



Research article

Biomass valorization for energy applications: A preliminary study on millet husk

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ABSTRACT

This study used millet husk which is a waste and gum Arabic as binder to develop briquettes for domestic cooking in Northern Nigeria. The objective was to investigate the effect of particle sizes, compaction pressures and binder concentrations on the physical, mechanical and thermal characteristics of the briquettes. Furthermore, the study also accessed the economic viability of the usage of millet husk briquettes as fuel. Particle sizes of 0.3, 0.4, 0.6 and 1.7mm; compaction pressures of 10, 15, 20 and 25 MPa and binder concentrations (gum Arabic) of 25, 30, 35 and 40% were used to densify the millet husk mixed with gum Arabic at room temperature with the aid of hydraulic press. The caloric value (15.27 MJ/kg) was determined using ASTM D2015, other physical and chemical properties of the millet husk was determined by proximate and ultimate analysis which showed that volatile matter (76%), ash content (6.5%) and sulphur content (0.3%) are within the recommended range for domestic cooking fuels. It was found that the density (438 kg/m³ and 669 kg/m³), impact resistance index (70–93%) and compressive strength of the millet husk briquettes increased with compaction pressures and binder concentrations and decreases with increase in particle sizes, while for porosity of the briquettes, the above case was a reversal. The performance of the briquettes for domestic cooking were accessed by ignition time (109 and 140 s); burning rate (0.09 g/s and 0.18 g/s) and water boiling test which took 5 and 11 min to boil 1 L of water as compared to fuel wood that takes longer. Economic analysis showed that utilizing the millet husk generated in northern Nigeria will lead to huge savings in fuel wood consumption, monetary savings of about ₦ 9,257,869,268.62, and reduction in deforestation and its attendant problems. A structured questionnaire as used to ascertain the acceptability of the produced briquettes. Most of the respondents (90%) in a survey expressed willingness to use millet husk briquette as replacement for wood. The study concludes that millet husk is good for briquetting for energy applications with high potential to reduce energy poverty, minimal waste and reduce indoor pollution for domestic cooking therefore, making millet cultivation more profitable in Northern Nigeria.

1. Introduction

It is generally acknowledged that the looming depletion of fossil fuels is one of the most pressing concerns confronting many countries. The ever-increasing price of such fuels on the global market appears to be having a negative impact on economies all over the world and the greenhouse effect of fossil fuels [1,2]. These situations have forced many persons especially rural dwellers in Northern Nigeria from the use of fossil fuel as a source of domestic energy to the use of wood and wood charcoal as they are cheap, abundant, accounting for about 51% of Nigeria's annual total energy consumption [3]. In Nigeria, the bulk of the energy usage is mostly for cooking at household level, which is mainly derived from biomass (67% fuelwood, 6% charcoal) and fossil fuel (18%

coal and kerosene [4]. The rate of usage of fuel wood as source of energy has its own disadvantages hardship on women and children, emission of toxic atmospheric pollutants which are responsible for many health issues [5,6]. As a result, any fuel alternative that is both cost-effective and environmentally friendly would be welcomed.

Agriculture produces significant quantities of residues which could contribute to energy production and reduce the use of fuel wood [7]. Northern Nigeria is at risk of desertification, owing to increased tree felling for domestic heating and cooking. In this part of the country, household cooking consumes more energy than any other end-use services [9]. Humans, plants, and animals that rely on the forest/woodland ecosystem for food and shelter are now being affected by deforestation [10]. Categories of biomass include agricultural residues, biomass

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plantation and forest residues, of these agricultural residues which represents a large and under-exploited potential energy resource, is accounted to be the most abundant and cheapest of them all [10]. The amount of agricultural residue produced at any given time is proportional to the amount of main crop produced and the amount of residue. As a result, it is possible to estimate the amounts of agricultural residues produced using the residue to product ratio (RPR). According to [13] and the work of [14] the resource base of residue in Nigeria has it that cassava, groundnut, sorghum, oil palm, millet, maize, cowpea, plantain, palm kernels have residue product ratio (RPR) as 2.0, 2.3, 1.25, 0.230, 1.75, 4.328, 1.75, 0.50 and 0.25 respectively. Agricultural residues have been identified as a potential source of biomass for energy application, but direct usage in their raw form is often difficult as it gives raise to toxic emissions, poor ignition quality, excessive smoking and low combustion efficiency due to their uneven and troublesome characteristics as high moisture content, low bulk density, fibrous nature etc. [15].

Based on the large amount of millet grown, millet husk a by-product is gotten in large quantities. There are nine species of millet in the world, according to [16], with a total production of 28.38 million tons, of which 11.36 million tons (40 %) were produced in Africa. Nigeria produces about 40% of Africa's millet (4.53 tons, with the northern part of the country producing more than 80% of the millet [17]. Nigeria has been ranked as the world's second-largest millet producer (Food and Agricultural Organization of The United Nations: Economic and Social Department). The Statistics Division 2007 Millet hulls are a fibrous by-product of millet grain dehulling. As at 2020, two million metric tons of millet was produced in Nigeria, about 40% of the harvested millet weight is extracted as hulls after harvest [18,57]. Many consumers decorticate (dehull) the kernel before grinding it in to various particle sizes for use as different products. Pearl millet is usually decorticated by washing the clean grain in water. The water is removed and the grain is crushed using a stone mortar and wooden pestle [59]. The hull is removed by washing or winnowing the sun-dried crushed material, and collected in polythene bags for other purpose or are discarded in field where they are being burnt.

Some researchers have used millet by-products with some success [19]: Predicted the performance of millet bran briquettes (using a Neural Network Approach) and concluded that ANN can be used as a fast and versatile modeling method for any non-linear problem involving biomass briquettes with a higher degree of accuracy. The combustion characteristics of briquettes fuels made from sorghum panicle – pearl millet with cassava starch as binder were investigated by [20], and it was discovered that sorghum panicle–pearl millet briquettes have a higher calorific value and produce higher heating values than pongamia–tamarind shell briquettes [21]. investigated the combustion properties of briquettes made from different particle sizes of finger millet straws, and it was discovered that milled finger millet straws had a high volatile matter content with low moisture and ash content, indicating that finger millet straws are a potential renewable energy source. From the works of [19–21], different residue components of millet bran, finger, and stalks were used as briquetting material. [22], in their work, considered maize and millet husks blends as briquetting material in certain ratios and used starch paste as binder [23] determined the optimum conditions for preparing from foxtail millet by investigating the effects of moisture content, temperature and applied pressure on the briquette quality using response surface methodology.

Gum Arabic is a leguminous tree species that is well adapted to Sudan and Sahalian agro-ecology of Africa. In Nigeria, estimated hectarage of gum Arabic both cultivated and the wild form (forest reserves) is put at 2.5 million (ha) [24]. Production of Gum Arabic is in the northern region of Nigeria which coincides with the region where pearl millet is predominantly cultivated in Nigeria [25] examined the effect of binder type

and ratio on the physical and combustion properties of charcoal briquettes produced from wood residues of neem. The authors used starch and gum Arabic as the binder types, the study showed that gum Arabic bonded briquettes had better physical and combustion properties than starch bonded briquettes.

From available literature, there is very little research on pearl millet hulls briquettes. Therefore, a knowledge gap on pearl millet hull briquette exists, which this research intends to fill. Pearl millet hulls briquettes using gum arabic as binder will be produced and the effect a feed process variable, particle size distribution and some operating s such as compaction pressure and binder ratio on the combustion properties of the briquettes will be investigated via an experimental and economic analysis on the feasibility of using pearl millet hulls to produce briquettes as an alternative to fuel wood for cooking in the rural areas of Nigeria, particularly northern Nigeria, where there is a large abundance of pearl millet and gum Arabic.

2. Materials and methods

2.1. Materials

In this study, Millet hull was obtained from a farm while gum Arabic from Dadin Kowa market both in Maiyama Local Government Area of Kebbi State, Nigeria. The millet hull was then crushed into different particle sizes (0.3mm, 0.4mm, 0.6mm and 1.7mm) based on the BS1377-2 [27]. The samples were then stored in zip lock plastic bags ready for analysis. The sample and Gum Arabic were sent to the Chemical Engineering department Ahmadu Bello University Zaria, Kaduna State for analysis to determine their physical properties, chemical composition and calorific value (Table 1). The pearl millet hulls of different particle sizes (0.3, 0.4, 0.6 and 1.7 mm) were mixed with gum Arabic (an extract from *acacia Senegal L.*) at binder concentration of 25%, 30%, 35% and 40% by weight respectively before introduction into the mould by hand and compacted at different pressures (10, 15, 20 and 25 MPa). A total of sixty-four (64) different samples were prepared at four levels of the three factors investigated. Each sample was replicated thrice. The briquettes were formed in a cylindrical mould of diameter 65 mm mm and 75 mm long (with a plunger of 64.6mm diameter and 80mm long). The mould was filled with the mixtures and densified at different pressures, with a manually operated 20-tonne air hydraulic piston press (KENNEDY Model HBP020, UK). The hydraulic press was held at the respective compacting pressures for 45 s (dwell time) before release and extrusion from the mould. A stop watch was used for the purpose of timing. Drying the briquettes to a moisture content of 8.5% at an average relative humidity 75% and temperature of 28 °C took between 18 and 21 days. Proximate and ultimate analyses were conducted on the produced briquettes using ASTM E870 – 82 (2015) [28] and ASTM D3178, D3179, D3177 standards respectively [29]. Calorific values were determined using ASTM *astm:D2015 – 00* standard procedures [30,31]. The moisture content was determined using ASTM D3173 standard procedure (ASTM, 1993) [32]. The moisture content reported in this article are on wet mass basis unless otherwise stated.

The initial density of the mixture of millet and gum Arabic mixture were determined using the formula

$$\rho = \frac{\text{Mass (kg)}}{\text{Volume (m}^3\text{)}} \quad (1)$$

Each particle size was taken in turn and used to produce briquettes with respective binder concentration and compaction pressure. The gum Arabic was weighed in a digital balance to determine its percentage by weight and then dissolved in water and was allowed to gelletize before mixing with the hull [33]. The samples were conditioned to moisture

Table 1. Proximate and ultimate analyses of millet husk and gum Arabic.

Parameter	Proximate Analysis		Ultimate Analysis	
	Millet Husk	Gum Arabic	Millet Husk	Gum Arabic
Moisture Content (%)	8.20	6.63		
Ash Content (%)	6.50	5.05		
Fixed Carbon (%)	16.50	23.05		
Volatile Matter (%)	68.80	64.26		
Higher Calorific Value (MJ/kg)	15.27	12.24		
Carbon (%)			56.80	61.21
Hydrogen (%)			5.31	4.42
Oxygen (%)			35.00	28.31
Nitrogen (%)			0.86	0.97
Sulphur (%)			0.30	0.21

content of 15 % by weight to make the mixture suitable for briquetting [34].

2.2. Physical and mechanical properties of briquettes

2.2.1. Compressed density and relaxed density

Compressed density of the briquettes was determined immediately after the briquette was removed from the mould using Eq. (1), while the relaxed density (RD) was determined 12–19 days after removal from the press and sun – drying according to ASTM D5373 standard procedures [25,35].

$$\text{Relaxed Density} = \frac{108,000 \times M \text{ (g)}}{\pi (d_1 + d_2 + d_3)^2 \times (l_1 + l_2 + l_3)} \quad (2)$$

where M (g) is the mass of briquette while d_i and l_i ($i = 1, 2, 3$) are the diameters (mm) and lengths (mm) respectively measured at three different points on the briquettes.

2.2.2. Impact resistance index

The impact resistance index (IRI) was determined by adopting ASTM astm:D440 standard methods for drop shatter for coal [35]. Each briquette sample was repeatedly dropped from a height of two meters on a concrete floor [36]. The number of drops (N) taken by each briquette to break into pieces was recorded. Impact resistance index was then calculated from the formula

$$\text{IRI} = \frac{N}{n} \times 100 \quad (3)$$

where n = number of pieces that weigh up to 5 % or more of the initial mass of the briquette after N drops.

2.2.3. Compressive strength

The Compressive strength of briquettes was determined using a universal testing machine (INSTRON 3382) with a load cell capacity of 50 kN and a cross-head speed of 1 mm/min in accordance with ASTM D2166-85 until the structure of the briquette failed. The maximum force the briquette was able to withstand was then recorded and used to determine the compressive strength of the briquette with the help of the formula [37].

$$\text{Compressive Strength} = \frac{\text{Force (N)}}{\text{Area of briquette (cm}^2\text{)}} \quad (4)$$

2.2.4. Porosity of the briquettes

Porosity is a measure of the void spaces in a material and is a fraction of the volume of voids over the total volume; it generally lies between 0 – 1. It determined using the formula [38].

$$\text{Potosity} = \left(1 - \frac{\text{Bulk Density}}{\text{True Density}} \right) \quad (5)$$

2.3. Thermal characteristics of the briquettes

2.3.1. Ignition time

In order to determine ignition time, each briquette was oven dried at 105 ± 3 °C to constant masses in 24 hours to drive off moisture in the briquettes for effective combustion. A dried briquette was then ignited at the edge with a Bunsen burner and the time taken for each briquette to start burning was recorded in seconds [39].

$$\text{Ignition time} = \frac{\text{distance burnt (mm)}}{\text{total time taken (sec)}} \quad (6)$$

2.3.2. Burning rate

Burning rate is the mass loss per unit time due to combustion. In order to determine the burning rate of the briquettes; a briquette was placed on a steel wire mesh grid resting on three supports to allow free flow of air. Now the whole system was placed on a digital mass balance. The briquette was ignited from top and mass loss data was taken at intervals of 10 s [40].

$$\text{Burning rate} = \frac{\text{mass of total consumed (g)}}{\text{total time taken (min)}} \quad (7)$$

2.3.3. Water boiling test

Since the briquettes are going to be used for domestic cooking, their suitability is been accessed by water boiling. 83 grams of each briquette sample was measured and put on a metal domestic briquette stove to boil 1 L of water using aluminum pot the process used as outlined by [41]. The measured time taken to boil the water, the temperature, the remaining ash and briquette left are used for the calculation.

2.4. Economic analysis

Cost analysis was determined to access whether briquette produced from millet hull is economically viable to fuel wood used in this part of the country for domestic cooking. . The aim is to determine how much of fuel wood can be substituted by millet hull and its monetary value. The millet hull was considered a waste that is free and the cost of processing it as briquette was assumed to be of no effect in the analysis since a similar cost exists also in wood processing and is captured in the price. The parameters used in this analysis include:

- Average annual millet production for Nigeria (M_t), kg
- Husk ratio in millet (W), kg
- Average calorific value of millet hull briquette (C_m), MJ/kg
- Average calorific value of wood (C_w), MJ/kg

- Average Price of fuel wood (P_w), N

Two kilograms of millet was threshed manually by pounding in a mortar. The hull was separated by winnowing. The husk ratio in millet, W was determined using the formula

$$W = \frac{M_h}{M_m} \times 100 \% \quad (8)$$

where, M_h = Mass of husk; M_m = Mass of whole millet (2 kg)

The average annual husk produced in Nigeria, $M_t = W \times M_t$, kg (9)

$$\therefore \text{Annual wood equivalent, } W_m = \frac{HC_m}{C_w} \quad (10)$$

In monetary terms, cash saved due to fuel wood substitution with millet husk briquette,

$$N_w = P_w \times W_m, \text{ naira} \quad (11)$$

As part of the economic analysis, a survey was conducted on the potential acceptability of the briquettes and existing potential uses of the millet husk that are likely to compete with briquetting for fuel. Two questions were asked in a structured questionnaire distributed to 50 millet farming households in some communities in Kebbi state, Nigeria.

- i. State any existing use(s) of millet husk that in your opinion may reduce the quantity of husk available for briquetting.
- ii. From your cooking (or other uses) experience with the briquettes, will you be willing to use it as replacement for wood if available?

3. Results and discussion

3.1. Proximate and ultimate analysis of briquettes

The results of proximate and ultimate analyses of millet husk briquette with gum Arabic as binder are presented in Table 1. It shows that the millet husk and gum Arabic have moisture contents of 8.20 % and 6.63 % respectively, which is below the moisture content required for briquetting by [41], but within the minimum ranges of 8–12 % as reported by [42] for agricultural waste. The table further shows that the millet husk and gum Arabic, have calorific values of 15.27 MJ/kg and 12.24 MJ/kg respectively, which is the most important of fuel characteristics [42]. The obtained values are lower than the average value range of 18–20 MJ/kg reported by [43], but greater than minimum requirement (14.5 MJ/kg) recommended by [44]. This can be attributed to the fair amount of fixed carbon and hydrogen contents, which are the major sources of heat in a material during combustion. The high oxygen contents of 35 % and 28.31 % for millet husk and gum Arabic shows that the briquettes will require less oxygen from the atmosphere and it sometimes as a result of high degree of inherent moisture. The ultimate analysis shows that the sulphur contents are 0.30 % and 0.21 %, and falls within safe limits for indoor fuels respectively [44]. The volatile matter is the amount of fuel that is release as gases when the densified biomass is heated. The higher this is, the faster the fuel burns; its reaction rate is more and it is easily ignited [44]. For biomass, a typical range is from 65–85 % wt which is in agreement with 76 % volatile matter for the millet husk [45], with a low ash content of 6.5 % which is a common characteristic of biomass residues [46]. The initial densities of millet husk/-binder mixtures are shown in Table 2. The table shows that the initial

densities increased with increase in binder concentration. This agrees with results obtained by [33] while working on fonio husk, a plant in the same family with millet.

3.2. Handling characteristics of millet husk briquettes

3.2.1. Compressed density and durability of the briquettes

The effect of binder concentration and compaction pressure on the compressed density of millet husk briquette is shown in Table 3. It shows that the compressed density of the briquettes ranged between 438 kg/m³ and 669 kg/m³, while impact resistance varied between 70 % and 93 % which is in line with the range found by [47]. According to the table, an increase in compaction pressure and binder concentration resulted in an increase in the compressed density and durability (Impact Resistance) of the briquettes. These densities are higher than the initial densities of the uncompressed mixture, thereby making briquetting a worthy venture [48]. Briquettes made with a hydraulic piston press are typically less than 1,000 kg/m³ and have a density of between 300 and 600 kg/m³, according to the findings of the study by [49,50].

3.2.2. Relaxed density of the briquettes

The effects of Compaction Pressure, Particle size and binder concentration on the relaxed density of the millet husk briquettes are shown in Figure 1. It shows that the relaxed density of the briquettes varied between 383 kg/m³ and 411 kg/m³, which were observed to be higher than the initial density of unprocessed mixture of millet husk and binder, ranging between 167 kg/m³ and 213 kg/m³. The relaxed density increased with increase in compaction pressure and decreases with particle sizes at 25 % binder concentration as shown in Figure 1a.

These results suggest that the relaxed density of the briquettes produced increases with increasing compacting pressure level with smaller particle size are likely to have higher relaxed density than those with larger particle size. This result confirms that of other researchers [51,52]. The reason for this trend is that increasing the compacting pressure will lead to the particles of biomass material being closely packed due to reduction of void ratio and plastic deformation of the millet husk particles, therefore leading to increased density of the briquettes [53]. Additionally, if the raw material is finer, it gives a larger surface area for bonding which results in the production of briquette with higher density. Figure 1b, shows that the relaxed density increased with binder concentration at different particle sizes of 1.7, 0.6, 0.4 and 0.3mm respectively. These results agree with the findings of [33] for briquettes made from fonio husk. The increase in relaxed density with compaction pressure and binder concentration can be attributed to possible increase in compactness due to increased plasticity and decrease in the size of voids due to decrease in particle size [33]. It was observed that from the work of [54] the highest compressed density of 1437 kg/m³ was obtained for briquettes made of cassava binder at 30% binder concentration under 150 kPa compacting pressure, while the lowest value of 952.46 kg/m³ was obtained from gelatin binder at 10% binder concentration under 50 kPa compacting pressure. It was observed that the compressed density of the briquettes increased with increase in binder ratio and compaction pressure.

3.2.3. Compressive strength of the briquettes

The Compressive strength varied between 0.67 N/cm² and 8.2 N/cm². It increased with increasing compaction pressure, but decreased with increase in particle size. This trend can be attributed to the fact that

Table 2. Initial densities of millet husk/binder mixtures.

Binder Concentration (%)	25	30	35	40
Initial Density (kg/m ³)	167	181	201	213

Table 3. Effects of binder concentration and compaction pressure on density and durability of millet husk briquettes.

Binder Concentration (%)	Compaction Pressure (MPa)	Compressed Density (kg/m ³)	Impact Resistance Index (%)
25	10	434	70
	15	455	74
	20	503	77
	25	507	79
30	10	438	73
	15	467	75
	20	525	78
	25	569	80
35	10	458	73
	15	481	75
	20	537	85
	25	662	90
40	10	473	83
	15	493	85
	20	545	91
	25	669	93

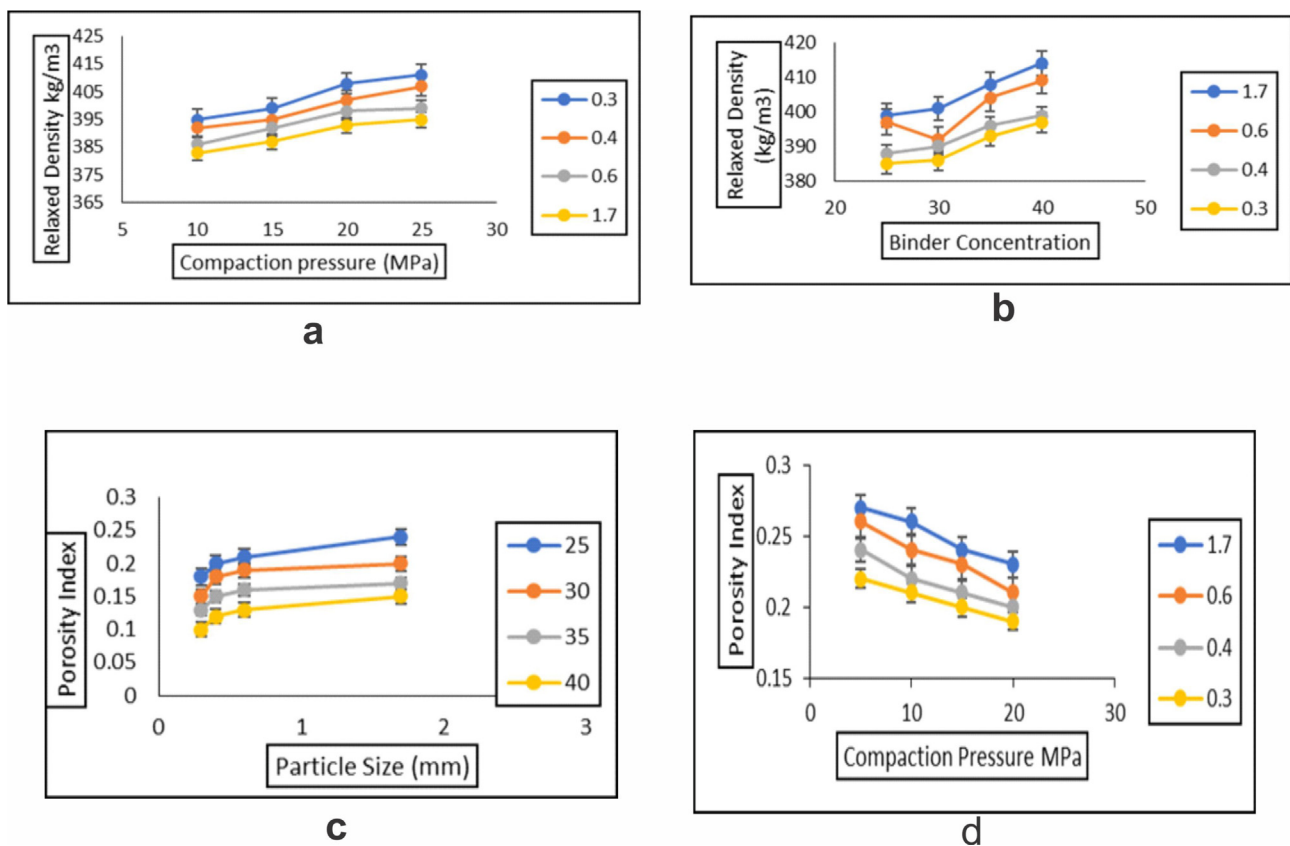


Figure 1. (a) Effect of variation of compaction pressure on relaxed density of briquettes at 25% binder concentration (b) Effect of variation of binder concentration on relaxed density of briquettes (c) Effect of particle size on porosity index of briquettes made at 10 MPa compaction pressure (d) Effect of compaction pressure on porosity index of briquettes made at 25% binder concentration. Values are means ± standard deviation (n = 3).

the smaller particle sizes are likely to bond better with smaller voids, forming stronger solids than the larger particles. The compressive strengths are however generally good and likely to enable easy handling of the briquettes [48]. On the other hand, the compressive strength of the briquettes was observed to vary from 6.7 N/cm² and 9.2 N/cm² with variation in binder concentration and particle size. It increased with increasing binder concentration but decreased with increasing particle

size. The significance of this result is that higher binder concentrations and smaller particle sizes make the briquettes stronger, thus easier to handle. This finding supports the claims of [49,51] and [52] that pellet durability (mechanical strength) is inversely proportional to particle size because smaller particles have more surface area for moisture addition during steam conditioning, resulting in improved starch gelatinization and better binding.

3.2.4. Porosity of the briquettes

The effects of various parameters on the porosity index of the briquettes are shown in figure 1c and d. The porosity index ranged between 0.19 and 0.27. It increased with increasing particle size, but decreased with increasing binder concentration and compaction pressure.

This trend shows that increasing particle size increases the likelihood of larger pores, while increasing compaction pressure and binder concentration means more plastic deformation and bonding among the particles, hence smaller pores and less porosity. This result indicates that higher binder concentration, compaction pressure and smaller particle size result in better briquettes; in terms of porosity; on which water absorption of the briquettes depend. The optimum values of these parameters may however require to be determined in future studies for optimum performance.

3.3. Thermal properties of the briquettes

3.3.1. Proximate and ultimate analysis of the millet husk briquettes

The results of the proximate and ultimate analysis of the millet briquettes are presented in Table 4. It shows that the volatile matter for millet husk alone is 51 %, moderate for ease of ignition and mild emission. The calorific value is 16.13 MJ/kg, close to the average value for wood, 18.8 MJ/kg [55], making it a good substitute for wood especially as it is derived from waste. The nitrogen and sulphur contents are low, indicating low NO_x emission and corrosion rate of combustion and ash handling equipment. The high oxygen content of 37.10 % means less air will be required for its combustion than wood. According to [66], briquettes from agricultural residues showed less average CO emissions than that of fuel wood briquettes while for NO_x the reverse is the case, but for SO₂ emissions are very similar for both depending on their Sulphur content. Although agro-based briquettes have higher potassium and ash content, it did not show higher particulate matter emissions than fuel wood [59].

3.3.2. Ignition time

The influence of the various parameters on the ignition time of the briquettes is shown in Figures 2e and 2f. It shows that the ignition time ranged between 109 s and 140 s. The ignition time decreased with increasing particle sizes for all binder concentrations. According to [56], the lowest ignition time values were attributed to high porosity (increase in particle size) between inter and intra-particles, which allows for easy oxygen percolation and outflow of combustion briquettes due to low bonding force.

Figure 2a, shows that the ignition time increased with increasing binder concentration and compaction pressure for all particle sizes as shown in Figure 2b. Increased in compaction pressure automatically increased the density of briquettes and consequently, delayed the ignition time of the briquettes. Furthermore, briquettes compressed to a higher density will tend to have a lower porosity, and thus elongate the ignition time [56].

This trend shows that briquettes made with large particle size millet husk will ignite faster, but those made at high compaction pressures and binder concentrations will take more time to ignite [55]. This can be attributed to the fact that larger particles leave larger pores in the briquette, allowing more air through it to support combustion. On the other hand, high compaction pressures and binder concentrations entail more plastic deformation of the particles and more bonding, allowing little room for air passage to support combustion. The values obtained from this study are within the range of 19–186 s for bio-coal briquettes made by mixing the materials at various concentrations of 10–50% with coal [39]. Briquettes for domestic use should have a low porosity index, low volatile content, and low ash content [57].

3.3.3. Burning rate

The influence of particle size, compaction pressure and binder concentration on the burning rate of the millet husk briquettes are shown in

Figures 2c and 2d. The burning rate ranged between 0.09 g/s and 0.18 g/s. The burning rate increased with increase in particle size as shown in Figure 2c.

From the study of [56], the obtained briquette burning rate values decreased as the binder percentage was increased. The implication of this observation is that with the briquettes produced, more fuel may be needed for cooking. The briquettes made with 50 % binder had the slowest rate of combustion. As a result, briquettes without a binder burned more quickly than those with a binder [56]. The burning rate decreased with increasing compaction pressure and binder concentration. See Figures 2c and 2d.

Increase in density of briquettes occasioned by increase in binder concentration and compaction pressure results in a decrease in the burning rate of the briquettes due to smaller pores, thereby allowing little air supply into the briquettes for combustion [56]. The influence of the particle size on the burning rate of the briquettes might be due to the fact that the bigger particle sizes could have more pores in-between them than smaller particle sizes, thus, increasing porosity index of the briquette. The high porosity index reduces the time taken for adjacent particles to ignite and burn due to increased air flow to support combustion [56]. This trend agrees with the findings of [33] while studying briquettes made from fonio husk.

3.3.4. Water boiling test

The results of the water boiling test of the millet husk briquettes with Gum Arabic as binder are shown in Figure 3. The raw millet husk briquettes particle size at 10MPa with 25% binder composition took 5 min to boil one liter of water while with 40% binder compositions took 11 min to boil one liter of water. This indicates that boiling time increase with increase in binder composition and decreases with increase in particle size as for the same binder composition. From the result obtained [58], it was observed that the water heated with rice husk - starch briquette took 15 min to boil 2 L of water compared to fire wood that took 21 min to boil the same quantity of water. This implies that millet husk briquettes in this study can conveniently substitute fuel wood.

3.4. Economic analysis

Substituting the values of the parameters in equations 9 – 12 yielded the results in Table 5. It shows that utilizing all the average quantity of millet husk produced annually in Nigeria will allow about one billion, three hundred and twenty-two million, five hundred and fifty-two thousand, seven hundred and fifty-two kilograms of fuel wood to be saved. This will translate into monetary savings of about nine billion, two hundred and fifty-seven million, eight hundred and sixty-nine thousand, two hundred and sixty-eight naira only annually. The results of the potential acceptability survey shows that more than 90 % of the respondents were willing to accept millet husk briquettes as replacement for wood if made available.

Table 4. Proximate and ultimate analyses of millet husk briquettes.

Parameter	Proximate Analysis	
	Proximate	Ultimate
Moisture Content (%)	6.40	
Ash Content (%)	5.20	
Fixed Carbon (%)	37.30	
Volatile Matter (%)	51.10	
Higher Calorific Value (MJ/kg)	16.13	
Carbon (%)		58.20
Hydrogen (%)		6.21
Oxygen (%)		37.10
Nitrogen (%)		0.85
Sulphur (%)		0.30

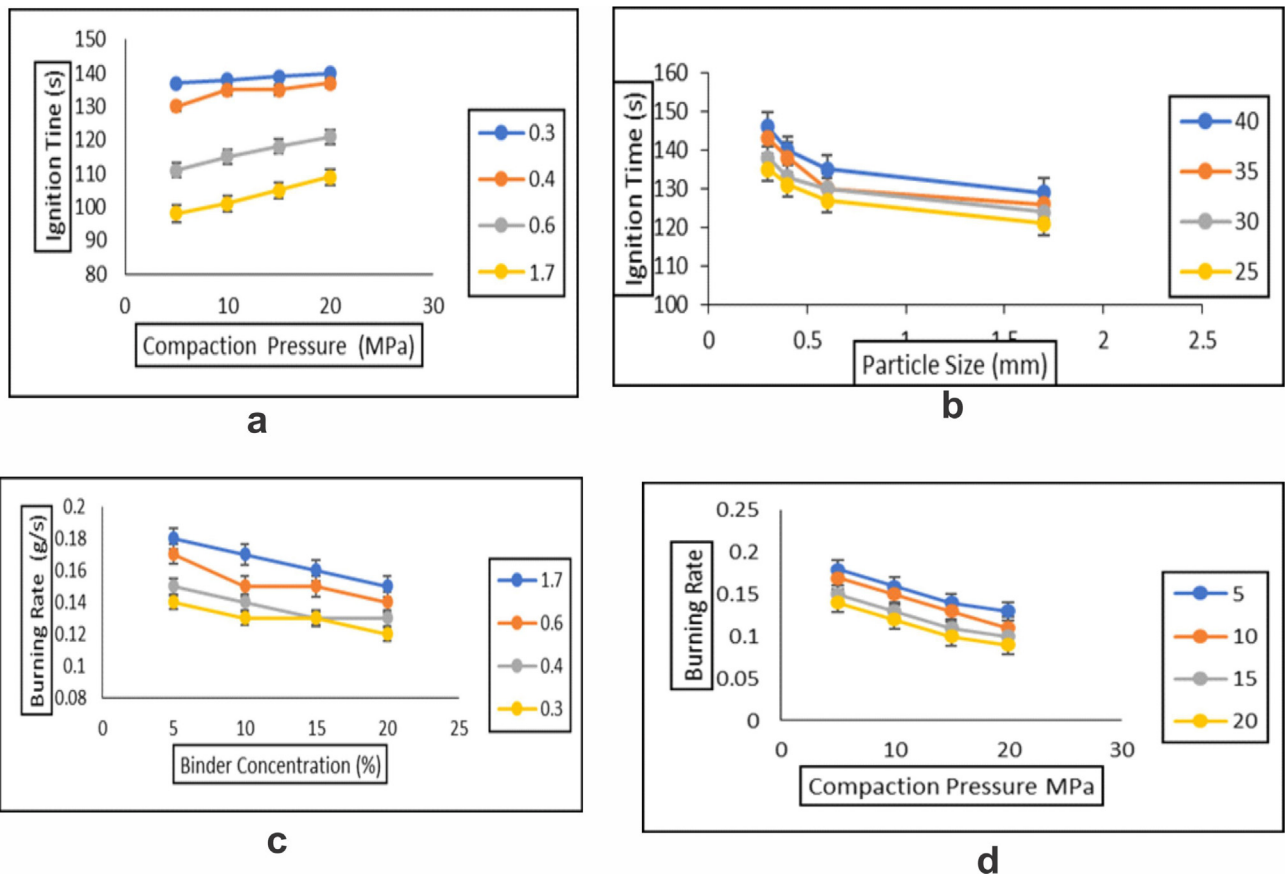


Figure 2. (a) Effect of particle size and binder concentration on the ignition time of briquettes made at 10MPa compaction pressure. (b) Effect of compaction pressure variation on the ignition time of briquettes produced with 25% binder concentration. (c) Effect of binder concentration variation on the burning rate of briquettes produced at 10MPa compaction pressure. (d) Effect of compaction pressure variation on briquettes burning rate. Values are means \pm standard deviation (n = 3).

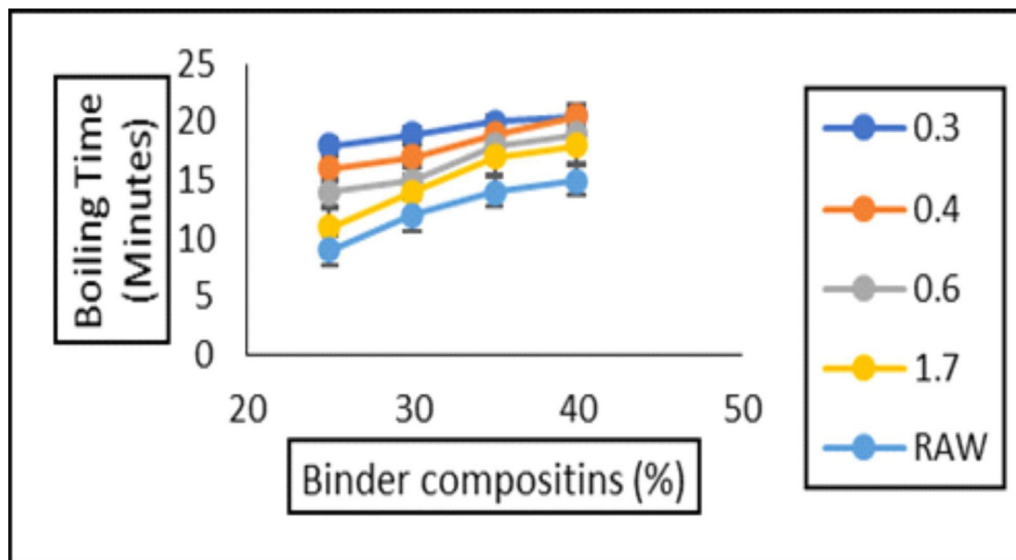


Figure 3. Effect of Binder composition on boiling time of millet husk Briquettes of different particle sizes at 10 MPa compaction pressure. Values are means \pm standard deviation (n = 3).

Table 5. Possible fuel wood and monetary savings due to millet husk utilization.

M_m	M_h	M_t	C_m	C_w	P_w	W	H	w_m	N_w
2 kg	0.36 kg	7905×10^6 kg***	16.13 MJ/kg	18.8 MJ/kg*	N7/kg**	19.50 %	1541475000 kg	1322552752.66 kg	N9257869268.62 (\$25716303.52)

*** CEIC, 2017.

* Gunther, et al., 2020.

** Kuhe, et al., 2017.

If implemented, this will reduce deforestation in Nigeria while improving the income of the millet farmers. The waste will be reduced and green-house gas emission due to the open rotting of the wastes will also be mitigated. The resulting widespread briquette making will provide jobs for the youth, giving room for more economic development.

4. Conclusion and recommendations

The study used millet husk with gum Arabic as binder to produce briquettes and determined the effect of particle size, compaction pressure and binder concentration on the physical, mechanical and combustion properties of the produced briquettes. The result reveals that it was possible to produce briquettes from millet husk with considerably fuel properties for use as domestic fuel for cooking. Particle size, compacting pressure and binder concentration affect the density, compressive strength, impact resistance index, porosity, ignition time and burning rate of the briquettes produced thereby influencing their quality.

The briquettes produce enough energy for cooking as compared to wood fuel used predominantly in Northern Nigeria. Also, they are considered as carbon neutral because when growing the biomass removes as much CO₂ as is emitted into the atmosphere from its combustion and based on the toxic emission of atmospheric pollutants which are responsible for an appreciable number of health problem from the use of fuel wood, the briquettes produced are renewable, environmentally friendly, economically viable and generally willing to be acceptable by the dwellers of this region.

It is recommended that further studies be carried out to determine optimum values for relevant parameters for the production of the briquettes.

Declarations

Author contribution statement

Aondoyila Kuhe: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Achirgbenda Victor Terhemba: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Humphrey Iortyer: Analyzed and interpreted the data; Wrote the paper.

Umar Abacha: Performed the experiments; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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