European Journal of Sustainable Development Research
2024, 8(4), em0270
e-ISSN: 2542-4742
https://www.ejosdr.com/

MODESTUM

Research Article

OPEN ACCESS

Production and optimization of briquette (solid fuels) from waste biomass using industrial starch as binder

Ebube Daniel Ezeokolie [1*], Temple Uzoma Maduoma [1], Ejiro Marvis Akpotabor [2], Olusola Akanni [3], Abubakar Abdullahi Garbati [4], Augustine Abah Odeh [5], Precious Moses Chukwu [6], Fidel Nneka Achoronye [1], Joel Nnamdi Esonwune [1]

[1] Department of Chemical Engineering, Federal University of Technology Owerri, Owerri, Imo State, NIGERIA
[2] Department of Chemistry, Delta State University, Abraka, Delta State, NIGERIA
[3] Institute of Ecology and Environmental Studies, Obafemi Awolowo University, Ile-Ife, Osun State, NIGERIA
[4] Civil Engineering Built Environment, The Patrice Lumumba Peoples' Friendship University, Moscow, RUSSIA
[5] Department of Environmental Pollution Technology, Federal University of Technology Owerri, Owerri, Imo State, NIGERIA
[6] Department of Electrical and Electronics Engineering, University of Uyo, Uyo, Akwa Ibom State, NIGERIA
***Corresponding Author:** ebubedaniel04@gmail.com

Citation: Ezeokolie, E. D., Maduoma, T. U., Akpotabor, E. M., Akanni, O., Garbati, A. A., Odeh, A. A., Chukwu, P. M., Achoronye, F. N., & Esonwune, J. N. (2024). Production and optimization of briquette (solid fuels) from waste biomass using industrial starch as binder. *European Journal of Sustainable Development Research, 8*(4), em0270. https://doi.org/10.29333/ejosdr/15138

ARTICLE INFO

Received: 30 Sep. 2023

Accepted: 01 Jul. 2024

ABSTRACT

This study aims to develop an efficient means of transforming municipal solid waste and agricultural waste to produce and optimize briquettes from biomass as an alternative energy source capable of replacing fossil fuels. The project involved the production of briquettes from paper, sawdust, and charcoal, using industrial starch, and sodium hydroxide pellets as binders. The fuel briquettes were produced from paper and charcoal combination, paper, charcoal and sawdust combination, sawdust and charcoal combination, and wastepaper and sawdust combination at different amounts of binders of 100%, 120%, 140%, 160%, and 180% weight of water to the respective briquettes produced. The combustion-related properties were determined. The data obtained, and the optimization of the briquettes produced from paper, charcoal, and sawdust combinations were done using the design expert software program. From the experiment, it was seen that the briquettes made from the paper, charcoal, and sawdust combination had a better combustion capacity with heating values of 34,469.1 KJ/kg, an ash content of 7.656%, and a volatile matter content of 87% for 180% binder. Also, from the result obtained, it can be confirmed that the briquettes made from paper, charcoal, and sawdust had a higher dry density value of 985.6 g. The cost analysis and evidence from literature show that briquettes are not only a better and more reliable alternative fuel source to the high-rising conventional cooking fuel available but also reduce the problems associated with rapid deforestation environmental degradation, and pollution.

Keywords: municipal solid waste, agricultural waste, briquettes, biomass, alternative energy, fossil fuels

BACKGROUND OF STUDY

Rapid industrialization, urbanization, and a growing global population's energy demands have spurred research into transforming biomass into energy. This points to biomass as a promising alternative energy source and resource. In developing countries, rural households and a few urban dwellers have depended heavily on wood fuels as their main energy source (Mainimo et al., 2022). It is known that large quantities of agro and forestry-based residues are heavily generated annually; such residues include rice husk, coffee husk, sugarcane bagasse, and groundnut shells, as well as residues from wood-based biomass. Wood waste like sawdust, bark, slabs, etc., accounts for between 15% and 60% of the volume in sawmills and between 40% and 70% of the volume in plywood industries in Nigeria and many developing countries (Jekayinfa et al., 2020). The abundance of these wood wastes in wood processing mills makes them economically attractive as an alternative source of energy. Valuable products can be obtained from these agricultural products, such as briquettes, which have proven to be an important substitute source of energy for domestic uses. In Nigeria, for instance, a significant portion of the population, estimated at around 70%, relies on wood, charcoal, and other biomass fuels for domestic cooking (Adamu et al., 2020). Biomass has received prominence as an acceptable source of renewable energy fuel. In recent years, biomass has garnered significant attention as a viable and sustainable source of renewable energy (IEA, 2023; Perea-Moreno et al., 2019). A study by Achakulwisut et al. (2023) found that replacing fossil fuels with biomass in power plants could significantly reduce carbon dioxide emissions, ranging from 75% to 90%. Another study, published in environmental science and pollution research in 2021, suggests that sustainable biomass production and efficient conversion technologies can contribute to achieving net-zero emissions goals (Maurya et al., 2021). However, large-scale biomass use raises concerns about deforestation and land-use changes. This signifies the need for innovation in biomass use, like creating composite briquettes from waste materials. Such advancements can optimize biomass for cleaner, more sustainable energy (European Commission, 2022).

Over the years, global warming has been a significant problem that has gained international concern. The high energy demand for transportation, industrial, and domestic activities has resulted in problems associated with environmental issues. The replacement of biomass fuel with conventional or fossil fuels is a viable alternative to mitigate global warming since it is a carbon-neutral fuel (Garrido et al., 2017; IEA, 2023). Energy and chemicals that originate from fossil resources can result in the release of CO_2 into the atmosphere, along with other harmful and toxic compounds. About 90% of the global emission of CO_2, which reached approximately thirty-four billion tons of greenhouse gases in 2011, was estimated to have been generated from the combustion of fossil fuels. Moreover, since raw biomass resources are finite, using them as fuel raises concerns about long-term supply security. This is a critical issue for humanity (Hidayah & Syafrudin, 2018).

The use of wood fuel for cooking comes with various health problems, mostly for those completely exposed to smoke. In rural areas and other places, the exposure to smoke when using wood fuel for cooking is done in an unventilated place. Research has also shown that the smoke given off when biomass is burned contains large amounts of pollutants, which, at different concentrations, pose a great risk to humans (Odame & Amoah, 2023). Exposure to biomass smoke increases the risk of common diseases, both in children and adults. In children, especially, the smoke also causes acute lower respiratory infections such as pneumonia (Kurmi et al., 2012; Thacher et al., 2013). Therefore, to prevent these problems and those associated with environmental pollution, these biomass materials can be compacted into products with higher density (e.g., briquettes), thus converting them into high-quality biofuel products.

Briquetting biomass is a mechanical compaction process that involves the densification of large materials to produce a compact material with higher energy per unit volume (Garrido et al., 2017). This process is done to form fine particles into a designed shape. It can be considered a tested measure for controlling waste. Briquetting can be used to deliver an alternative fuel source as a preventative solution to ecological problems, though, depending on the material of interest (Asamoah et al., 2016). Biomass briquettes are a proven way of managing waste. Fuel briquettes are made from compressed biomass substances, such as agricultural waste, charcoal dust, or wastepaper, that are used for cooking, water heating, and space heating in houses (Onukak et al., 2017).

In the briquette process, compacted materials in fine forms are made into regular shapes and sizes, which does not allow separation to occur during transportation, storage, or even combustion. In some techniques for briquetting, the materials are compressed without adding any binder, while in others, binders are added to hold the particles tightly (Aransiola et al., 2019). In some parts of East Africa, people make fuel briquettes by hand in a rudimentary manner. Because the heat value of the briquettes improves with density, hand-pressing the components into a solid ball can make high-density briquettes. Briquettes as fuel have several advantages, including turning a waste material into a valuable resource and lessening the environmental difficulties associated with the disposal of these materials into rivers and lakes. Second, trees and other biomass materials will have more time to generate energy. However, agricultural leftovers are natural soil conditioners, and their usage as energy could have a negative impact on the quality of agricultural soil (Urra et al., 2019). Numerous types of biomass waste have been used to produce and develop briquettes. The advantage of being able to transform low density, low heating value, and high moisture content biomass into highly efficient fuel briquettes is being researched in briquette development. A variety of sources have been used and newer ones are being explored with the Interest of using locally available materials as raw materials for briquette production in various developing countries. In Nigeria, Nwabue et al. (2017) produced a multi-component briquette comprising coal, plastics, and biomass. Rezania et al. (2016) investigated the use of water hyacinth as a potential raw material for the production of briquettes. Velusamy et al. (2021) experimented with the combustion characteristics of briquette fuels from sorghum panicle–pearl millets using cassava starch binder (Nwabue et al., 2017; Rezania et al., 2016; Velusamy et al., 2021).

Biomass briquettes show promise as an alternative to conventional fuels, but not without limitations. These limitations include combustion efficiency, environmental impact, optimizing the briquetting process, and cost-effectiveness. Existing research primarily focuses on individual biomass materials or single-binder formulations, resulting in suboptimal performance in certain aspects. Also, while many studies have demonstrated the technical feasibility of biomass briquette production, there is a need for a comprehensive economic analysis. This research aims to address some of these issues by assessing the cost-effectiveness of briquette production, considering factors such as raw material acquisition, equipment costs, labor, and potential revenue from briquette sales. Such economic insights are crucial for assessing the viability of scaling up briquette production as an alternative energy source. This research, however, presents a novel approach by utilizing a composite mixture of paper, sawdust, and charcoal with starch as a binder, significantly advancing the state of the art in briquette production. Through rigorous analysis and optimization techniques, we aim to:

1. Investigate the combustion performance, heating value, and ash content of briquettes formed with varying binder percentages and composition ratios.
2. Identify the optimal combination of materials and binder proportions that maximizes energy output, minimizes environmental impact, and lowers production cost.

3. Evaluate the feasibility and economic viability of utilizing this briquette production method on a larger scale in the Nigerian context.

The goals are to showcase the full potential of composite biomass briquettes as a sustainable fuel and promote environmental protection. We aim to achieve this by developing a viable and efficient method to transform both municipal solid waste (MSW) and agricultural residues.

MATERIALS AND METHOD

Collection of Samples

The biomass materials used in this experiment are sawdust (mahogany, oak, and gmelina arborea), wastepaper, and charcoal dust. The sawdust was sourced from *ogboosisi* sawmill along Naze-Egbu Road in Owerri, Imo State. The wastepaper sample was collected from the Federal University of Technology Owerri (FUTO) waste recycling hub, and the charcoal dust was purchased at a local market in Obinze, Owerri, Imo State. The industrial starch was sourced from the local market in Owerri. The caustic soda pellets were collected from the chemical engineering lab in FUTO. Water used in the binder preparation was collected from the storage tank in the Polymer and Textile Engineering Workshop in FUTO.

Preparation of Raw Materials

The wastepaper was made to pass through a waste compactor truck and discharged into the waste sorting shredding machine where the needed soft white paper was sorted or separated from the unwanted brown corrugated cartons. About 5 kg of the white soft paper was collected and stored in a bag (dry bag) to prevent biological activity (air and moisture interactions).

About 5 kg of the sawdust was stored in a bag (polymeric bag) and then dried to remove some amount of moisture present. 10 kg of the charcoal was also stored in a bag (polymeric bag). The charcoal was then sieved to separate larger charcoals from fine charcoals to obtain a uniform particle size.

Production of Briquette

This experimental design was done for three different experimental formations:

1. E1–Paper and charcoal
2. E2–Paper, charcoal and sawdust
3. E3–Sawdust and charcoal
4. E4–Paper and sawdust.

The diagram of E1–Paper and charcoal, E2–Paper, charcoal and sawdust, E3–Sawdust and charcoal, E4–Paper and sawdust are shown in **Figure 1**, **Figure 2**, **Figure 3**, and **Figure 4**, respectively.

Procedures

1. The water, industrial starch, and pellets of sodium hydroxide were added into the mixing bowl and stirred with the mixing spatula until all lumps from the starch and sodium pellets were completely dissolved. At this

Figure 1. Wastepaper and charcoal (Source: Authors' own elaboration)

Figure 2. Wastepaper, charcoal, and sawdust (Source: Authors' own elaboration)

Figure 3. Sawdust and charcoal (Source: Authors' own elaboration)

Figure 4. Wastepaper and sawdust (Source: Authors' own elaboration)

stage, the mixture was a bit milky white, quite watery, and a bit slimy.

2. The waste samples (charcoal dust and paper) were added into the mixture one part at a time and completely combined.
3. After the mixture was ready, the mold was prepared by turning the gear under the machine in an anti-clockwise movement. This lowers the levers and exposes a batch of four holes which serves as the mold.
4. Using the dispensing spoon, the mixture was distributed evenly into the molds.
5. The machine was covered and sealed using the lid and densification was carried out by turning the gear under the machine in a clockwise movement. This compresses the mixtures in the molds and releases excess water.
6. After densification, the compressed mixture was removed from the mold and placed on the drying tray. It was then placed under the sun until it is completely hard and dry.

Combustion Properties of Briquettes

To get ready for the combustion tests, the briquette samples underwent a process of crushing and screening to achieve a particle size of < 0.5 mm. Subsequently, various ASTM standard techniques were employed to assess the combustion characteristics of these briquette samples.

Calorific value/heating value

The calorific or heating value (HHV) of each briquette sample was calculated using the Nhuchhen and Afzal's (2017) model which has an excellent prediction accuracy of 10% inside the error bar. The relationship can be expressed as Eq. (1) (Ajimotokan et al., 2019):

$$HHV\ (\text{MJ/kg}) = 0.1846\, V_m + 0.0352 F_c, \tag{1}$$

where HHV is calorific or heating value, F_c is fixed carbon, and V_m is volatile matter.

Volatile matter

One sample of each briquette formation was placed in a container of known mass and measured. After which, it underwent a drying process until a consistent mass was achieved. Following this, the samples were subjected to a temperature of 900 °C in the furnace for 7 minutes and weighed again after cooling. The measurement of volatile matter (V_m) was then determined as the percentage of mass lost using the formula described in Eq. (2), which is expressed as follows (Ajimotokan et al., 2019):

$$Vm\ (\text{wt.\%}) = \frac{B-C}{B} \times 100\%, \tag{2}$$

where B is the weight of the dried sample and C is the weight of the furnace-dried sample.

Fixed carbon

The percentage fixed carbon of each sample of briquette was estimated using the relation in Eq. (3) (Ajimotokan et al., 2019):

$$Fc\ (\text{wt.\%}) = 100 - (Vm + Mc + Ac), \tag{3}$$

where Fc is the (wt.%) fixed carbon obtained for each briquette sample, Vm is the (wt.%) volatile matter obtained for each briquette sample, and Mc is the moisture obtained for each briquette sample,

Ash content

For each type of briquette formation, an initial measurement was taken on a single sample, after which it was put into a crucible whose weight was known and then dried in an oven until a consistent mass was reached. Following this, the samples were exposed to a temperature of 800 °C in a furnace for five hours and were subsequently weighed once they had cooled down. The percentage of mass lost during this process was then employed to compute the ash content, using the formula presented in Eq. (4), as expressed below (Ajimotokan et al., 2019):

$$Ac\ (\text{wt.\%}) = \frac{D}{B} \times 100\%, \tag{4}$$

where Ac is the percentage ash content, D is the weight of ash (furnace dried), and B is the weight of the oven-dried sample.

Moisture content

The moisture content of each briquette sample was obtained by taking the weight (W1) of the briquette sample immediately after it was removed from the mold and after it had been sun-dried (W2) for seven days, and using the relation in Eq. (5) (Ajimotokan et al., 2019):

$$Mc\ (\text{wt.\%}) = \frac{W1-W2}{W1}. \tag{5}$$

Compressive strength

The compressive strength of the briquette samples shows their durability and was determined by subjecting each to a compressive test. The compressive strength of a material was carried out to determine the compressive force per unit area the material can withstand. For this experiment, a flexural test machine of 100 kN capacity was used. The briquettes were, respectively inserted under the crushing point of the machine. The machine was operated manually with a hydraulic press handle to generate enough compressive pressure and the meter observed. At maximum compressive strength, the meter stops reading as the briquette samples deforms. The meter reading at this point of deformation which was a measure of force exerted upon the briquettes by the machine was recorded.

Dry density

The dry density of the briquettes was determined using the following procedure: Briquettes were fully dried in an oven at 105 °C for 24 hours to remove any moisture. The mass of each dry briquette was measured using a laboratory balance with a precision of 0.01 g. The dimensions of each briquette (diameter and height) were measured using a vernier caliper with a precision of 0.01 mm. The dry density was calculated using the Eq. (6):

Table 1. Moisture content and dry density for briquette production, E1–Paper and charcoal dust using starch as a binder

S/N	% of industrial starch added	Wet mass of briquette (g)	Dry mass of briquette (g)	Moisture content (%)	Dry density (g/cm^3)
1	100	1,700	784	1.1683	0.3469
2	120	2,030	810	1.5061	0.3584
3	140	2,400	825	1.9090	0.3650
4	160	2,770	883	2.1370	0.3907
5	180	3,100	896	2.4598	0.3964

Table 2. Moisture content and dry density for briquette production E2–Paper, charcoal, and sawdust using starch as binder

S/N	% of industrial starch added	Wet mass of briquette (g)	Dry mass of briquette (g)	Moisture content (%)	Dry density (g/cm^3)
1	100	1,865	862.4	1.1625	0.3815
2	120	2,250	891.0	1.5251	0.3942
3	140	2,250	907.5	1.8099	0.4015
4	160	2,935	971.3	2.0217	0.4297
5	180	3,300	985.6	2.3482	0.4361

Table 3. Moisture content and dry density for briquette production E3–Sawdust and charcoal dust using starch as binder

S/N	% of industrial starch added	Wet mass of briquette (g)	Dry mass of briquette (g)	Moisture content (%)	Dry density (g/cm^3)
1	100	1,615.0	774.80	1.1683	0.3295
2	120	1,928.5	769.50	1.5061	0.3404
3	140	2,280 .0	783.75	1.9090	0.3467
4	160	2,631.5	838.85	2.1370	0.3711
5	180	2,945.0	851.20	2.4598	0.3766

Table 4. Moisture content and dry density for briquette production E4–Wastepaper and sawdust using starch as binder

S/N	% of industrial starch added	Wet mass of briquette (g)	Dry mass of briquette (g)	Moisture content (%)	Dry density (g/cm^3)
1	100	1,745.0	745.20	1.1733	0.3295
2	120	1,928.5	733.50	1.6061	0.3404
3	140	2,780.0	773.75	1.8110	0.3467
4	160	2,451.5	822.37	1.9370	0.3711
5	180	2,845.0	862.20	2.1258	0.3766

$$\text{Dry density } (g/cm^3) = \text{Mass of dry briquette } (g)/\text{volume of briquette } (cm^3). \tag{6}$$

RESULTS AND DISCUSSIONS

Moisture Content and Dry Density

Table 1, **Table 2**, **Table 3**, and **Table 4** show the values of the percentage moisture content and dry density of the three formations of the fuel briquettes produced. From the results, it can be seen that for each 100%, 120%, 140%, 160%, and 180% of binders used, the E2 formation (charcoal dust, sawdust, and paper) gave the highest dry density values in g/cm^3 followed by E1 briquette formation (charcoal dust and paper) and the least being the E3 briquette formation (charcoal dust and sawdust). Also, the values for the percentage moisture content are almost the same for the charcoal dust-paper and charcoal-sawdust briquette formations.

From the graph in **Figure 5**, it can be seen that the percentage moisture content is proportional to the dry density, while the percentage binder used is proportional to both qualities. Therefore, the E3 sample (charcoal dust and sawdust) is the optimum among other briquette formations for moisture content and dry density. The results for the moisture content and dry density of the briquettes produced:

1. E1–Wastepaper and charcoal dust

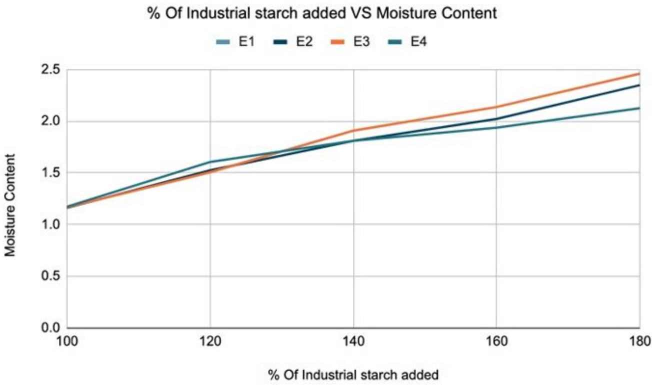

Figure 5. A graph of % of industrial starch added and moisture content for briquette production (Source: Authors' own elaboration)

2. E2–Wastepaper, charcoal dust and sawdust
3. E3–Sawdust and charcoal dust
4. E4–Wastepaper and sawdust.

They are shown in **Table 1**, **Table 2**, **Table 3**, and **Table 4**, respectively.

The graphical representation of the moisture content for E1–Paper and charcoal, E2–Paper, charcoal and sawdust, E3–Sawdust and charcoal, and E4–Wastepaper and sawdust are shown in **Figure 5**.

Table 5. Percentage of volatile matter, percentage of fixed carbon and calorific/heating value of briquettes for E1–Paper and charcoal

% binder used	% volatile matter	% fixed carbon	Heating value (kJ/kg)	Ash content (%)
100	79	15	32,927.1	5.322
120	84	16	32,930.4	5.245
140	85	21	32,942.2	6.133
160	83	20	32,951.7	6.897
180	80	24	32,962.6	7.124

Table 6. Percentage of volatile matter, percentage of fixed carbon and calorific/heating value of briquette for E2–Sawdust and charcoal

% binder used	% volatile matter	% fixed carbon	Heating value (kJ/kg)	Ash content (%)
100	85	18	34,469.1	5.433
120	84	15	34,471.3	5.357
140	85	14	34,475.4	6.653
160	83	12	34,478.7	5.974
180	87	14	34,482.5	7.656

Table 7. Percentage volatile matter, percentage fixed carbon and calorific/heating value of briquettes for E3–Sawdust and charcoal dust

% binder used	% volatile matter	% fixed carbon	Heating value (kJ/kg)	Ash content (%)
100	79	15	32,927.1	5.545
120	84	16	32,930.4	6.213
140	85	21	32,942.2	6.544
160	83	20	32,951.7	6.886
180	80	24	32,962.6	7.346

Table 8. Percentage volatile matter, percentage fixed carbon and calorific/heating value of briquettes for E4–Wastepaper and sawdust

% binder used	% volatile matter	% fixed carbon	Heating value (kJ/kg)	Ash content (%)
100	73	14	33,224.1	5.166
120	81	16	32,345.4	5.322
140	81	18	32,942.2	5.775
160	84	20	32,561.7	6.356
180	86	22	32,962.6	7.223

Combustion Properties Result

Table 5, **Table 6**, **Table 7**, and **Table 8** show the heating or calorific value of the fuel briquettes together with the values of the percentage volatile matter, ash content, and percentage fixed carbon. It can be observed from the results that for each 100%, 120%, 140%, 160%, and 180% of binders used, the E2 sample, charcoal dust, sawdust, and paper had the highest calorific values in kJ/kg, followed by E1, charcoal dust and paper and then E3, charcoal dust and sawdust. The values for the percentage of volatile matter and the percentage of fixed carbon follow the same trend. From these values, it can be stated that the percentage of binder used is proportional to the heating or calorific value.

Also, from **Figure 6**, it can be observed that the optimum sample for combustion property is the E2 briquette sample.

The results for the combustion properties such as volatile matter, fixed carbon, calorific/heating value, and ash content for the various briquette samples are tabulated.

The graphical representation of the ash content and combustion properties for E1–Paper and charcoal, E2–Paper, charcoal, and sawdust, E3–Sawdust and charcoal, E4–Wastepaper and sawdust is shown in **Figure 6**.

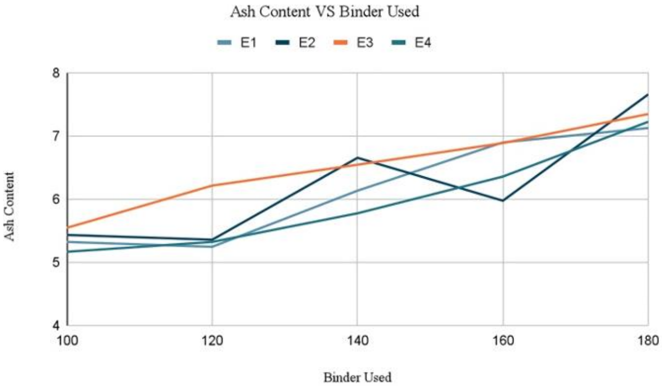

Figure 6. Combustion properties–Graph of binder against ash content for the briquette *x*- and *y*-axis in percentage (%) (Source: Authors' own elaboration)

Water Boiling Test, Ignition Time, and Burning Rate

The water boiling test was carried out to determine the burn rate and efficiency of the produced briquettes using water of 1,000 ml volume. The water was boiled with the briquettes produced. Comparing the time taken to boil the water and the burning characteristics of briquettes is important in assessing

Table 9. Burn rate of briquettes for 1,000 ml water and 180% binder

Briquette sample	Mass consumed (g)	Ignition time (min)	Water boiling test (min)	Burning time (g/min)
E1	61	0.32	32.32	1.89
E2	66	0.45	25.03	2.64
E3	65	1.06	18.13	3.59
E4	68	1.43	14.37	4.73

Table 10. Result of compressive test

Formation	E1 formation	E2 formation	E3 formation	E4 formation
Diameter (mm)	105.000	105.000	105.000	105.000
Compression force (kN)	100.000	100.000	100.000	100.000
Weight (g)	79.330	121.450	113.220	82.360
Compressive strength (Mpa)	0.654	0.972	0.905	0.685

Table 11. Design experimental runs for E1–Paper and charcoal

Run	Paper (grams)	Charcoal (grams)
1	200.00	100.00
2	150.00	79.29
3	200.00	200.00
4	100.00	200.00
5	100.00	100.00
6	150.00	150.00
7	79.29	150.00
8	220.71	150.00

Table 12. Design experimental runs for E2–Paper, sawdust, and charcoal

Run	Saw dust (grams)	Charcoal (grams)	Paper (grams)
1	150.00	234.09	150.00
2	100.00	200.00	200.00
3	150.00	65.91	150.00
4	65.91	150.00	150.00
5	150.00	150.00	234.09
6	200.00	100.00	100.00
7	100.00	100.00	100.00
8	150.00	150.00	150.00

Table 13. Design experimental runs for E3–Sawdust and charcoal

Run	Sawdust (grams)	Charcoal (grams)
1	200.00	200.00
2	150.00	150.00
3	220.71	150.00
4	150.00	150.00
5	200.00	100.00
6	150.00	79.29
7	100.00	100.00
8	150.00	150.00

Table 14. Design experimental E4–Paper and sawdust

Run	Paper (grams)	Sawdust (grams)
1	150.00	234.09
2	100.00	200.00
3	150.00	65.91
4	65.91	150.00
5	150.00	150.00
6	200.00	100.00
7	100.00	100.00
8	150.00	150.00

both the performance of briquettes and their likely acceptance in domestic fireplaces.

From **Table 9**, it was observed that the higher the mass of water consumed, the higher the ignition time and burning time. Therefore, an increase in the percentage of water causes the briquettes to ignite late, producing less smoke with a high rate of combustion. However, these briquettes produced had a fast rate of combustion due to their lower density and loose particles.

The result for the ignition time test, water boiling test, and burn rate for using 1,000 ml water and binder of 180% binder for the different briquette samples is shown in **Table 9**.

In general, it was observed that almost all the briquettes did not burn too well until they were hot enough to support an open flame.

Compressive Test Result

Table 10 shows the result for the compressive strength of briquettes generated from the compressive strength analysis with a uniform compression force of 100 kN and a binder of 180% binder. **Table 10** showed that the diameter and compression force for the briquette formation sample are constant. The weights for the E1 sample, E2 sample, E3 sample, and E4 sample are 79.33 g, 121.45 g, 113.22 g, and 82.36 g, respectively. This indicated that the E2 briquette formation has the optimum compressive test result.

Table 10 shows the result for the compressive strength of briquettes generated from the compressive strength analysis with a uniform compression force of 100 kN and a binder of 180% binder. Compressive strength was calculated using the Eq. (7) and Eq. (8):

$$Compressive\ strength\ (MPa) = \frac{Compression\ force\ (kN)}{Cross{-}sectional\ area\ (mm\text{^}2)}. \tag{7}$$

$$Area = \pi\left(\frac{Diameter}{2}\right)^2. \tag{8}$$

Experimental Design Runs of Produced Briquettes

The experimental design runs for E1–Paper and charcoal, E2–Paper, charcoal, and sawdust, E3–Sawdust and charcoal, and E4–Paper and sawdust are shown in **Table 11**, **Table 12**, **Table 13**, and **Table 14**, respectively.

Table 15. Fixed cost

Fixed cost	
Briquette mold	= N500.00
Pot stand	= N500.00
Drier	= N7,000.00
Compression device	= N7,000.00
Total fixed cost	= N18,500.00

Table 16. Operating cost

Operating cost	
Transportation of materials	= N3,000.00
Overhead	= N5,000.00
Total operating cost	= N8,000.00

Note. Material used e.g., sawdust, paper, charcoal, and water are all gotten at no cost because they are considered as waste

Table 17. Salvage value cost

Salvage value cost	
Briquette mold	= N2,500.00
Pot stand	= N300.00
Drier	= N5,500.00
Compression device	= N5,500.00
Total salvage value cost	= N13,800.00

Table 18. Optimized values of briquettes produced from paper and charcoal

% binder used	**Heating value (kJ/kg)**
100	32,927.1
120	32,930.4
140	32,942.2
160	32,951.7
180	32,962.6

Cost Analysis

A cost analysis was carried out on the briquettes produced, as follows.

Table 15 shows fixed cost.

Table 16 shows operating cost.

Table 17 depicts salvage value cost.

$$\text{Total cost of producing 100 briquettes} = N18{,}500 + N8{,}000\text{-}N13{,}800 = N12{,}700. \tag{9}$$

The cost of one briquette will therefore be $\frac{12{,}700}{100} = N127$.

The cost analysis presented provides a practical understanding of the economic viability of briquette production from repurposed waste materials. It highlights several key findings that correspond with the research objectives of exploring sustainable and cost-effective energy alternatives. The cost analysis reveals that while there are upfront fixed costs associated with establishing the production process, the ongoing operational costs are relatively modest. The salvage value costs further indicate that the investment in equipment holds residual value, contributing to the long-term sustainability of the briquette production venture.

Furthermore, the negligible cost of raw materials, sourced from waste products such as sawdust, paper, charcoal, and water, reinforces the environmentally friendly and cost-effective nature of biomass briquettes.

Table 19. Optimized values of briquettes produced from paper, charcoal, and sawdust

% binder used	**Heating value (kJ/kg)**
100	34469.1
120	34471.3
140	34475.4
160	34478.7
180	34482.5

Table 20. Optimized values of briquettes produced from charcoal and sawdust

% binder used	**Heating value (kJ/kg)**
100	34,469.1
120	34,471.3
140	34,475.4
160	34,478.7
180	34,482.5

Table 21. Optimized values of briquettes produced from paper and charcoal

% binder used	**Heating value (kJ/kg)**
100	31,945.1
120	32,330.4
140	32,672.2
160	32,951.7
180	32,992.6

Statistical and Optimization of the Energy Value of the Briquette Produced

The energy, heating, and calorific values of the briquette samples produced are presented in **Table 18**, **Table 19**, **Table 20**, and **Table 21**. These values are subject to variation based on the process parameter combination utilized. To obtain the optimal energy value, a quadratic equation was formulated using the design expert software. Eq. (10) establishes a correlation between the coded variable and the energy value.

$$Y=5.64+0.078X+0.15Y-0.29Z-0.71XY+0.069XZ-0.55X^2-0.69Y^2-0.59Z^2. \tag{10}$$

The quadratic model illustrates how the energy value is influenced by three factors, denoted as X, Y, and Z. This model encompasses both single-factor and multi-factor coefficients, which respectively represent the impact of individual factors and the combined effect of multiple factors. Positive terms signify synergistic effects, while negative terms indicate antagonistic effects. The overall model's adequacy is supported by a substantial F-value of 1939.97 obtained from the sequential model sum of squares (**Table 22**). The statistical analysis reveals a high regression coefficient, with $R^2 = 0.9994$, along with a modified RZ value of 0.9989, closely aligning with the expected R^2 value of 0.9986, thus confirming the model's adequacy. The coefficient of variation was found to be 0.91 percent. As the adequate precision value of 116.979 exceeds 4, it indicates an adequate signal-to-noise ratio, allowing the model to navigate within the design space. In conclusion, it is important to note that among the various samples produced, the 2-briquette sample exhibits the highest/optimal heating value.

Table 22. Significance of regression coefficients of energy value for paper, charcoal, and sawdust briquettes with a starch binder

Source	Degree of freedom	Sum square	Mean square	F-value	p-value (prob > F)
Model	9.0	25.56000	2.84000	1939.970	< 0.0001
X	1.0	0.09800	0.09800	66.710	<0.0001
Y	1.0	0.35000	0.35000	235.790	< 0.0001
Z	1.0	1.35000	1.35000	926.210	< 0.0001
XY	1.0	3.99000	3.99000	2725.980	< 0.0001
XZ	1.0	0.03800	0.03800	25.830	0.0005
YZ	1.0	0.02500	0.02500	17.290	0.002
X^2	1.0	7.54000	7.54000	5150.860	< 0.0001
Y^2	1.0	11.80000	11.80000	8062.250	< 0.0001
Z^2	1.0	8.61000	8.61000	5880.460	< 0.0001
Residual	10.0	0.01500	0.00146		
Lack of fit	5.0	0.00231	0.00461	0.190	0.9553
Cor. total	19.0	25.57000			

Note. Mean = 4.19; CV% = 0.91; Standard deviation = 0.038; PRESS = 0.036; Adj. R^2 = 0.9989; R^2 = 0.9994; Adeq. precision = 116.979; & Pred. R^2 = 0.9986

The galvanized energy of biomass briquettes was effectively optimized through the utilization of the design expert program. To achieve a quadratic model, an experimental design in response surface methodology (RSM) called central composite design was employed. This approach allowed for precise control and analysis of the briquettes, leading to a thorough understanding of their properties and optimal performance.

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j. \qquad (10)$$

Results for optimization of E1 briquettes sample

Table 18 shows optimized values of briquettes produced from paper and charcoal.

Results for optimization of E2 briquettes sample

Table 19 shows optimized values of briquettes produced from paper, charcoal, and sawdust.

Results for optimization of E3 briquettes sample

Table 20 shows optimized values of briquettes produced from charcoal and sawdust.

Results for optimization of E4 briquettes sample

Table 21 shows optimized values of briquettes produced from paper and charcoal.

Table 22 shows significance of regression coefficients of energy value for paper, charcoal, and sawdust briquettes with a starch binder.

CONCLUSION

Briquettes made from biomass have typically shown good prospects as a potential source of fuel or replacement for conventional fuel. This research was conducted to investigate the properties, performance as well and optimization of the produced briquettes. The optimization of the energy values of paper, sawdust, and charcoal composite briquettes using starch as a binder was done using RSM and a design expert. The data obtained, and the optimization of the briquettes produced from paper, charcoal, and sawdust combination was done using the design expert software program. From the experiment, it was seen that the briquettes made from the E2-paper, charcoal, and sawdust combination gave a better combustion capacity with heating values of 34,469.1 kJ/kg, ash content of 7.656%, and volatile matter of 87% for 180% binder.

Also, from the result obtained, it can be confirmed that the briquettes made from the E2–Paper, charcoal, and sawdust gave a higher dry density value of 985.6g. The cost analysis carried out shows that briquette not only is a better and more reliable alternative fuel source to the high-rising conventional cooking fuel available but also reduces the problem associated with rapid deforestation as well as environmental degradation and pollution. The results from this study have shown that the use of paper, sawdust, and charcoal to produce biomass briquettes may be a viable way to reduce various effects of environmental pollution, reducing cost coupled with the problem of degradation of natural resources.

Future research should expand beyond the current biomass mix by exploring options like rice straw, hay, and garden residues, while simultaneously investigating adaptations for diverse burning systems like stoves, boilers, and kilns to improve burner efficiency. Optimizing mixing through potential mechanization and exploring further particle size variations beyond 2 mm can expedite production and refine briquette properties.

Finally, developing efficient handling and transportation systems for readily available raw materials will optimize the logistical aspects of the briquette value chain, paving the way for wider-scale adoption in Nigeria and beyond.

Author contributions: EDE: conceptualization, data curation, formal analysis, investigation, visualization, writing – original fraft; **TUM:** data curation, formal analysis, investigation, visualization, writing – original draft, writing – review & editing; **EMA:** methodology; **OA:** project administration, validation; **AAG:** formal analysis, supervision; **AAO:** resources; **PMC:** methodology; **FNA:** data curation, investigation, resources, visualization; **JNE:** project administration. All co-authors agree with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that the study did not require approval from an ethics committee since the study did not involve human participants nor the sacrifice of animals and the data used were author-generated or collected from secondary sources in the public domain that does not collect or store identifiable data. The highest ethical principles of scientific publications were followed during the study.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

REFERENCES

Achakulwisut, P., Erickson, P., Guivarch, C., Schaeffer, R., Brutschin, E., & Pye, S. (2023). Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions. *Nature Communication, 14*, 5425. https://doi.org/10.1038/s41467-023-41105-z

Adamu, M. B., Adamu, H., Ade, S. M., & Akeh, G. I. (2020). Household energy consumption in Nigeria: A review on the applicability of the energy ladder model. *Journal of Applied Sciences and Environmental Management, 24*(2), 237-244. https://doi.org/10.4314/jasem.v24i2.7

Ajimotokan, H. A., Ehindero, A. O., Ajao, K. S., Adeleke, A. A., Ikubanni, P. P., & Shuaib-Babata, Y. L. (2019). Combustion characteristics of fuel briquettes made from charcoal particles and sawdust agglomerates. *Scientific African, 6*, Article e00202. https://doi.org/10.1016/j.sciaf.2019.e00202

Aransiola, E. F., Oyewusi, T. F., Osunbitan, J. A., & Ogunjimi, L. A. O. (2019). Effect of binder type, binder concentration and compacting pressure on some physical properties of carbonized corncob briquette. *Energy Reports, 5*, 909-918. https://doi.org/10.1016/j.egyr.2019.07.011

Asamoah, B., Nikiema, J., Gebrezgabher, S., Odonkor, E., & Njenga, M. (2016). *A review on production, marketing and use of fuel briquettes*. International Water Management Institute. https://doi.org/10.5337/2017.200

European Commission. (2022). *Sustainable use of non-food biomass for energy: State of the art and future prospects*. https://www.s2biom.eu/images/Publications/S2biom_review_state-of_the_art_Final.pdf

Garrido, M., Conesa, J., & Garcia, M. (2017). Characterization and production of fuel briquettes made from biomass and plastic wastes. *Energies, 10*(7), Article 850. https://doi.org/10.3390/en10070850

Hidayah, N., & Syafrudin. (2018). A review on landfill management in the utilization of plastic waste as an alternative fuel. *E3S Web of Conferences, 31*, Article 05013. https://doi.org/10.1051/e3sconf/20183105013

IEA. (2023). Bioenergy market report 2023. *International Energy Agency*. https://www.iea.org/reports/bioenergy-2

Jekayinfa, S. O., Orisaleye, J. I., & Pecenka, R. (2020). An assessment of potential resources for biomass energy in Nigeria. *Resources, 9*(8), Article 92. https://doi.org/10.3390/resources9080092

Kurmi, O. P., Lam, K. B. H., & Ayres, J. G. (2012). Indoor air pollution and the lung in low- and medium-income countries. *European Respiratory Journal, 40*(1), 239-254. https://doi.org/10.1183/09031936.00190211

Mainimo, E. N., Okello, D. M., Mambo, W., & Mugonola, B. (2022). Drivers of household demand for cooking energy: A case of Central Uganda. *Heliyon, 8*(3), Article e09118. https://doi.org/10.1016/j.heliyon.2022.e09118

Maurya, P. K., Mondal, S., Kumar, V., & Singh, S. P. (2021). Roadmap to sustainable carbon-neutral energy and environment: Can we cross the barrier of biomass productivity? *Environmental Science and Pollution Research, 28*(36), 49327-49342. https://doi.org/10.1007/s11356-021-15540-8

Nhuchhen, D., & Afzal, M. (2017). HHV predicting correlations for torrefied biomass using proximate and ultimate analyses. *Bioengineering, 4*(4), Article 7. https://doi.org/10.3390/bioengineering4010007

Nwabue, F. I., Unah, U., & Itumoh, E. J. (2017). Production and characterization of smokeless bio-coal briquettes incorporating plastic waste materials. *Environmental Technology & Innovation, 8*, 233-245. https://doi.org/10.1016/j.eti.2017.02.008

Odame, M. L., & Amoah, A. (2023). Household exposure to the risk of cooking smoke: Evidence from sub-Saharan Africa. *Energy Nexus, 12*, Article 100256. https://doi.org/10.1016/j.nexus.2023.100256

Onukak, I., Mohammed-Dabo, I., Ameh, A., Okoduwa, S., & Fasanya, O. (2017). Production and characterization of biomass briquettes from tannery solid waste. *Recycling, 2*(4), Article 17. https://doi.org/10.3390/recycling2040017

Perea-Moreno, M.-A., Samerón-Manzano, E., & Perea-Moreno, A.-J. (2019). Biomass as renewable energy: Worldwide research trends. *Sustainability, 11*(3), Article 863. https://doi.org/10.3390/su11030863

Rezania, S., Din, M. F., Kamaruddin, S. F., Taib, S. M., Singh, L., Yong, E. L., & Dahalan, F. A. (2016). Evaluation of water hyacinth (eichhornia crassipes) as a potential raw material source for briquette production. *Energy, 111*, 768-773. https://doi.org/10.1016/j.energy.2016.06.026

Thacher, J. D., Emmelin, A., Madaki, A. J. K., & Thacher, T. D. (2013). Biomass fuel use and the risk of asthma in Nigerian children. *Respiratory Medicine, 107*(12), 1845-1851. https://doi.org/10.1016/j.rmed.2013.09.009

Urra, J., Alkorta, I., & Garbisu, C. (2019). Potential benefits and risks for soil health derived from the use of organic amendments in agriculture. *Agronomy, 9*(9), Article 542. https://doi.org/10.3390/agronomy9090542

Velusamy, S., Subbaiyan, A., & Thangam, R. S. (2021). Combustion characteristics of briquette fuels from sorghum panicle-pearl millets using cassava starch binder. *Environmental Science and Pollution Research, 28*(17), 21471-21485. https://doi.org/10.1007/s11356-020-11790-0