KAMPALA INTERNATIONAL UNIVERSITY
KIU
Journal of Science, Engineering and Technology

KJSET Research Article

Effectiveness and sustainability of millet husk briquette as an alternative source of thermal energy

Madaki Ismail Abdullahi, Adamu Yusuf, and Malik Onozare Hafsat

Chemical Engineering Department, Ahmadu Bello University, Sokoto Road, Zaria, Kaduna State, Nigeria
Ismailmadaki777@gmail.com, yusufbinadam@yahoo.com, hafmalik22@gmail.com

Corresponding Author: yusufbinadam@yahoo.com

Paper history:
Received 08 November 2025
Accepted in revised form 30 December 2025

Keywords
Millet husk, Carbonization, Briquettes, Starch, Binders, Thermal properties.

Abstract

The study aimed to investigate the effects of varying starch binder concentrations on the physical and thermal characteristics of carbonized and uncarbonized millet husk briquettes, and to compare their properties. This was achieved using a universal material testing machine to produce briquettes by varying the binder concentration to 25 – 40 % for both carbonized and uncarbonized samples. A proximate analysis results show an increase in moisture content (8.27 – 10.53 %), ash content (10.32 – 22.54 %), and volatile matter (40.03 – 54.03 %), but with a decrease in fixed carbon (41.35 and 12.98 %) for the uncarbonized and carbonized millet husk briquette. The physical properties show a range of compressed density (647.91 – 488.9 kg/m^3), relaxed density of (666.67 – 548.5kg/m^3), relaxation ratio (0.9719 – 0.9), and compaction ratio (2.91 – 2.76) for the carbonized and uncarbonized millet husk briquette. At the same time, the thermal properties show that the ignition time ranges from 3.6 to 14 seconds, with calorific values of (14.12 to 11.56 MJ/Kg) for the carbonized and uncarbonized millet husk briquette. However, based on the findings, carbonized briquettes have better characteristics and desired properties than uncarbonized briquettes for both domestic and industrial uses, based on the analyses. The findings also show that it is better to produce carbonized and uncarbonized briquettes at a binder concentration of 25 % considering the properties analyzed, where carbonized briquettes had better properties.

1.0 Introduction

Energy is essential to human livelihood and makes significant contributions to economic, social, and environmental features of human development. The ever-increasing price of fossil fuels in Nigeria and the global market appears to be hurting economies. Fuel wood, which is also used as an alternative fuel, has its disadvantages hardship on women and children, emission of toxic atmospheric pollutants, which are responsible for many health issues, like global warming and air pollution (Aondoyila, Achirgbenda, & Humphrey, 2021). Moreover, energy demand is constantly increasing with the increasing population of the world, and fossil fuels are getting depleted day by day. It is high time to convert biomass wastes such as millet husk, sawdust, rice husk, etc., into useful biomass briquettes, which will be a substitute for some of the fossil fuels. This calls for sustainable energy production and supply, such as renewable energy technologies (Yomesh *et al,* 2019).

Agriculture produces significant quantities of residues, which could contribute to energy production and reduce the use of fuel wood and fossil fuels for heating and domestic cooking in Nigeria (Elum *et al*., 2017; Japhet *et al*., 2020). Agricultural residues are usually bulky materials and have low densities, which makes their transportation an uneconomical process, and their usage is limited hence One option of improving the density of such materials is the use of the briquetting process, which may be defined as the process of compaction of residues into a product of higher density than the original raw material (Ahmed, 2015).

In recent years, the use of biomass as a source of energy has become of great interest worldwide because of its environmental advantages. Biomass, a domestic energy source, is naturally abundant and presents a promising renewable energy opportunity that could provide an alternative to the use of fossil resources. Biomass is the third largest primary energy source in the world, after coal, and it still meets a major fraction of the energy demand in rural areas of most countries. In all its forms, biomass currently provides about 1250 million tonnes of oil equivalent (mtoe) of primary energy, which is about 14% of the world's annual energy. The use of biomass feedstock(s) as a substitute for fossil fuel(s) has an additional importance from climate change consideration since biomass has the potential to be CO_2 neutral. Many countries, including Nigeria, produce huge quantities of agro residues, but they are used inefficiently, causing extensive pollution to the environment. Apart from the problems of transportation, storage, and handling, the direct burning of loose biomass in conventional grates is associated with very low thermal efficiency and widespread air pollution (Adejumo & Adebiyi, 2021; Oyegoke *et al*., 2023). As a result, the briquetting of the husk could mitigate these pollution problems while at the same time making use of this important industrial/domestic energy resource. Utilization of agricultural residues is often difficult due to their uneven and troublesome characteristics. The process of compaction of these residues into a product of higher density than the original raw material is known as densification. Densification has aroused a great deal of interest in developing countries all over the world lately as a technique for upgrading residues as an energy source (Mathias, 2005).

Densification of biomass is obtained by applying mechanical force onto the particulates to create inter-particle bonding, which makes well-defined shapes and sizes such as briquettes, pellets, and fuel logs. Densification of biomass is the main purpose of briquette making, since it leads to a reduction in the transportation cost, increased calorific value per unit volume, and produces a uniform, eco-friendly, and stable fuel for large-scale heat and power plant requirements (Kayasth *et al*., 2024). Briquetting technology is one of the densification processes. Biomass densification, which is also known as briquetting of sawdust and other agro residues, has been practiced for many years in several countries (Kpalo *et al*., 2020; Yunusa *et al*., 2020). Historically, biomass briquetting technology has been developed in two distinct directions. Europe and the United States have pursued and perfected the reciprocating ram/piston press, while Japan has independently invented and developed the screw press technology (Grover & Mishra, 1996). The by-products and wastes of agriculture and wood industries are a major source of biomass used in the production of biofuels. Densification of waste to form a densified, homogeneous, and durable product is of great importance because uniformly shaped and sized products can be easily handled using standard handling and storage equipment (Jing, Decong, & Kai Wu, 2019).

In the present time, the increasing energy needs of the world and the continually growing population tend to result in a lot of waste and higher energy demands. The consumption of several agricultural products has regularly left the stems, leaves, and peels from the tree, either wasted or thrown away. Producing bio-briquettes can also help to address the increasing energy demand. There is numerous research carried out in sourcing solutions to reutilize these organic wastes by turning them into something beneficial to mankind. Large quantities of vegetable and fruit waste are left unused or allowed to decompose, creating serious environmental problems. Nonetheless, these problems can be overcome by generating bio-briquettes that are affordable, renewable, and sustainable (Philip, Mia, & Sindol., 2022).

Briquettes, to a large extent, are worth venturing into the future since fuel prices are rising. Secondly, as the effects of deforestation are expected to cause a rise in prices of wood fuel and charcoal, hence briquetting of biomass can have a legitimate economic role to play without any need for subsidy. Briquettes have a gross calorific value of up to 4,200 kcal/kg, and approximately 2.2kg of briquettes are equivalent to 1 liter of furnace fuel. According to the Food and Agriculture Organization of the United Nations (FAO), briquettes are a good substitute for wood because of their consistent quality, which can enable a price premium to be obtained over wood (Mike, 2019).

While numerous studies have assessed agricultural residues (such as coconut shell, rice husk, banana peel, and corn straw) as briquette feedstocks, they typically use conventional binders like corn, cassava, or potato starch (Gupta *et al*., 2022; Solórzano *et al*., 2025). In contrast, millet husk has only been examined in a few preliminary studies; for example, Kuhe *et al*. (2021) used gum Arabic as a binder in millet husk briquettes. Importantly, starch from sweet potato peels has not been employed in these prior briquetting studies for raw and carbonized millet husk. Recent reviews explicitly note that the effects of binders in carbonized (biochar) briquettes are currently scarce in the literature (Obi *et al*., 2023). By introducing sweet-potato-peel starch and systematically comparing carbonized and uncarbonized millet husk, the present work fills these gaps and expands the toolkit of sustainable solid fuels.

2.0 Materials and Methods

2.1. Materials

Millet husk (MH) was collected from a nearby farm in Tutu Wada, Zaria Local Government, Kaduna State, Nigeria. The sweet potato peels (SPP) were collected from food vendors around Ahmadu Bello University, Zaria.

2.2 Starch extraction process

The potato peels (PP) were collected and washed thoroughly to remove sand and other impurities. The PP was then transferred to an electric blender, and water was added, which served as a grinding aid. The mixture was sieved and filtered, and the filtrate was allowed to settle for 5 hours, after which the brownish water was then decanted gently while the starch was well settled at the bottom of the container. The resulting starch was mixed with water again and allowed to settle for 3 hours, which is known as starch washing. The water was also decanted, and the wet starch was then dried at room temperature for 5 hours. And finally, the dried and powdered starch was obtained.

2.3 Millet husk briquette production procedure

The production of carbonized and uncarbonized millet husk briquettes using starch produced from sweet potato peels as a binder was carried out, where both samples of millet husk (MH) underwent pretreatment to remove the adhering soil, dirt, and other associated contaminants. The sample was divided into two to produce the carbonized millet husk (CMH) and the uncarbonized millet husk (UCMH).

Carbonization was carried out in a muffle furnace at a temperature of 300 ^{o}C for 45 minutes, while the uncarbonized sample underwent a size reduction process using a pestle and mortar. The starch powders were added to 45ml of distilled water, ensuring that the samples were formed without any lumps or clogs. Later, 135 ml of hot water was added to the binder solution in order to form a gelatinized starch solution (Binder). Each 10g of the carbonized and uncarbonized millet husk samples was respectively mixed at binder concentrations of 25%, 30%, 35%, and 40% as in the work of Aondoyi & Iortyer (2021). In this work, briquettes were produced by utilizing the universal material testing machine (SM1000) with the highest limit of 1000kN, as (TUF-C-1000 SERVO) used by Velusamy *et al.* (2021). The samples were introduced into the cylindrical briquetting mould by hand, with an internal diameter of 25 mm and a height of 80 mm, and the hydraulic press was used to obtain the desired size. A constant force of 20 KN was used for each briquette produced. After the successive process, shaped briquettes were obtained. The briquettes were produced in triplicate, sun-dried in an open space to remove the inherent moisture content to a tolerable level. Measurements were taken, which were used to conduct analyses and to determine the average values (Arzika, *et al*., 2022).

3.0 Results and Discussions

3.1 Starch Analysis (Amylose and Amylopectin)

The starch from SPP was extracted and characterized before use, and the result is presented in Table 1.

Table 1: The amount of amylose and amylopectin present in the starch

Sample ID	Amylose (%)	Amylopectin (%)
First run	35.65	64.35
Second run	40.13	59.87
Average	37.89	62.11

The literature for amylose and amylopectin of sweet potato ranges from 20 – 30% and 70 – 80% respectively, hence from the result obtained, the average value for the amylose content of the sweet potato peels was obtained to be 37.89, which means it provides good binding properties due to it is ability to form a strong film. This helps to improve the mechanical properties of the briquette. For amylopectin, the average value of 62.11% makes the starch more adhesive and flexible, which enhances the ability to bind the materials effectively without being too rigid.

Proximate Analysis for the Millet Husk

Table 2 gives the details of the proximate analysis of the raw material (Millet husk).

Table 2: Summary of the proximate analysis for millet husk

Parameter	Value
Moisture content (%)	9.02
Ash content (%)	5.64
Volatile matter (%)	55.975
Fixed carbon (%)	29.41
Calorific value (MJ/kg)	17.9

Table 2 shows that the moisture content of 9.02 represents the amount of water present in the millet husk, and the value obtained agrees with the findings of Ayub *et al*. (2015). An ideal moisture content for biomass materials should be below 10%, and this makes millet husk suitable for use as biofuel. Ash content of 5.64% and the moderate value obtained suggest relatively less residue after combustion, which is beneficial for its utilization as fuel, unlike high ash content, which causes operational issues. For the volatile matter, 55.975% obtained suggests that it is suitable for direct combustion, as it makes the material easier to ignite. A fixed carbon content of 29.41 shows potential for prolonged heat production, which is valuable in thermal applications. The calorific value of the millet husk obtained is within the range of 15-20 MJ/kg for biomass, showing that millet husk falls within an acceptable range for bioenergy applications.

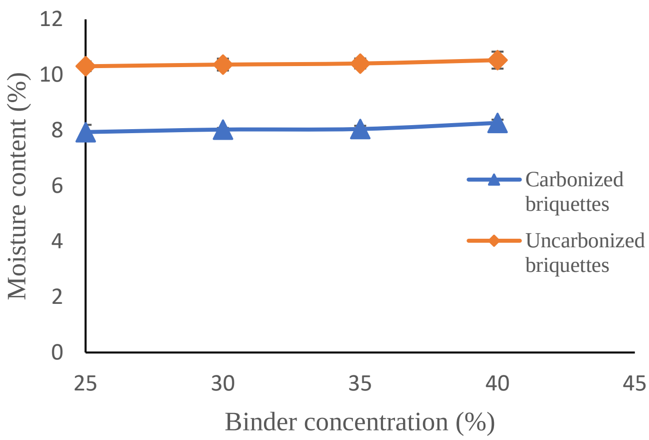

Figure 1: Graph of moisture content of carbonized and uncarbonized briquettes against binder concentration

From Figure 1, it is observed that the moisture content for both carbonized and uncarbonized briquettes produced increases as the binder concentration increases. This is expected simply because the gelatinized starch typically enhances the moisture content of the briquette. From the values obtained for both carbonized and uncarbonized briquettes, the moisture content is within the range of 8-12% for agricultural waste, as reported by Kuhe & Iortyer (2021), and above the range of 5 and 10% for successful densification reported by Arzika *et al*. (2022). As illustrated in Figure 1, there is a slight increase in the moisture content of the carbonized briquettes as the binder concentrations increase from 25% to 40%. This shows that the binder slightly affects the moisture retention in carbonized briquettes. Similarly, the uncarbonized briquettes follow the same trend and depict a similar effect of binder concentration. However, uncarbonized briquettes have higher moisture content than the carbonized ones for all binder concentrations. This is simply due to carbonization activity carried out for the carbonized briquettes, which removes more moisture and consequently increases the burning efficiency and, of course, enhances their suitability for domestic fuel, whereas uncarbonized briquettes with high moisture content reduce the burning efficiency, which results in more smoke production while burning.

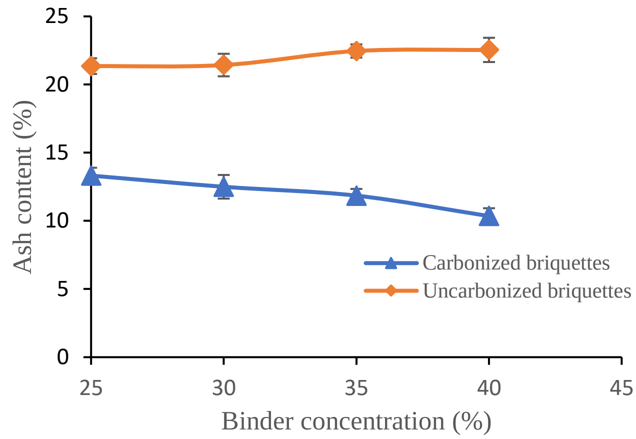

Figure 2: Graph of ash content of carbonized and uncarbonized millet husk against binder concentration

As illustrated in Figure 2, the percentage ash content of carbonized briquettes decreases as the binder concentration increases, while the reverse is the case for uncarbonized briquettes. The increase in ash content was, however, very small over a wide range of binder concentrations. However, from the results obtained, the uncarbonized sample showed ash content above the general value range of 5-20% as stated in the work of Arzika *et al*. (2022). This could be due to the organic nature of the binder, and possibly due to the presence of alkali-earth metals in the feedstock used (Njue, 2019). For the carbonized briquettes it was observed that as the binder concentration increased from 25 to 40 %, the ash content tends to decrease, and this shows that the more the binder the dense the carbonized briquette will be, and the lower the ash content to be produced because the binder helps in forming a denser and more cohesive briquette structure, reducing the amount of ash left after burning. As in the case of uncarbonized briquettes, a direct relationship was observed between the ash content and the binder concentration, and the increase in the ash content is possibly due to the presence of more non-combustible components in the binder itself, which contributes to the overall ash content. Comparatively, carbonized briquettes are more efficient to be used as a fuel source due to their lower ash content, and this outlined the importance of carbonization as it helps in removing non -non-combustible residues. On the other hand, the increased ash content of uncarbonized briquettes is due to a high quantity of non-combustible residues, and this makes it inefficient and of lower quality.

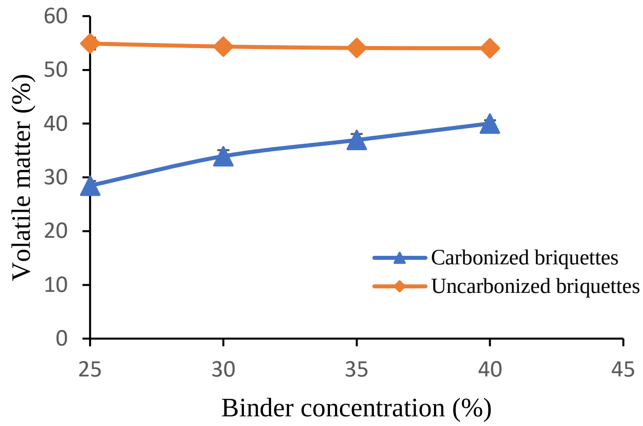

Figure 3: Graph of volatile matter of carbonized and uncarbonized briquettes against binder concentration

It is realized that the percentage of volatile matter for carbonized briquettes (Figure 3) ranges from 28.47 to 40.03 at a binder range of 25 to 40% showing that the volatile matter increases as the binder increases, and this agrees with the work of Arzika *et al.* (2022). But the value is low compared to the findings of Kuhe & Iortyer (2021) for millet husk briquette made using gum Arabic as a binder. However, the low volatile matter obtained is crucial, which shows that there is minimal emission of gases, which is a primary concern to the users, as stated in the findings of (Njue, 2019). For the uncarbonized briquettes, the volatile matter ranges from 54.89 to 54.03% at a binder range of 25 to 40%. This range shows that the binder concentration has a minimal effect on volatile matter content, and the results agree with those of Kuhe & Iortyer (2021). The results show that volatile matter decreases as binder concentration increases. Comparing the two briquettes produced, it was observed that the volatile matter content is significantly higher in uncarbonized briquettes. This is expected because the carbonization process typically drives off volatile components, resulting in a more stable and less reactive briquette. Moreover, for carbonized briquettes, the lower the binder concentration, the lower the volatile matter and the better the combustion efficiency of the briquette, whereas for uncarbonized briquettes, the lower the binder concentration, the more the volatile matter and the lower the combustion efficiency of the briquettes. This is because the binder helps in reducing the volatility of the volatile components in the uncarbonized briquette.

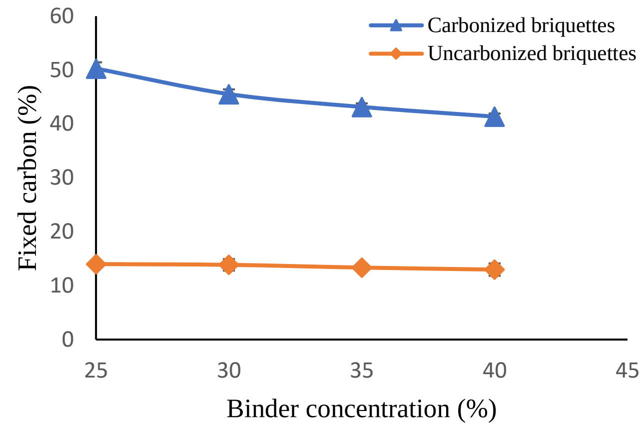

Figure 4: Graph of fixed carbonized and uncarbonized briquettes against binder concentration

As illustrated in Figure 4, fixed carbon content for both carbonized and uncarbonized briquettes decreases as the binder concentration increases, and this agrees with the findings of Arzika *et al.* (2022). For the carbonized briquettes, the fixed carbon content ranges from 50.27 to 41.35% at a binder concentration of 25 to 40%, indicating that a high fixed carbon content is achieved at lower binder concentrations. This high fixed carbon content implies high calorific value. Similarly, the fixed carbon content of uncarbonized briquettes was observed to decrease as the binder concentrations increased. The decrease for the carbonized sample, however, was more rapid. but the fixed carbon content decreases slightly with increasing binder concentration, indicating that binder concentration has less effect on fixed carbon content in uncarbonized briquettes. In both cases, high fixed carbon content was observed at a lower binder concentration of 25% and High carbon content of the briquettes indicates that the briquettes have a high burning capability, as stated by (Njue, 2019).

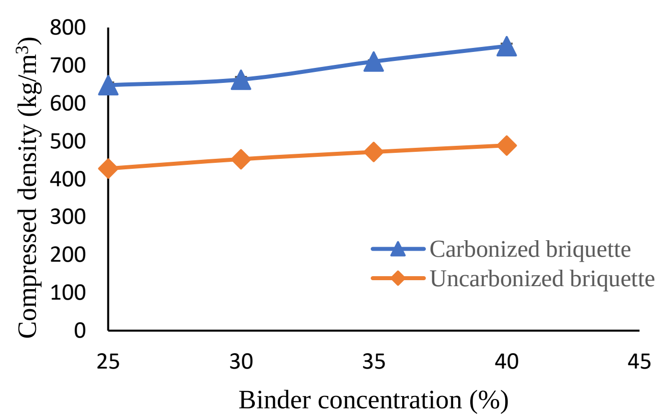

Figure 5: Graph of compressed density for carbonized and uncarbonized briquettes against binder concentration

The compressed density of the briquette is the density after compression. From Figure 5, it is seen that the compressed densities of both carbonized and uncarbonized briquettes produced increase as the binder concentration increases, and this agrees with the findings of Arzika *et al*. (2022) for a briquette made from millet husk using gum Arabic and molasses as binders. For the carbonized briquette, the increase in compressed density with an increase in binder concentration shows that the binder concentration improves the cohesion and compactness of the briquette, and this compaction is better at a higher binder concentration of 40%. The uncarbonized briquette also follows the same trend as the carbonized briquette. Comparatively, both the carbonized and uncarbonized briquettes attained a high value of compressed density, but the carbonized briquettes have higher densities compared to uncarbonized briquettes at all the binder concentrations, and this is simply due to the carbonization being carried out, which reduces the volatile compounds, increasing the density of the briquette and offering better structural integrity of the briquettes. However, the increase in binder concentrations for both carbonized and uncarbonized briquettes improves the density, which is a desirable parameter for fuel briquettes.

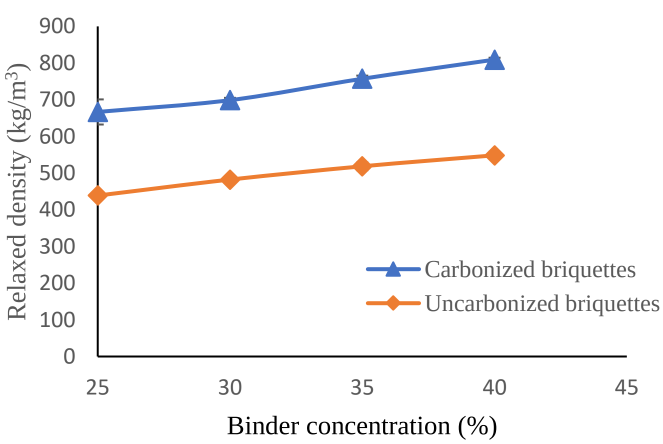

Figure 6: Graph of Relaxed density for carbonized and uncarbonized briquettes against binder concentration

Relaxed density gives the relative stability of the briquette after compression. Figure 6 shows that the relaxed density increases as the binder concentration increases, and this agrees with the findings of Kuhe & Iortyer (2021), a preliminary study on millet husk using gum Arabic as a binder. The relaxed densities of the carbonized briquette ranged from 666.67 kg/m³ at a binder concentration of 25% to 787.01 kg/m³ at a binder concentration of 40% indicating that at higher binder concentrations, the briquette attained more structural stability. On the other hand, the relaxed density of the uncarbonized briquette is relatively low compared to the carbonized briquette. The relaxed densities range from 438.8 kg/m³ at 25% binder to 525.3 kg/m³ at 40% binder. Comparing the two results, it is observed that carbonized briquettes have higher relaxed densities compared to uncarbonized briquettes at all binder concentrations. This is expected because carbonization increases material density by removing moisture and volatile substances, resulting in a more compact carbon structure. Hence, for both carbonized and uncarbonized briquettes produced, it is observed that the more the binder concentration, the higher the relaxed density and the better the dimensional stability of the briquettes.

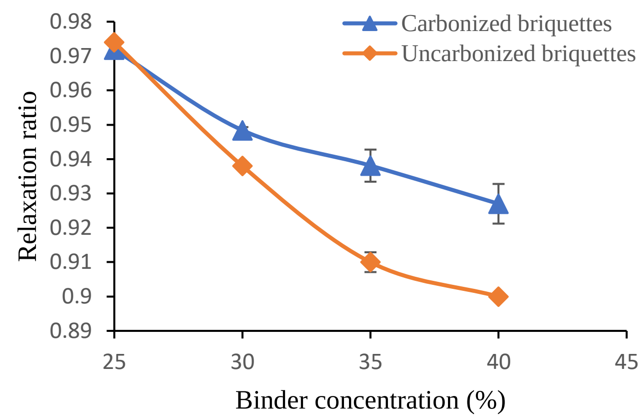

Figure 7: Graph of Relaxation ratio for carbonized and uncarbonized briquettes against binder concentration

The relaxation ratio in briquettes indicates how well the briquettes retain their shape and density after being compressed. From Figure 7, it was observed that the relation ratio decreases as the binder concentration increases. The relation ratio in both cases decreases with an increase in binder ratio. For carbonized briquettes, the relaxation ratio decreases from 0.9719 at a binder concentration of 25% to 0.927 at a binder concentration of 40% whereas for the uncarbonized briquette, the relaxation ratio reduces from 0.974 to 0.9 at a binder concentration of 25% and 40% respectively. The decrease in relaxation ratio as the binder concentration increases shows that higher concentrations of the binder result in more compactness of the briquette. However, the decrease in the trend of the relaxation ratio of the briquette produced is more in uncarbonized briquettes. This shows that uncarbonized briquettes attained better stability as the binder concentration increased. Comparatively, both carbonized and uncarbonized briquettes produce, the more the binder, the lower the relaxation ratio, and the better the ability of the briquette to retain its shape after compression.

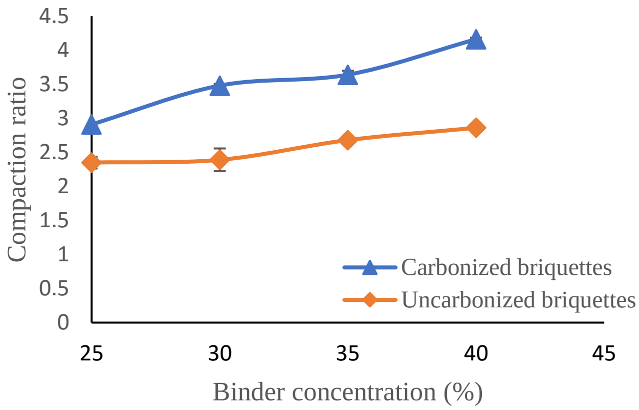

Figure 8: Graph of compaction pressure for carbonized and uncarbonized briquettes against binder concentration

The compaction ratios (Figure 8) for carbonized and uncarbonized millet husk briquettes were observed to be increasing as the binder increased, and this deviates from the findings of Arzika *et al*. (2022). Their work showed that the compaction ratio decreases as the binder increases. However, this deviation could be due to the organic nature of the binder used, which enhances the compaction of the briquettes produced. The increased compaction ratio in carbonized briquettes was observed to be increasing progressively from 2.91 at 25 % to 4.16 at 40 % showing that higher binder concentrations effectively fill the void spaces, which leads to better compaction of the briquettes whereas uncarbonized briquettes, the compaction ratio also increases as the binder concentration increases but the increase in compaction ratio is not as high as carbonized briquettes. Comparing the results of both carbonized and uncarbonized briquettes shows that Carbonized briquettes consistently show higher compaction ratios than uncarbonized briquettes at all binder concentrations, highlighting the beneficial effects of carbonization on the compactness of the briquettes.

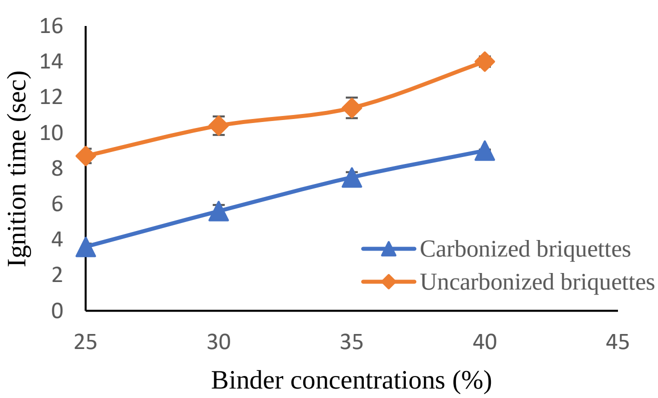

Figure 9: Graph of ignition time for carbonized and uncarbonized briquettes against binder concentration

As illustrated in Figure 9, the ignition time of the briquettes was observed to be increasing as the binder concentrations increased in both carbonized and uncarbonized briquettes produced, for the carbonized briquettes the ignition time ranges from 3.6 sec to 9.0 sec at a binder concentration of 25 to 40 % which shows that the more the binder concentration, the longer it takes for the briquettes to catch fire. Similarly, the uncarbonized briquettes had an ignition time of 8.7 sec to 14 sec. In both cases, the results indicate that the low ignition time could be attributed to the high porosity exhibited between inter- and intra–particles of the briquettes, which enables easy percolation of oxygen and outflow of combustion briquettes as stated by Arzika *et al*. (2022). It can also be observed that carbonized briquettes have less ignition time compared to uncarbonized briquettes. This further supports the idea that increased binder concentration adds moisture content or alters the material structure, making ignition more challenging and longer in uncarbonized briquettes and, of course, quicker and easier to ignite for the carbonized briquettes simply due to the carbonization being carried out, which reduces the moisture content and increases the heating value of the briquettes.

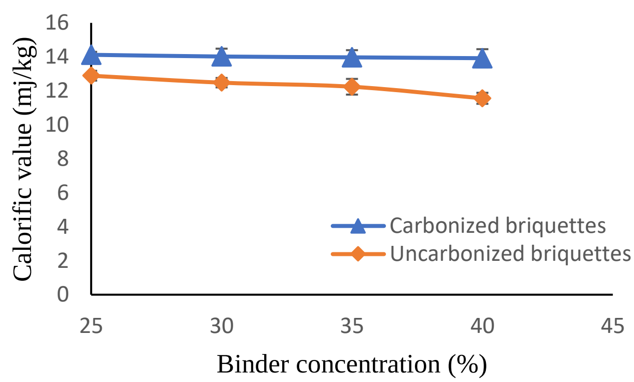

Figure 10: Graph of calorific value for carbonized and uncarbonized briquettes against binder concentration

Figure 10 shows the relationship between calorific value and binder concentrations of carbonized and uncarbonized millet husk briquettes. The results show that the calorific value in both cases decreases as the binder concentration increases, which deviates from the findings of Arzika *et al*. (2022), who reported that the calorific value increases with increasing binder concentration. These abnormalities could be due to the organic nature of the binder, which signifies that the binder dilutes the energy content per unit mass of the briquettes; hence, in both cases, it is imperative to produce the briquettes at a lower binder concentration. In comparison to carbonized and uncarbonized briquettes, it shows that high calorific value is achieved in carbonized briquettes due to carbonization having been carried out on the feedstock, which reduces the volatile matter and moisture, whereas the uncarbonized briquettes contain more moisture, which reduces their heating values.

Summary of findings for properties of carbonized and uncarbonized millet husk briquettes

The evaluation of millet husk briquettes through proximate analysis, physical property assessment, and fuel property characterization (Table 3) provides insight into their suitability as alternative solid fuels. Proximate analysis showed that carbonized briquettes exhibited significantly lower moisture content and volatile matter, alongside higher fixed carbon, compared to the uncarbonized samples. This indicates enhanced combustion stability and improved energy concentration. Conversely, uncarbonized briquettes recorded higher volatile matter and ash content, reflecting their raw lignocellulosic nature and potentially higher emissions during combustion.

Physical property evaluation revealed that carbonized briquettes possessed greater density, better mechanical durability, and improved structural integrity due to the carbonization process, which promotes stronger bonding and reduces internal moisture. Uncarbonized briquettes, while still compact, generally displayed lower compressive strength and higher susceptibility to breakage during handling and transportation.

Fuel property analysis further demonstrated that carbonized millet husk briquettes have superior heating value because carbonization increases the proportion of fixed carbon and reduces non-combustible components. Their reduced moisture and volatile matter also facilitate cleaner and more efficient burning. In contrast, the lower calorific value and higher smoke output of uncarbonized briquettes make them less efficient for high-temperature applications, although they remain viable for domestic heating and cooking.

Finally, carbonized millet husk briquettes show improved fuel quality and combustion performance, making them more suitable for efficient and cleaner energy production, while uncarbonized briquettes offer a simpler, lower-cost alternative for basic household use.

Table 3: Summarizes the proximate analysis, physical properties, and fuel properties results of the carbonized and uncarbonized millet husk briquettes

Binder concentration (%)	***Moisture content (%)***		***Ash content (%)***		***Volatile matter (%)***		***Fixed carbon (%)***		***Calorific value (mj/kg)***	
	A	***B***	***A***	***B***	***A***	***B***	***A***	***B***	***A***	***B***
25	*7.94*	*10.31*	*13.32*	*21.35*	*28.47*	*54.89*	*50.27*	*14*	*14.12*	*12.89*
30	*8.03*	*10.37*	*12.5*	*21.43*	*33.94*	*54.34*	*45.53*	*13.86*	*14.02*	*12.48*
35	*8.05*	*10.41*	*11.85*	*22.46*	*36.95*	*54.07*	*43.15*	*13.35*	*13.97*	*12.24*
40	*8.27*	*10.53*	*10.35*	*22.54*	*40.03*	*54.03*	*41.35*	*12.98*	*13.92*	*11.56*

	Compressed density (kg/m³)		***Relaxed density (kg/m³)***		***Relaxation ratio***		***Compaction ratio***	
	A	***B***	***A***	***B***	***A***	***B***	***A***	***B***
25	*647.91*	*427.8*	*666.67*	*438.8*	*0.972*	*0.974*	*2.91*	*2.35*
30	*662.73*	*452.65*	*698.85*	*482.3*	*0.948*	*0.938*	*3.48*	*2.39*
35	*710.32*	*471.7*	*757.15*	*518.5*	*0.938*	*0.91*	*3.64*	*2.68*
40	*751.03*	*488.9*	*809.3*	*548.5*	*0.927*	*0.9*	*4.16*	*2.76*

	Calorific value (MJ/kg)		***Ignition time (sec)***	
	A	***B***	***A***	***B***
25	*14.12*	*12.89*	*3.6*	*8.7*
30	*14.02*	*12.48*	*5.6*	*10.4*
35	*13.97*	*12.24*	*7.5*	*11.4*
40	*13.92*	*11.56*	*9.0*	*14*

Where: A = Carbonized millet husk briquette and B = Uncarbonized millet husk briquette

4.0 Conclusions

In this research, briquettes were successfully produced from carbonized and uncarbonized millet husk. They were produced using gelatinized starch as a binder extracted from sweet potato peels, and the effect of binder concentrations on the physical, thermal, and proximate properties was determined. The results were compared to the briquettes produced, and the following conclusions were made:

i. The starch extracted from the sweet potato peels is well-balanced for use as a briquette binder. It is adhesive enough to bind the particles efficiently. The results obtained for amylose and amylopectin are favorable for forming stable, cohesive briquettes with good combustibility and mechanical strength

ii. Varying the binder concentrations showed a significant impact on the physical and thermal properties, hence the result shows that higher binder concentrations generally improve briquettes stability the proximate analysis shows that carbonized briquettes attained desired and better results of the moisture content, volatile matter, and fixed carbon content at low binder concentrations of 25% than uncarbonized briquettes at the same binder concentration but for the ash content it was observed that at a binder concentration of 40%, the briquettes produced low ash content in both cases and the lower the ash content the better the fuel properties of the briquettes, moreover the carbonized briquettes has low ash content than uncarbonized briquettes in this regard.

iii. Comparison between carbonized and uncarbonized briquettes revealed that carbonization significantly improved the calorific value and combustion efficiency while reducing smoke emission. Moreover, in terms of their compressed densities, relaxed densities, relaxation ratio, and compaction ratio, and from the results obtained, it was also observed that at a high binder concentration of 40%, more compaction is attained, and hence denser the briquettes will be, a desirable parameter for fuel briquettes.

Recommendations and limitations

While the present lab-scale study (10 g samples, binder range 25–40% and a single carbonization regime of 300 °C for 45 min) demonstrates that carbonized millet-husk briquettes bound with sweet-potato-peel starch have improved heating and mechanical properties, further work is needed before large-scale adoption. Future studies should include pilot-scale production and optimization of binder loading and carbonization conditions, combustion and emissions testing in typical cooking/heating stoves, storage/durability trials, and techno-economic and life-cycle assessments to confirm environmental and economic benefits. The main limitations of this work are its small, laboratory-scale sample size, the limited range of binder and carbonization conditions tested, and the absence of field trials and emission/air-quality measurements.

Acknowledgements

The authors would like to express their gratitude to Ashaka Cement for their valuable contribution towards the completion of these findings.

Declaration of conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Adejumo, I. O., & Adebiyi, O. A. (2021). Agricultural Solid Wastes: Causes, Effects, and Effective. *Strategies of sustainable solid waste management*, 139.

Ahmed, E. (2015). DESIGN AND MANUFACTURING OF SCREW-EXTRUDER BASED BRIQUETTING MACHINE FOR AGRICULTURAL RESIDUES. *Misr Journal of Agricultural Engineering*.

Aondoyila, K., Achirgbenda, V. T., & Humphrey, I. (2021). Biomass valorization for energy applications: A preliminary study on millet husk. *www.cell.com/heliyon*.

Arzika, A. T., Abdulhameed, S., Yunusa, M. B., Sani, G., Adamu, S. M., Yusuf, S., . . . Muhammad, a. M. (2022). Comparative Analysis of Gum Arabic and Molasses (Binders) in Briquette Produced from Millet Husk. *Journal of Physical Science and Innovation*.

Ayub, H. R., Tarus, H. K., Bichang'a, D. O., & Kegesa, D. A. (2015). Briquettes from Finger Millet Straws at Room Temperature and Low Compacting Pressure without a Binder.

Elum, Z. A., Modise, D. M., & Nhamo, G. (2017). Climate change mitigation: the potential of agriculture as a renewable energy source in Nigeria. *Environmental Science and Pollution Research*, *24*(4), 3260-3273.

Grover, P., & Mishra, S. (1996). *BIOMASS BRIQUETTING: TECHNOLOGY AND PRACTICES.*

Gupta, N., Mahur, B. K., Izrayeel, A. M. D., Ahuja, A., & Rastogi, V. K. (2022). Biomass conversion of agricultural waste residues for different applications: a comprehensive review. *Environmental Science and Pollution Research*, *29*(49), 73622-73647.

Japhet, J. A., Luka, B. S., Maren, I. B., & Datau, S. G. (2020). The potential of wood and agricultural waste for pellet fuel development in nigeria—A technical review. *Int. J. Eng. Appl. Sci. Technol*, *4*, 598-607.

Jing, Z., Decong, Z., & Kai Wu, X. Z. (2019). The optimum conditions for preparing briquette made from millet bran using Generalized Distance Function. *Renewable Energy*.

Kayasth, M., Malik, K., Kumari, S., Sindhu, M., & Mehta, S. (2024). Physical Approach to Biomass Conversion. In *Biomass Energy for Sustainable Development* (pp. 20-34). CRC Press.

Kpalo, S. Y., Zainuddin, M. F., Manaf, L. A., & Roslan, A. M. (2020). A review of technical and economic aspects of biomass briquetting. *Sustainability*, *12*(11), 4609.

Kuhe, A., Terhemba, A. V., & Iortyer, H. (2021). Biomass valorization for energy applications: A preliminary study on millet husk. *Heliyon*, *7*(8).

Kuhe, A., Terhemba, A. V., & Iortyer, H. (2021). Biomass valorization for energy applications: A preliminary study on millet husk. *Heliyon*, *7*(8).

Mathias, L. (2005). *Technology Packages: Screw-press Briquetting Machines and Briquette-fired Stoves.*

Mike, T. (2019). *Briquette production manual.*

Njue, A. M. (2019). Efficacy of Sewage Sludge Briquettes Mixed with Sugarcane Bagasse as a Fuel Alternative. *THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE*.

Obi, O. F., Pecenka, R., & Clifford, M. J. (2022). A review of biomass briquette binders and quality parameters. *Energies*, *15*(7), 2426.

Oyegoke, T., Oyegoke, A. F., Fasanya, O. O., & Ibrahim, A. A. G. (2023). State of agro-wastes management in Nigeria: Status, Implications, and way Forward. In *Waste Recovery and Management* (pp. 241-272). CRC Press.

Philip, D. C., Mia, M. T., & Sindol., K. N. (2022). An Overview on the Production of Bio-briquettes from Agricultural Wastes: Methods, Processes, and Quality. *Journal of Agricultural and food Engineering*.

Solórzano, R., Paquiyauri, A., Neyra, W., Siqueira-Bahia, R. D. C., & Vallejos Torres, G. (2025). Analysis of binder proportions on the calorific value in a briquette made from cocoa pod husk in the Peruvian Amazon. *Frontiers in Energy Research*, *13*, 1661636.

Velusamy, S., Subbaiyan. A., Thangam, R., (2021). Combustion Characteristics of Briquette Produced fuels from Sorghum Panicle-pearls Millet using Cassava Starch as Binder

Yomesh, S., Pujyalal, S., Swarup, B., Shivangi, M., & Lathiya, M. (2019). Development of Manually Operated Piston Press Type briquetting Machine. *International Journal of Current Microbiology and Applied Sciences*.

Yunusa, S. U., Mensah, E., Preko, K., Narra, S., Saleh, A., & Sanfo, S. (2024). A comprehensive review on the technical aspects of biomass briquetting. *Biomass Conversion and Biorefinery*, *14*(18), 21619-21644.