samples can reduce the stickiness of lignin, while lower moisture content prevents the dilution of lignin, limiting its ability to bind surrounding materials (Akintaro *et al*., 2017). When moisture content is low, briquettes ignite easily, burn cleanly, and are expected to yield higher calorific values. In contrast, briquettes with high moisture content tend to waste heat on vaporizing excess water, often resulting in lower burning rates, reduced heat of combustion, and increased smoke emissions (Akowuah *et al*., 2012).

Carbonization of the Samples

To obtain a sample rich in fixed carbon, corn cobs and corn husks were carbonized at varying residence times of 1, 2, and 3 hours (Figure 4). This variation aimed to determine the optimal carbonization time and yield for the studied samples. The yield of carbonization reflects the percentage of volatile materials eliminated and the amount of fixed carbon produced.

The results of the carbonization process are illustrated in Figure 4. Can be seen, after 1 hour, the lowest yield was with 45.22% for corn cob compared to 59.16% for corn husk. At the 2-hour mark, carbonized corn cob (CCC) exhibited a higher yield than carbonized corn husk (CCH), while at 3 hours, CCH yielded more than CCC.

Since the differences in yields at 2 and 3 hours were minimal, the 2-hour residence time was selected for briquetting purposes, as it was also more economical in terms of electricity usage.

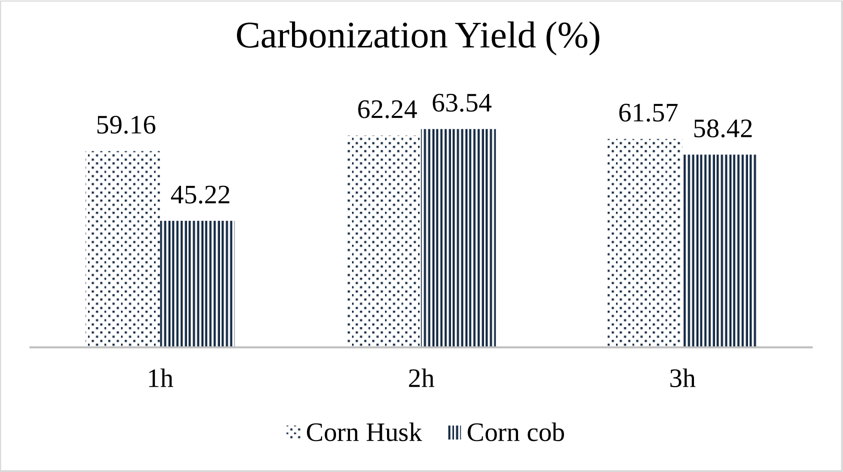


Figure 4: Carbonization Yield of corn husk (CCH) and corn cob (CCC) at residence times of 1, 2 and 3 hours.

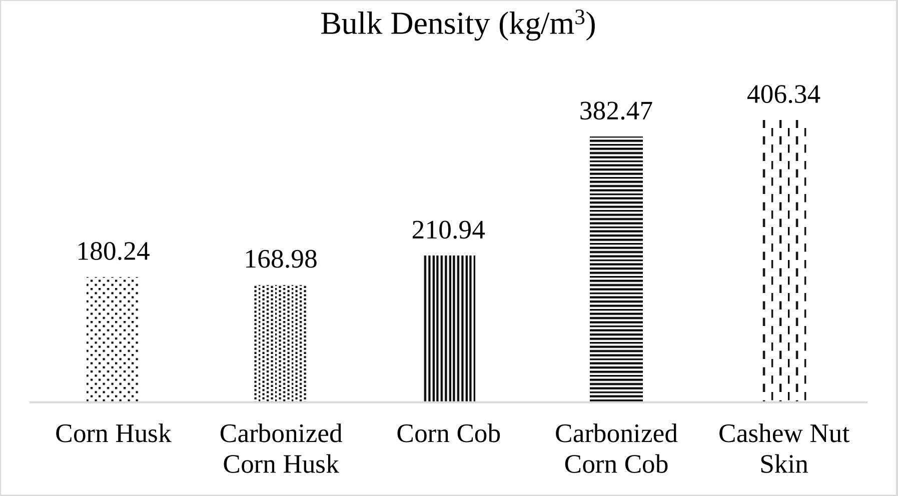


Figure 5: Bulk density of samples.

The goal of carbonizing corn cob and corn husk is to produce char with high energy density and carbon content (Oliy and Muleta, 2020). Carbon enhances the burning capacity of materials due to its nature as a good fuel. When carbon is present, it reacts with oxygen during combustion, leading to an exothermic oxidation reaction that releases significant heat (Wang *et al*., 2024). Fuels with higher fixed carbon content burn more slowly, resulting in longer residence times in the combustion equipment (Chen *et al*., 2021). Kluska *et al*. (2020) observed that carbonization temperature significantly influences char yield, with average yields decreasing from 43.1% at 300 °C to 22.7% at 700 °C. They noted that the temperature range of 300 to 500 °C represents the main phase of carbonization, during which the most significant mass loss occurs.

Samples Bulk Density

The bulk density of the biomass samples regarding to corn cob (CC), carbonized corn cob (CCC), corn husk (CH), carbonized corn husk (CCH) and cashew nut skin (CNS) is presented in Figure 5. The lowest bulk density was recorded at 168.98 kg/m³ for CCH, while the highest was 406.34 kg/m³ for CNS.

Density is a crucial physical characteristic of fuel briquettes, influencing factors such as transportation, handling, energy content, ignition, and combustion. Higher density typically correlates with a greater energy-volume ratio (Adeleke *et al*., 2022; Da Silva *et al*., 2022).

The results for bulk density and energy density of the samples carbonized corn cob and cashew nut skin (CCCNS), carbonized corn husk and cashew nut skin (CHCNS), as well as the produced briquettes, carbonized corn cob and cashew nut skin (BCCCNS), and carbonized corn husk and cashew nut skin (BCHCNS) are summarized in Table 3.

As shown in Table 3, there is an increase in bulk density from the prepared samples to the final briquettes. According to the literature, the density of briquettes is directly related to the density of the biomass used (Adeleke *et al*., 2022). Overall, the summarized density of the briquettes is higher than the initial density of the studied samples.

Table 3: Bulk density of samples and energy density of produced briquettes

Samples	Bulk Density (kg/m^3)	Energy Density (MJ/m^3)
CCCNS (50%-50%)	265.26±0.029	5,122.28±0.575
CHCNS (50%-50%)	359.96±0.017	7,379.34±0.357
BCCCNS (50%-50%)	1,001.63±0.005	20,273.27±0.444
BCHCNS (50%-50%)	988.93±0.021	19,341.58±0.106

The bulk density values obtained exceeded the minimum threshold of 600 kg/m^3 recommended by Mani *et al*., (2006) for effective transportation and secure storage. Density is also influenced by the lignin content of the raw materials (Satria *et al*., 2021). Ladapo *et al*. (2020) recorded 287.1 kg/m^3 for briquettes made from maize residues, which is significantly higher than the values observed in this study.

In comparison to previous findings, the density recorded here is higher than the 660-720 kg/m^3 range noted by Satria *et al*. (2021) for briquettes made from corn cobs and areca peel charcoal, likely due to the different types of binders used. This is because the difference of lignin of binder used. Mani *et al*. (2006) found bulk densities of briquettes ranging from 600 to 950 kg/m^3, depending on moisture content and pressure. Additionally, Oladeji and Enweremadu (2012), reported lower density values of 533 to 981 kg/m^3 for briquettes made from two varieties of corn cob, while Oliy and Muleta (2020) found an average bulk density ranging from 494.56 to 520.01 kg/m^3 for briquettes made from various corn cob types. The bulk density of the raw materials studied here exceeds the minimum recommended value of 40 kg/m^3 for wooden materials Kaliyan and Morey, (2010), making these briquettes suitable for packaging and transportation (Oliy and Muleta, 2020; Oladeji and Enweremadu, 2012).

Falemara *et al*. (2018) reported a density range of 440 to 530 kg/m^3 for briquettes made from wood residues and groundnut shells, noting that higher density correlates with longer burning times. The carbonized corn cob and carbonized corn husk briquettes demonstrated ease of transport and storage due to their higher mean bulk density.

The variation in bulk density can be attributed to factors such as the origin of the raw material, particle size and distribution, compaction pressure applied during briquetting, moisture content at the time of briquetting, as well as the type and quantity of binder used in the process.

The briquette made from a 50:50 mixture of carbonized corn cob and cashew nut skin (BCCCNS) had a bulk density of 1,001.63 kg/m^3 and an energy density of 20,272.27 MJ/m^3. In comparison, the briquette made from carbonized corn husk and cashew nut skin (BCHCNS) at the same ratio had a bulk density of 988.93 kg/m^3 and an energy density of 19,341.58 MJ/m^3.

Notably, the briquettes produced from CCC exhibited a higher energy density than those made from CCH with the same binder amount. Since energy density depends on the calorific value and briquette density, CCC briquettes outperformed those from corn husks due to their higher fixed carbon content and lower ash content.

Protásio *et al*. (2011), finding values of 23,822.9 MJ/m³ for coffee husk briquettes, 17,688.3 MJ/m³ for corn waste briquettes, and 17,458.9 MJ/m³ for eucalyptus sawdust briquettes.

Furtado *et al*. (2010) also calculated energy density for briquettes made from pine bark, chips, and sawdust, noting that their final values might have been overestimated due to moisture content not being accounted for, complicating comparisons with the results of this study.

Proximate Analysis

The results of the proximate analysis (ash, volatiles, and fixed carbon) for the studied samples are presented in Table 4. The ash content, which indicates the percentage of impurities that do not burn during combustion, ranged from a minimum of 2.83% for corn cob (CC) to a maximum of 41.76% for a mixture of corn cob and cashew nut skin (CCCNS) in a 70%-30% blend. A low ash content is preferable for thermal utilization, as high ash levels typically lead to lower calorific values (Efomah and Gbabo, 2015). Biomass with higher ash content tends to consume more fuel compared to that with lower ash content (Al-kayiem, 2013).

Among the studied briquettes, CC exhibited the highest mean volatile matter content at 84.49%, while the lowest was observed in the mixture of corn husk and cashew nut skin (CHCNS) at an 80%-20% ratio, with 22.91%. The lower volatile content in CHCNS may be attributed to the presence of fine particles, which can reduce ignition time by facilitating efficient thermal decomposition and rapid volatile release. A shorter ignition time accelerates the combustion process, preventing volatile compounds from remaining trapped in the briquette (Tanui, *et al*., 2023).

Biomass typically has a high volatile matter content, often exceeding 80%. This high volatility suggests that during combustion, a significant portion of the briquettes will volatilize and combust as gas in the combustion chamber (Efomah and Gbabo, 2015).

Table 4: Proximate analysis for studied samples

Sample	Ash (%)	Volaties (%)	FC (%)
CC	2.83±0.007	84.49±0.309	12.67±0.305
CH	10.76±0.062	70.55±0.042	18.02±0.041
CCCNS (50%-50%)	25.37±0.023	44.39±0.012	30.22±0.029
CCCNS (60%-40%)	37.62±0.029	31.51±0.004	30.85±0.045
CCCNS (70%-30%)	41.76±0.047	33.37±0.004	24.86±0.021
CCCNS (80%-20%)	37.96±0.044	31.24±0.021	30.78±0.047
CHCNS (50%-50%)	8.78±0.003	43.34±0.029	47.87±0.029
CHCNS (60%-40%)	9.25±0.010	38.30±0.019	52.44±0.027
CHCNS (70%-30%)	6.37±0.003	35.57±0.037	50.05±0.034
CHCNS (80%-20%)	6.93±0.014	22.91±0.060	70.15±0.056

The fixed carbon content for the produced briquettes ranged from 12.67% for corn cob (CC) to 70.15% for corn husk and cashew nut skin (CHCNS) in a 80%-20%. A lower fixed carbon content can result in longer cooking times due to reduced heat release, while fixed carbon serves as a rough estimate of a fuel's heating value (Efomah and Gbabo, 2015).

If volatile matter is high, combustion can initiate at lower temperatures, indicating that the charcoal is easy to ignite. However, high ash content may pose challenges during the combustion process (Li *et al.*, 2022).

Heating Value

The calculated results for the higher heating value (HHV) and lower heating value (LHV) are presented in Table 5.

Table 5: Higher and lower heating value

Biomass	HHV (MJ/kg)	LHV (MJ/kg)
Cashew nut skin (CNS)	19.00b ± 0.57	17.64b ± 0.57
CHCNS (50%-50%)	20.66a ± 0.34	19.31a ± 0.34
CCCNS (50%-50%)	21.86a ± 0.04	20.50a ± 0.04
Corn Husk (CH)	20.98a ± 0.56	19.63a ± 0.56
Carbonized corn husk (CCH) 1h	21.12b ± 0.10	19.76b ± 0.10
Carbonized corn husk (CCH) 2h	21.00a,b ± 0.53	19.65a,b ± 0.53
Carbonized corn husk (CCH) 3h	21.00a ± 0.08	19.64a ± 0.08
Corn cob (CC)	21.11a ± 0.21	19.75a ± 0.21
Carbonized corn cob (CCC) 1h	25.18a ± 0.07	23.83a ± 0.07
Carbonized corn cob (CCC) 2h	25.42a ± 0.51	24.07a ± 0.51
Carbonized corn cob (CCC) 3h	25.61b ± 0.29	24.26b ± 0.29

The values shown in Table 5 represent means ± standard deviation of the treatment, with equal letters on the same line indicating no significant differences according to the Tukey's test.

According to table 5, can be seen that the cashew nut skin had a lowest value of Higher Heating Value (HHV) of 19 MJ/kg, compared to the other biomasses.

The HHV for CCH did not vary significantly between the 1-hour (21.12 MJ/kg) and the 2-hours and 3-hours carbonization durations, both of which averaged 21.00 MJ/kg. Additionally, there was no significant difference in HHV before and after carbonization for CH, likely due to the high ash content in the CCH compared to the non-carbonized version. In contrast, CC displayed a notable increase in HHV following carbonization, with the highest values recorded at 25.18 MJ/kg for 1 hour, 25.42 MJ/kg for 2 hours, and a peak of 25.61 MJ/kg for CCC for 3 hours at 400 ºC.

Stolarski *et al*. (2018) found that fixed carbon content positively influences calorific value; higher fixed carbon leads to increased calorific values. Awulu *et al*. (2018) found a calorific value of 12.27 MJ/kg for corn cob briquettes. The increase in heating value is influenced by factors such as moisture content, ash content, and volatile matter (Awulu *et al*., 2018). The calculated LHV ranged from 17.64 MJ/kg to 24.26 MJ/kg, with the lowest value for cashew nut skin and the highest for CCC for 3 hours.

Since the ash, volatiles, and fixed carbon tests were conducted on a dry basis (the samples were oven-dried prior to testing), the useful calorific value corresponds to the lower calorific value of the respective sample.

Produced Briquettes

Briquettes, as shown in Figure 6, were produced using carbonized corn cob (CCC) and carbonized corn husk (CCH), with cashew nut skin as a binder in various mixing ratios: 80%-20%, 70%-30%, 60%-40%, and 50%-50%. Additionally, briquettes made solely from corn cob were also included.

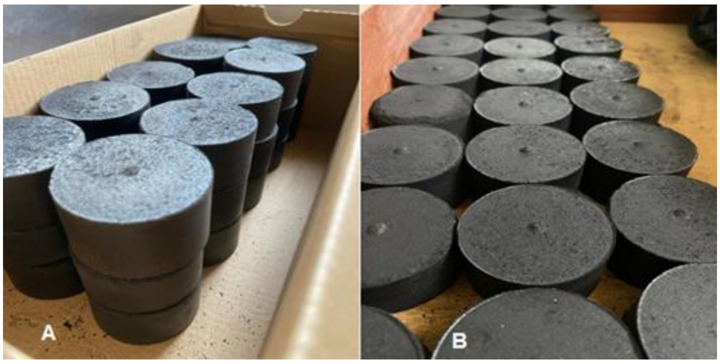


Figure 6: Produced Briquettes (a) BCCCNS (50%-50%) and (b) BCHCNS (50%-50%).

The best results were achieved with briquettes made from a 50:50 mixture of carbonized corn husk and cashew nut skin, as well as those made from a 50:50 mixture of carbonized corn cob and cashew nut skin. These selected briquettes were subsequently used for water boiling and emission tests.

Friability Index

The friability test allowed for the identification of the optimal biomass-binder combination and the most effective mixing ratio. The results of the friability index for the produced briquettes are presented in Table 6, along with their classification based on mass loss.

Table 6: Friability index for produced briquettes

Briquettes	Friability Index (%)	Classification
BCC	1.03±0.15	Non-Friable (NF)
BCH	6.32±0.18	Non-Friable (NF)
BCCCNS (50%-50%)	2.51±0.042	Non-Friable (NF)
BCCCNS (60%-40%)	4.99±0.170	Non-Friable (NF)
BCCCNS (70%-30%)	14.40±0.184	Slightly Friable (SF)
BCCCNS (80%-20%)	19.46±0.286	Medium Friability (MF)
BCHCNS (50%-50%)	2.56±0.022	Non-Friable (NF)
BCHCNS (60%-40%)	5.46±0.150	Non-Friable (NF)
BCHCNS (70%-30%)	16.31±0.216	Medium Friability (MF)
BCHCNS (80%-20%)	17.87±0.144	Medium Friability (MF)

According to Zanella *et al*. (2017), briquettes with mass losses of less than 10% are considered non-friable. In this study, the carbonized corn cob and carbonized corn husk briquettes produced in 50%-50% and 60%-40% ratios fall into this category.

Briquettes with mass losses between 15-24% are considered medium friable. This classification applies to BCCCNS (80%-20%), BCHCNS (70%-30%), and BCHCNS (80%-20%). Analysis of the friability index indicates that as the amount of binder increases, the carbonized briquettes become less friable. This is expected, as the binder enhances adhesion among the carbonized biomass particles.

According to the results in Table 6, the friability index of the briquettes were significantly influenced by the type of biomass used (carbonized corn cob, carbonized corn husk, and cashew nut skin). The lower the friability of a briquette, the greater its mechanical strength.

High friability in briquettes poses a disadvantage, as it can lead to a loss of integrity, complicating handling, transportation, and application. In combustion scenarios, overly friable briquettes may disintegrate prematurely, resulting in inadequate and unstable burning, which can adversely affect process efficiency (Mkini and Bakari, 2015).

Subsequent analyses were carried out for the briquettes that proved to be less friable, namely BCCCNS (50%-50%) and BCHCNS (50%-50%).

Dimensional Stability

The dimensional stability test measures the changes in diameter and length of briquettes after moulding. This test is crucial for assessing whether the briquettes absorb excess moisture from their environment, which can affect key parameters such as calorific value, weight, and dimensions. The results of the dimensional expansion test are illustrated in Figure 7.

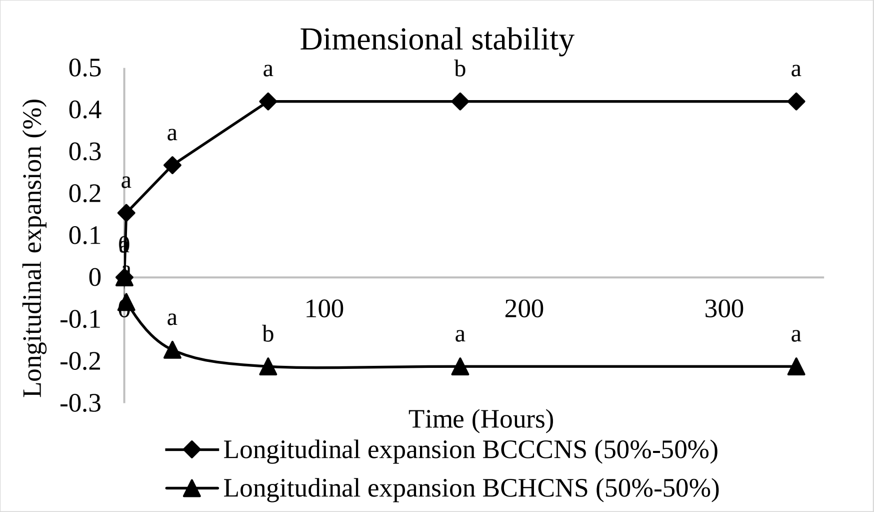


Figure 7: Briquettes Dimensional Stability. Equal letters on the same curve do not differ significantly for Tukey's test.

As shown in the graphs in Figure 7, the BCCCNS (50%-50%) briquettes exhibited noticeable expansion, while the BCHCNS (50%-50%) briquettes experienced slight compression over time. Notably, stability was achieved after about 72 hours for both briquettes.

The average expansion of the BCCCNS (50%-50%) was 0.42 ± 0.16%, whereas the BCHCNS (50%-50%) showed an average compression of 0.21 ± 0.03%. These results indicate good dimensional stability for the produced briquettes.

According to Da Silva *et al.* (2015) briquettes typically tend to expand after production, with variations depending on the type of biomass, particle size, moisture content, and storage conditions. In this study, the briquettes were packaged at room temperature.

One method to control expansion is by using binders during briquette production. However, incorporating binders may lead to changes in the production process and increased costs. Excessive expansion is undesirable, as it negatively impacts the mechanical properties of the briquettes. Greater expansion (lower dimensional stability) results in reduced mechanical resistance (Nakashima *et al*., 2018).

Combustion Index (CI)

Analysing the temperature and mass consumption during combustion, Figures 8 and 9 reveal typical profiles for temperature versus time and mass consumption versus time. The maximum temperatures achieved by each briquette differed slightly, with BCCCNS (50%-50%) averaging 730ºC and BCHCNS (50%-50%) averaging 750ºC. Charcoal reached a maximum temperature of 770ºC, while firewood recorded the lowest at 470ºC.

The briquettes ignited within 5 to 10 minutes, with this variation likely due to their arrangement in the combustor. When positioned to allow better air circulation, ignition occurred more quickly, facilitating the escape of volatiles and preventing air flow obstruction, which can also affect overall burning time.

During combustion, a period of burning precedes the peak temperature, followed by a rapid decline until stability is reached between 300 and 400ºC for briquettes and charcoal. Firewood, however, stabilized at a lower range of 200 to 300ºC.

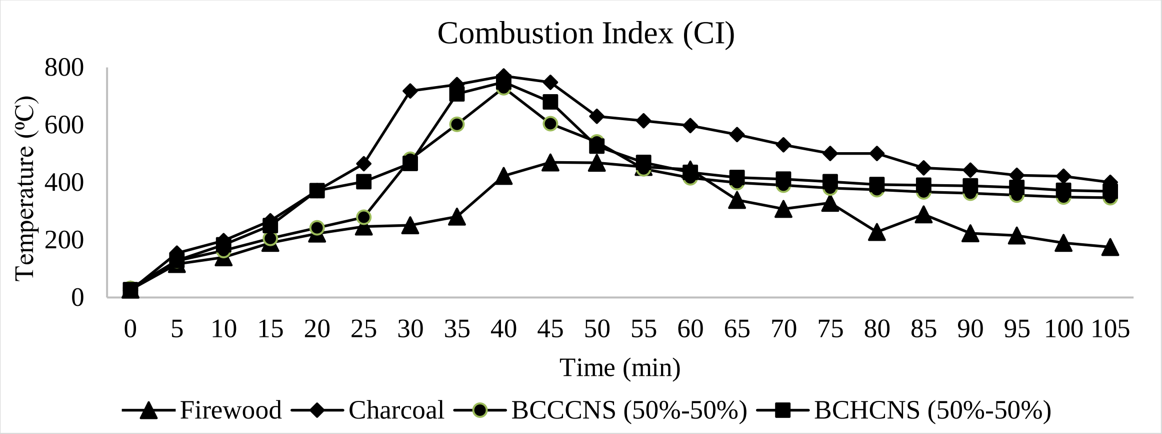


Figure 8: Temperature consumption during CI.

The mass consumption graph displayed a nearly linear decrease, transitioning to a logarithmic decline after reaching maximum temperatures. Both briquettes consumed about 65% to 70% of their mass during the test, while charcoal consumed only 50% and firewood consumed the most at 90%. The combustion Index (CI) for both briquettes is shown in Table 7.

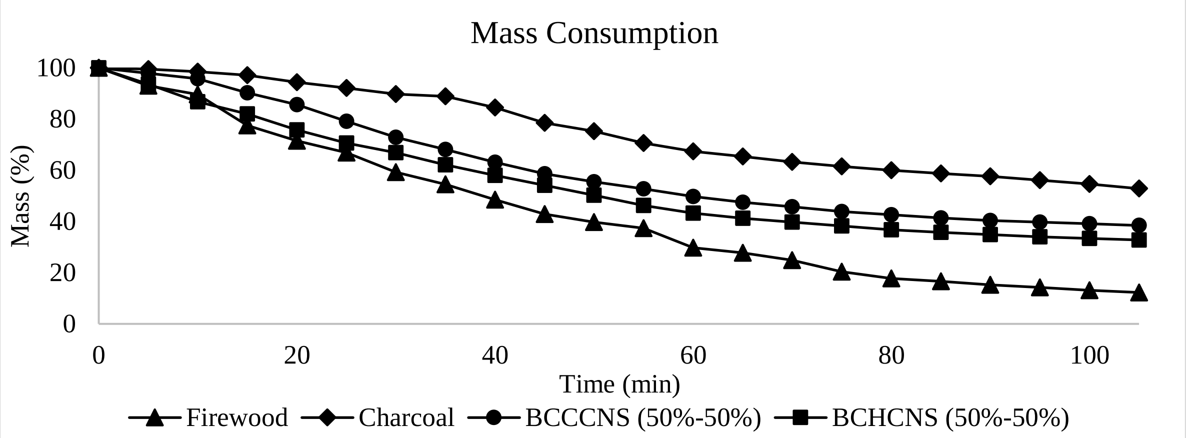


Figure 9: Mass consumption during CI.

Table 7: Combustion Index

Samples	CI
BCHCNS (50%-50%)	1.26 ± 0.04
BCCCNS (50%-50%)	1.34 ± 0.03
Charcoal	1.64 ± 0.04
Firewood	0.75 ± 0.05

According to the table 7, the BCCCNS (50%-50%) briquettes had a higher CI (1.34 ± 0.03) compared to the BCHCNS (50%-50%) briquettes (1.26 ± 0.04), which was expected given that the cob and cashew nut skin briquettes had higher calorific value and energy density. Charcoal had the highest CI value (1.64 ± 0.04), while firewood had the lowest (0.75 ± 0.05). This indicates that the briquettes exhibit characteristics similar to charcoal, demonstrating potential for replacing and reducing charcoal use.

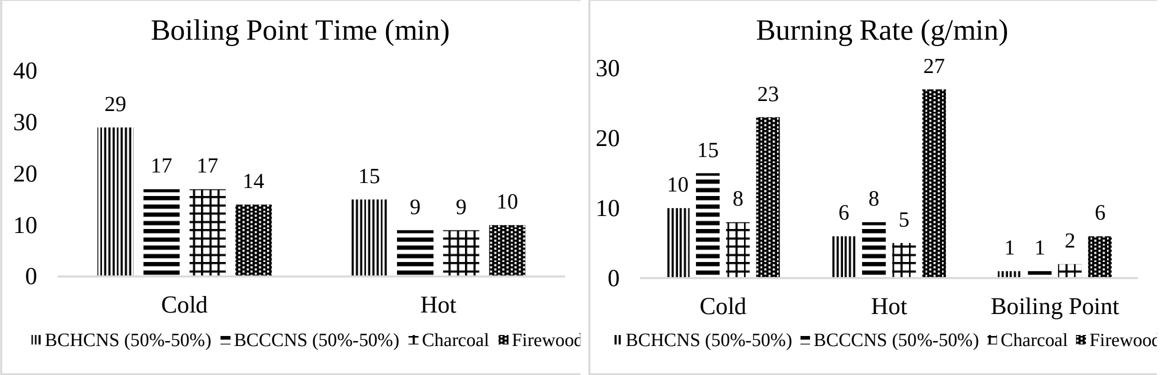
Figure 10: Images of combustion: A) Briquettes soaked in paraffin in the combustor; B) Ignition of the paraffin; C) Ignition of the briquettes; D) Emission of white smoke during boiling; E) Adherence of brownish oil in the pan; F) Formation of ash around the briquettes.

The results suggest that carbonization significantly contributed to generating high temperatures and reducing mass consumption, likely due to the high fixed carbon content, which is the primary source of heat.

For the boiling test, the briquettes were placed in the combustor along with paraffin (Figures 10 - A and B) and a small amount of pine chips to accelerate ignition. The highly flammable paraffin produced an immediate flame upon ignition (Figure 10 - C). Ignition times for the briquettes ranged from 5 to 10 minutes, with intense white smoke emitted during and after ignition, which is expected due to their high volatile content. A strong orange flame was also observed (Figure 10 - D), along with dark brown oil around the pan, likely cashew nut shell liquid (CNSL) from the cashew nut skin (Figure 10 - E). During the hot start and boiling phases, a layer of ash formed around the briquettes, providing insulation and reducing the burning rate (Figure 10 - F). It was also noted that while the briquettes remained stable during the test, they fragmented as they burned (Figure 10 - F).

Water Boiling Test (WBT)

The water boiling time (WBT) test was conducted simultaneously with the Combustion Index (CI) test due to a limited supply of briquettes. The results, including boiling point, burning rate, specific briquette consumption, and thermal efficiency, are illustrated in Figure 11.



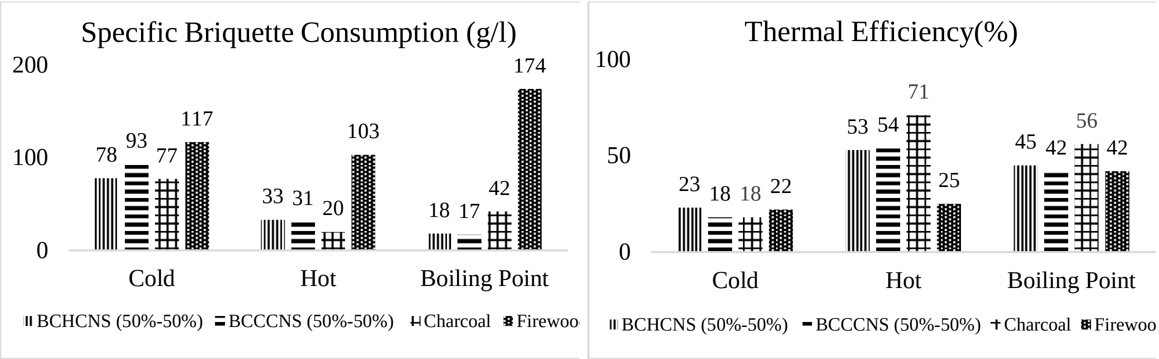


Figure 11: Results of boiling point teste, burning rate, specific consumption briquettes and thermal efficiency

The BCHCNS (50%-50%) briquette took longer to boil water, requiring 29 minutes compared to 17 minutes for the BCCCNS (50%-50%) during the cold start process. In the hot start, the BCHCNS (50%-50%) also lagged, taking 15 minutes, while the BCCCNS (50%-50%) only took 9 minutes to boil 2.5 litres of water. Although both briquettes showed performance close to that of coal and firewood, firewood was the fastest in the cold start process. Hassan *et al*. (2018) reported a water boiling time of 15.30 minutes for charcoal powder mixed with starch as a binder at a ratio of 85:15, while a mixture of charcoal powder and fermented waste paper at 80:20 had a boiling time of 12.41 minutes. In a study by Ikelle and Ivoms, (2014), water boiling times for coal dust briquettes, mixtures of coal dust and corn cob briquettes ranged from 1.63 to 4.57 minutes.

The burning rate of the energy sources ranged from 1 g/min to 27 g/min, as shown in Figure 11. The briquettes outperformed firewood, which recorded burning rates of 23 g/min during the cold start, 27 g/min during the hot start, and 6 g/min at boiling. However, charcoal still exhibited the best performance in both the cold start (8 g/min) and hot start (5 g/min) phases. The BCCCNS (50%-50%) achieved higher burn rates during the cold start and hot start, with values of 15 g/min and 8 g/min, respectively, compared to the BCHCNS (50%-50%), which recorded 10 g/min and 6 g/min. Both types of briquettes had the same burn rate of 1 g/min during the boiling phase. The BCCCNS (50%-50%) showed the lowest burn rate during the boiling process, while charcoal had the highest burn rate during the hot start. Nurba *et al.*, (2019) found a burning rate of 9.8 g/min for wood charcoal briquettes and 9.7 g/min for corn cob briquettes, values comparable to those recorded in this study for carbonized corn cob briquettes. The combustion rate is influenced by the reaction rate between carbon and oxygen on the briquette surface, as well as the diffusion rate of oxygen within the briquettes.

Abdulkareem *et al*. (2018) observed burning rates between 0.4386 g/min and 0.5173 g/min for various mixtures of charcoal, sawdust, and sugarcane bagasse in proportions of 20:20:60, 20:30:50, 20:40:40, 20:50:30, and 20:60:20. Hassan *et al*. (2018) recorded rates of 3.53 g/min to 4.76 g/min for charcoal powder mixed with starch as a binder at a ratio of 85:15, along with other mixtures. The briquettes did not burn out quickly, allowing them to generate useful energy for an extended period (Abdulkareem *et al.*, 2018). Additionally, airflow grooves in the stove and the size of the briquettes affect drying time, burning rate, and how frequently the user needs to refuel the stove while cooking (Hassan *et al.*, 2018).

In terms of specific briquette consumption, the BCCCNS (50%-50%) required a greater amount (93 g/L) to boil 1 litre of water during the cold start compared to the BCHCNS in 50%-50% (78 g/L). This trend continued in subsequent phases, where both briquettes exhibited similar consumption levels. When compared to charcoal and firewood, the BCHCNS(50%-50%) showed similar specific consumption to charcoal during the cold start, while charcoal had the best value (20 g/L) during the hot start. In contrast, firewood had a significantly higher average value of 110 g/L during these stages. During the boiling phase, the briquettes demonstrated a much lower specific consumption of 18 g/L compared to firewood at 174 g/L, and coal, which had a specific consumption just over double that of the briquettes at 42 g/L.

The combustor achieved slightly better thermal efficiency with the BCHCNS (50%-50%) compared to the BCCCNS (50%-50%), attributed to its favourable specific consumption results. Coal exhibited the highest thermal efficiency values (18-71%), while the briquettes ranged from 18% to 54%. In comparison, firewood's thermal efficiency values were lower, ranging from 22% to 42%. Tuates *et al*. (2016) reported thermal efficiency values for briquettes made from carbonized corn cobs at 19.02%, and mixtures such as CRH + Rice Hull (25%), CRH + Coconut Shell (22%), and CRH + Sawdust (15%).

Table 8 presents the average thermal efficiency values during the hot start and cold start phases, following the metrics established by the International Water Association (IWA).

Table 8: Thermal efficiency values during the hot start and cold start phases, according to the IWA

Average high-power thermal efficiency (hot and cold start) according to IWA performance metrics			
BCHCNS (50%-50%)	BCCCNS (50%-50%)	Charcoal	Firewood
37.7%	35.9%	44.7%	23.5%

Table 8 demonstrates that the briquettes achieved high yields ranging from 35.9% to 37.7%, significantly higher than firewood, which had a yield of 23.5%, but slightly lower than charcoal's yield of 44.7%. While charcoal outperformed the briquettes in the boiling test, the briquettes still showed promising results, effectively meeting energy demands comparable to firewood and helping to reduce reliance on charcoal.

Emission Test

Table 9 presents the total emissions from the boiling test in grams, allowing for analysis across the three phases: cold start, hot start, and boiling. The data includes emissions for both the produced briquettes and for charcoal and firewood.

Table 9: Total emissions of CO, CO_2 and PM2.5 gases during the boiling test

Phases	**BCHCNS (50%-50%)**			**BCCCNS (50%-50%)**			**Charcoal**			**Firewood**		
	CO (g)	**CO_2 (g)**	**$PM_{2.5}$ (mg)**	**CO (g)**	**CO_2 (g)**	**$PM_{2.5}$ (mg)**	**CO (g)**	**CO_2 (g)**	**$PM_{2.5}$ (mg)**	**CO (g)**	**CO_2 (g)**	**$PM_{2.5}$ (mg)**
Cold	11.09	25	7530	11.46	40	9152	16.49	1234	2	0.61	990	2
Hot	4.50	21	80	4.72	25	198	4.22	742	0	0.47	822	43
Boiling point	2.45	4	2	4.56	26	18	14.47	1579	1	1.46	1680	5

In the cold phase, CO emissions were more pronounced for charcoal compared to the BCHCNS (50%-50%) and BCCCNS (50%-50%) briquettes. During the hot phase, CO emissions were similar for tested briquettes and charcoal, all of which were higher than those for firewood. In the boiling phase, CO emissions were greater for BCCCNS (50%-50%) than for charcoal, BCHCNS (50%-50%), and firewood.

Although coal has lower volatile content than briquettes, CO emissions during combustion are influenced by various factors, including combustion efficiency and burning conditions. If the fuel is not burned efficiently, some carbon may convert to CO instead of CO_2. Generally, higher CO emissions are observed during the high-power phase both cold and hot during the water boiling test. This phase involves heating the fuel and combustion system, which can lead to less efficient initial combustion and increased CO release. Incomplete combustion may occur in the early stages, resulting in higher CO formation instead of CO_2. Additionally, inadequate mixing of air and fuel during these initial combustion phases can further contribute to inefficient combustion and elevated CO emissions.

In the cold phase, CO_2 emissions were most pronounced for charcoal, followed by firewood, and tested briquettes. In the hot and boiling phases, firewood exhibited the highest CO2 emissions, followed by charcoal, BCCCNS (50%-50%), and BCHCNS (50%-50%).

The cold start phase emitted higher quantities of gases compared to the other phases, with PM2.5 being the most significant emission, reaching levels of 7530 mg for BCHCNS (50%-50%) and 9152 mg for BCCCNS (50%-50%). This may have been influenced by the release of a brownish oil (possibly CNSL) observed around the pan (Figure 10 - E). During the hot start, these values dropped dramatically to 80 mg for BCHCNS (50%-50%) and 198 mg for BCCCNS (50%-50%), and further decreased to 2 mg and 18 mg, respectively, in the boiling phase.

CONCLUSIONS

The study concluded the following key points:

Carbonization of the biomass samples was performed in a muffle furnace at 400°C for 2 hours, resulting in the elimination of approximately 60% of the volatile content. This process enriched the biomass with fixed carbon, which is crucial for generating heat.

The study assessed various properties of briquettes made from biomass materials, finding that a 50:50 mixture of carbonized corn cob and cashew nut skin, as well as carbonized corn husk with the same binder, showed optimal performance. These briquettes exhibited excellent mechanical strength and energy density, qualifying them for energy applications.

The study evaluated the friability, dimensional stability, energy density, combustion characteristics, water boiling efficiency, and emissions of briquettes produced from various biomass materials. The results indicated that the briquettes were non-friable, enhancing their handling and transportation. The BCHCNS (50%-50%) exhibited slight expansion, while the BCCCNS (50%-50%) briquettes showed compression, both achieving good dimensional stability within 72 hours. Energy density values revealed that briquettes made from carbonized corn cob and cashew nut skin had superior bulk and energy densities compared to those made from carbonized corn husk, aligning with earlier research on the benefits of high lignin content.

Combustion tests demonstrated that both types of briquettes reached high temperatures, with BCCCNS (50%-50%) showing a higher combustion index, suggesting their potential to replace charcoal in heating applications. The water boiling test indicated that BCCCNS (50%-50%) briquettes were more efficient than

BCHCNS (50%-50%), outperforming firewood in terms of boiling time and specific consumption.

For both briquettes, CO emissions ranged from 2.45 g to 11.46 g, while CO_2 emissions ranged from 4 g to 40 g, significantly lower than those from charcoal. When comparing PM2.5 emissions between the two types of briquettes, BCCCNS (50%-50%) showed a greater release of suspended particles with a diameter of 2.5 µm or less.

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