

# Performance of Briquettes Produced from Sawdust of *Gmelina Arborea* and Montmorillonite Clay as Binder

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## Abstract

Clay had been used as binders in briquetting research activities, however their performance characterization in terms of quality and combustion have not been clearly evaluated or reported. This study therefore provide a qualitative evaluation of briquettes produced using sawdust of *Gmelina arborea* and montmorillonite clay. Sun-dried sawdust (~9% moisture contents) obtained from sawmills in Ishiagu, Ebonyi State were mixed with processed clay samples collected from earthen pot mould sites characterized, then used in briquette production using five mixing ratios of 90:10, 80:20, 70:30, 60:40, & 50:50 (weight/weight)% and standard test procedures for characterization. Data were analyzed using SPSS at  $p < 0.05$  significance levels. The quality characteristics of clay briquettes compared favourably with other binder types with an increase in performance as binder concentration increases. The briquettes combustion performance in air and stove are significantly affected by the agglomerated non-combustible clay particle impregnating the biomass matrix. Best combustion performance occurred at 10% binder concentration with no significant value-addition to ignition time, flame combustion and heating values. Above 10% binder addition, briquettes failed self-ignition, flame combustion, and retarded char combustion tests. This implied clay is a poor performing binder and the associated briquette are combustibly poor.

## Introduction

Binders are additive materials (naturally occurring or externally prepared) added to biomass feedstock to improve the agglomeration and structural properties and retain the shape, strength and quality of briquette (Obi et al., 2022). Ideal binders possess characteristics such as good binding capacity, good water retention, and water-soluble, mechanically and chemically stable and inexpensive. Research studies on binders focused on the development of more sustainable, combustible, better performing and cheaper binders, with diverse improved effects on briquette quality (Chin & Siddiqui, 2000, Kaliyan & Morey, 2009). The choice of binder in briquetting depended on factors such as bonding

strength, extent of smoke emissions, and performance during combustion, eco-friendliness and affordability.

Different materials primarily classified as either organic or inorganic (Obi et al., 2022) have been used in different densification applications either as binders, lubricants, additives or both combined (Davies, 2015). Conventionally, binder selection for feedstock agglomeration are dependent on both experience and elementary tests (Blesa et al., 2003). However, the performance of any selected binder for briquetting applications affects the properties of the briquette.

The application of composites as suitable alternative to the commonly used agricultural binders such as cassava starch and wood based binders like paper, is gaining increased research interests today

owing to the some inherent disadvantages of some other existing biological binders including non-availability in commercial quantities, low shelf life and smokiness. Utilization of clay as binder in briquetting had been a recurring research activity over decades due to a relatively cheap cost and plastic characteristics with better mechanical properties lower combustion efficiency than other base materials (Gopakumar, 2002; Andrade et al., 2011; Shu et al., 2012; Obi et al., 2022).

Clay predominately composed of fine-grained silica ( $\text{SiO}_2$ ), Alumina ( $\text{Al}_2\text{O}_3$ ) and water ( $\text{H}_2\text{O}$ ) plus appreciable concentrations of oxides of iron, alkali and alkaline earth, and crystalline minerals such as quartz, feldspar, and mica, with particle sizes less than 0.002 mm (Folaranmi, 2009). For instance Onchieku et al., (2012) produced charcoal briquettes from a mixture of bagasse and clay as binder. Davies (2015) reported the use of inorganic binders such as carbon methylcellulose carbon methylcellulose, sodium silicate and pretreated starch on alfalfa. However, most of these research outcomes dwelt extensively on physical and mechanical characteristics and less significant reports on the performance of these briquettes in terms of combustion characteristics.

## Materials and Methods

### Feedstock and binder materials

The experimental lignocellulose material is sawdust of *Gmelina arborea* species due to its enormous volume generated annually, especially in Nigeria (Okoroigwe, et al., 2012), and their utilization in pelletizing, briquetting and other energy heating applications (Obi et al., 2022). Obi et al., (2022) broadly classified binders as organic and inorganic and gave clay as common example of inorganic binder. Other researchers (Osuwan and Bunyakiat, 1987; Onchieku, et al., 2012; Otieno, and Otieno, 2020) had used clay as binders in briquetting experiments, providing a justification for the utilization of more predominant montmorillonite clay (Udeagbara et al., 2019) in this experiment.

### Briquetting apparatus

The experimental briquetting machine (Figure 1a) is a developed four-piston hydraulic press provided with two-pocket spring balances symmetrically positioned beside the a five-ton hydraulic jack to measure load applied in compression and also assists the retraction of base plate when pressure is relieved from the jack when the vent lock is open. Four pistons were dynamically positioned and attached to a squared-shape flat base-plate, 3 mm thick. Each piston is welded to a flat piston-base plate (2mm thick) using a 20mm diameter pipe at both ends respectively. Each cylinder was coupled to the frames using a 12mm bolt and nut. Material fed into the

cylinder is compressed by the piston to produce briquettes.

### Combustion apparatus

A biomass stove (Figure 1b) consists of two compartments; the combustion chamber lined with clay (where the briquettes are burnt) and the ash collection compartment. The main combustion chamber was separated from the secondary air inlet spout, and ash compartment using a strong wire-mesh grate supported by five pieces of 6.25mm rods embedded into the clay lining. The clay lining (25mm thick) provides insulation for the stove and also insulates the outer mild steel plate to reduce heat loss to the environment. The top dimensions of the combustion chamber is 486.7mm x 135.0mm and the base dimension of 10mm x 10mm, designed to accommodate a minimum of 4 pieces of briquettes of 50mm and 55mm average diameter and height respectively. The volumetric capacity of the combustion chamber is 518.6 cm<sup>3</sup>.

## Experimental methodologies

### Feedstock sample collection and preparation

The sawdust samples were obtained from sawmill located along Okue road in Ishiagu. The materials were sorted for foreign matter contents and used as received, requiring no size reduction. The materials were sundried to reduce the moisture content to 8-10% dry basis, reported as favourable for the production of stable briquettes (Davies, 2015).

### Binder material and preparation experiments

The clay (Montmorillonite) sample was collected from the earthen pot site at Amaeke, Ishiagu. The sample was pounded in wooden rammer to improve the plasticity, then dissolved in water and sieved with a 400-micron sieve mesh to filter sand and organic matter residues. The fine filtrate solution was allowed to settle for about 3-5days, then decanted to obtain clayey suspension. The clayey suspension was sundried to obtain clay cakes, which was again ground and sieved to obtain fine clay powder (approximate 125 microns), which was then stored in polythene (to prevent moisture absorption) preparatory for utilization in briquette production.

### Materials mixing and ratios

To determine the mixing ratios, two major factors were taking into consideration which are: breakdown time on materials, essential for material agglomeration (Amin et al., 2017) and the proportion of different materials on binder which significantly affect the final product strength and combustion performances. The proportions of feedstock mix to binder material ratios



Figure 1. The hydraulic briquetting machine (a) and (b) combustion stove.

were based on weight proportion while the mix ratio was determined by measuring out proportions (in grams) of *Gmelina* sawdust and binder to give the percentage ratio of biomass-binder mix (i.e., 90:10, 80:20, 70:30, 60:40 and 50:50 respectively) according to Yazdani and Ali, (2015).

#### **Machine operating conditions**

Two operating conditions considered during briquette production which are; residence time and operating pressure. A residence time of 5 minutes was allowed for the compressed material to remain under compressive load before ejection according to (Olorunnisola, 2007). For this experiment, an axial load of 45 kg (441.45 N) was applied to each cylinder of diameter 0.8m yielding a corresponding pressure of 169.80 kPa for briquette production.

#### **Experimental procedure, variables and design**

An average of three (3) replicate data samples obtained from measured variables such as percentage mass of *Gmelina*, binder concentration (%), and response variables (compressed density i.e. density measured immediately after extrusion from the mould, and relaxed density i.e. density measured after 30 days of curing). The effects of the interactions of each variable were estimated using factorial experimental design and analysis of variance of mean values for each level of interaction (Muazu & Stegemann, 2015).

#### **Characterization experiments**

##### **Raw material particle size**

Material characterisation parameters determined include the particle size distribution, particle density, geometric mean sizes, and particle moisture. Particle size distribution plays a critical role in mixing performance determination, and densification. Therefore, particle size distribution and geometric mean diameter were determined using ASAE Standard S319.4

test procedures (Adapa et al., 2009, Karunanithy, et al., 2012) in three replicates for analytics. This analysis is essential to the densification process and quality assurance program. Due to the heterogeneous nature of the sawdust samples, classification was based on oversized, coarse, pin and fine fractional sizes. The particle size characteristics is important to briquette quality determination.

##### **Particle density determination**

The density of loose biomass was determined according to ASTM D7481-09 standard. Sawdust was poured into a 100 cm<sup>3</sup> graduated volumetric cylinder to marked volume and weighed. The particle density was evaluated using weight-volume ratio relationship (Maharani et al., 2010).

##### **Clay characterization**

Characterization experiments were carried out at the hydraulics laboratory of the Federal College of Agriculture Ishiagu. The rheological properties such as plastic viscosity, yield point and apparent viscosity as well as pH value of the clay suspension are essential characteristics measured to determine clay performance. Rheological experiment API RP-13B Standard procedures were employed at the laboratory to determine the clay rheological properties. The viscosity and torque angle percentage was measured using an NDJ-8S viscometer at 12m/s, and the 58.5 percentage meter mark was 1461.5 mPa.s while the pH value was slightly higher at (6.35) was measured with a conductivity meter. The experiment was performed at an ambient temperature condition of 30°C, using an L2 spindle operating at 12.0 rpm. To determine the rheological properties clay, suspended sample of clay-to-water (25 g: 350 ml) was thoroughly stirred at a constant speed according to Nweke et al., (2015). The homogeneous mixture of the clay and water was then poured into the viscometer sample plastic cup, and agitated at specified speeds (12m/s) for a few seconds for stabilization and then for 10 minutes). The

viscometer automatically measures the viscosity (mPa.s), gel strength (torque value percentage), and the yield point (YP).

### **Briquette production**

Figure 2 showed the pictures of briquette samples produced from mixtures of *G. arborea* sawdust and clay binders at 5 different binder levels (Kathuria and Grover, 2012). The charged materials were compressed in the mould and left for 5 minutes under load before ejection. After ejection, the briquettes were weighed, and left to dry and cure for about 30 days to further reduce its moisture content to an equilibrium state for stability, storage and evaluation.

### **Briquette characterization**

Briquette characterization tests were carried out using scientific standard testing methods and analysis which include physical, mechanical and combustion tests. The methods employed in the measurement of

these variables are summarised in Table 1. Measured variables include; density, compressive strength, durability, water absorptivity, shattering and abrasion resistance.

### **Briquettes combustion performance tests**

Combustion performance explained the response of briquette to time taken for ignition, flame propagation, burn rates and smoke emission characteristics. These characteristics were investigated by burning briquette in free air (Figure 3). Briquette ignition timing was achieved using a stopwatch to time how long it take for each briquette placed on a steel wire mesh on a hollow dish to ignite. Flame propagation was evaluated by measuring the height of flame produced from each briquette. Briquette burn rate was determined by mass reduction for each briquette as it burns. Each briquette was weighed and recorded till the briquette mass had been reduced to between 3-5% of its initial weight. Smokiness was evaluated on the basis of observed smoke generated during flame burning.



Figure 2. Sample briquettes produced at different binder concentrations.

Table 1. Standard tests for briquette characterisation and references

Briquette characteristics	Method summary standard test	Reference
Physical	Gravimetric and dimensional characteristics	Mohamed et al., 2019 ; Martinez et al., 2019
Mechanical	Stability, impact resistance test (durability)	Wamukonya and Jenkins, 1995;
Chemical	Proximate and ultimate characteristic	ASTM, 2002 Ajimotokan et al., 2017 Nhuchhen and Afzal, 2017; Parikh et al., 2007
Combustion	Briquette ignition and burn characteristics	ASTM- E1321-13, 2013; Onuegbu et al., 2012
Stove performance	Tests water boiling test and controlled cooking test	Olorunnisola, 1999

## Results and Discussions

### Characterization of *G. arborea* sawdust and binder

#### Feedstock characteristics

To clearly define the effects of feedstock physical characteristics on briquettes quality, characterization was performed to determine particle size analysis procedure, the *G. arborea* sawdust samples were divided into four fractional sizes: oversized (OS), coarse size (CPS), coarse pin (CPP), and fine pin particles (FPP), with a considerable amount of dust specks. The study revealed the following sizes: large (2.38mm), coarse (1.70mm), coarse pin (0.85mm), fine size (0.50mm), and fine particle size (0.40mm), identical to Rizki et al. (2010). The geometric mean particle length measured on the sieves is 8.57 mm, and the mean standard deviation obtained was 4.594, with a maximum standard error of 2.27 at a 95% confidence interval. According to Rizki et al., (2010), these characteristics were deemed suitable for briquetting. At a mean moisture content of 9.41%, the mean particle density was 159 0.02 kg/m<sup>3</sup>, which is within the (124-240 kg/m<sup>3</sup>) range of values reported by Rizki et al (2010).

#### Clay characteristics

Table 2 present a summary of clay analysis values obtained from this study, compared with values obtained by Udeagbara et al., (2019) within the same experimental location in Ebonyi state. The results

showed some similarity in some properties with negligible difference in others. The difference could be explained from the viewpoint of instrumentation and experimental conditions.

### Briquette characterization

#### Briquette physical characteristics

The colour of briquettes produced (Figure 2) varied from deep brown (for higher clay concentrations) to light brown for low concentration. Quality examination after 7 days of approximate 6hrs of sun-drying per day, the briquettes can be stacked for transportation without physical damage. This result showed that the briquettes reached equilibrium moisture faster, and only cured for the remaining 13-21 days recommended for briquettes before determination of its relaxed density. These quality characteristics agreed with the report of Olorunnisola, 2007 on briquetting coconut fiber and paper waste binder. Briquettes produced have smooth outer and inner surfaces (with no visible surface cracks), cylindrical in shape with central/internal hole of mean internal and external diameters of 15 mm and 80mm respectively.

#### Gravimetric characteristics

Table 3 represents the summary of gravimetric characteristics of briquettes. The mean dry weight values of briquettes increased with increase in binder concentration after 30 days of drying due to increase in weight proportion of clay addition.



**Figure 3.** Phase-burning of briquettes in open air [(a) Ignition (b) Flame combustion (c) Char decomposition].

**Table 2.** Properties of sample (local clay suspension)

Properties	*Local clay	**Sample (brown) clay
Density (ppg)	8.80	9.00
Sand content (%)	0.50	0.50
pH value	5.65	6.35
Cake thickness (inch)	1/32	1/32
Specific gravity	1.06	1.06
Viscosity (cp)	4.50	1461.5 mPa.s

\*Udeagbara et al., (2019), \*\*Experimental value

**Table 3.** Physical properties of briquettes

Binder mix ratio (%w/w)	Briquette weight		Diameters		Height		
	(kg)		(mm)		(mm)		
	W0	W30	External	%Elongation	H0	H30	%Elongation
Mean dimensions of clay briquette samples							
90:10	0.129	0.048	79.45	1.16	45.89	46.58	1.50
80:20	0.114	0.050	79.47	1.18	45.36	45.85	1.08
70:30	0.116	0.051	79.41	1.10	45.43	45.96	1.17
60:40	0.104	0.051	79.45	1.16	45.12	45.67	1.22
50:50	0.107	0.058	79.44	1.14	45.35	45.91	1.23

### **Briquette stability (dimensional changes)**

Briquette stability defines the degree to which a briquette resist changes in dimensions after production. Table 3 equally showed dimensional changes from briquettes along the diametral and longitudinal axis. The external diameters of briquettes do not vary with increase in binder concentration with low percentage (1.10-1.18)% diametral elongations. Low binder concentration briquettes experienced the least diametral and axial expansion probably due to the strong inter-particle adhesive forces between clay and feedstock particles. Variation in these diametral values is significantly minimal compared with values obtained for briquetting experiments (Olorunnisola, 2007; Bello & Onilude, 2020), thereby confirming that significant expansion takes place primarily along the axial load direction than diametral axis.

Literature reports have established that briquettes compressed in enclosed cylinders exhibited greater

expansion in the longitudinal (height) direction of load application than diametral axis (Olorunnisola, 2007). The percentage height elongations for briquettes varied from (1.23-1.50) % while diametral elongation varied from 1.10% to 1.18% with highest percentage elongations recorded for briquettes with 10% binder concentration. From these results, the briquettes produce are considered structurally more stable than literature values. In addition, it can be affirmed that briquette dimensional variations could primarily be due to pressure application and material behaviour under applied load (Araque et al., 2022). This result agreed with report of Olorunnisola (2007) on minimal dimensional changes along the diametral axis are not so negligible contrary to low-density briquettes.

### **Briquette compressed and relaxed density**

The results of values obtained for compressed and relaxed densities by weight are presented in Table 4. The

mean maximum compressed densities (i.e. density determined immediately after production) and relaxed densities (i.e. density determined after 30 days from production) are (471 to 558 kg/m<sup>3</sup>) and (209 to 256) kg/m<sup>3</sup> respectively. Similar observations were reported by Oladeji (2015) and Bello et al., (2022). However, Aransiola et al., 2019, reported higher values of compressed density up to 1437 kg/m<sup>3</sup> for clay briquettes. It can be observed the table that clay briquettes have higher relaxed densities than the recommended minimum value of 200 kg/m<sup>3</sup> for safe transportation and storage of briquette (Mani et al., 2004). This implied that the type of binder used and binder ratios influences relaxed density and briquettes'

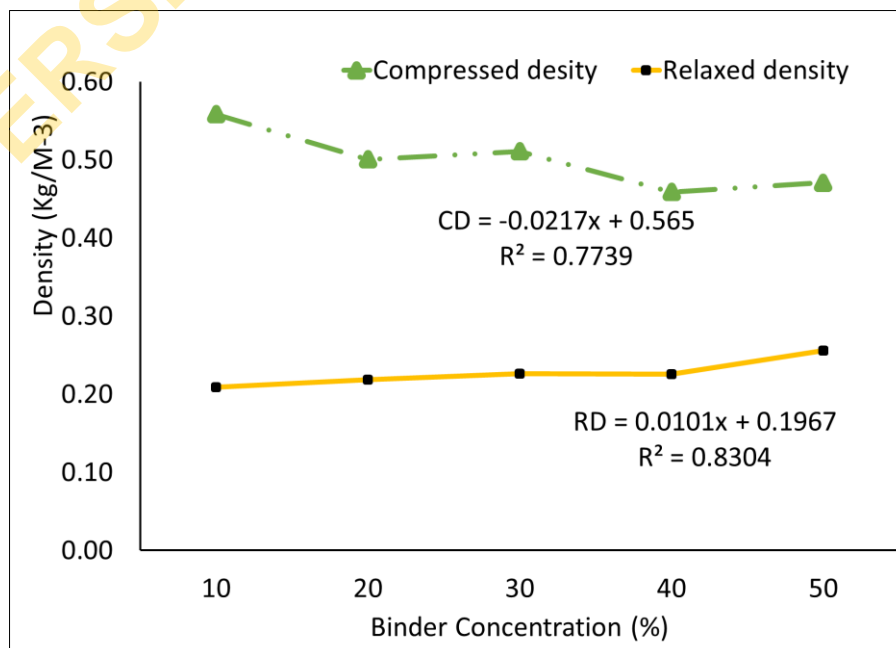
dimensional stability and that dimensionally stable briquettes were produced at higher relaxed densities.

#### **Effects of binder ratio on briquette compressed and relaxed densities**

Relationships between the compressed density and binder concentration of briquettes is shown in Figure (4). From each chart, the compressed density decreased with an increase in binder ratio with high positive correlation coefficients. From this result, the effects of binder ratios on compressed density are significant at ( $P < 0.05$ ) with high positive correlation. These results agreed with Mani et al., (2004) that binder

**Table 4.** Densities and relaxation ratios of briquettes

Binder ratio (%w/w)	Sawdust + clay binder		
	Briquette density (g/cm <sup>3</sup> )		Relaxation ratio
	Compressed	Relaxed	
Mean dimensions of clay briquette samples			
90:10	0.558	0.209	2.673
80:20	0.500	0.218	2.291
70:30	0.511	0.226	2.259
60:40	0.459	0.226	2.032
50:50	0.471	0.256	1.841
Mean	0.608	0.199	3.055



**Figure 4.** Compressed/relaxed densities and binder ratio.

ratio and type has significant effects on the compressed density. This implied that the briquettes can adequately withstand transportation stress without damage. In similar manner, there is an increase in relaxed density as the binder ratio increases. Similar trends occurred between compressed density and binder proportions reported by Davies and Davies (2013), and consequently on relaxed density as contrary to literature reports stated otherwise according to Sotannde et al., (2010), thereby validating the resulting outcome. This view are in agreement with results of Davies and Davies, (2013).

To establish the effects of binder type and concentration on compressed and relaxed density, analysis of variance (ANOVA, Table 5) revealed that binder concentration had a positive strong significant correlation on compressed and relaxed densities with positive coefficient of determinations ( $R^2=0.9968$  and  $R^2=0.999$ ) respectively. This report confirmed that binder type and concentration had significant influence on relaxed density and thereby establish the validity of the result.

### **Briquette durability (Impact resistance and water resistance capacity)**

Briquette durability was measured by evaluating the shatter index, impact resistance index and dispersion in water. These tests are essential to know how well the briquettes will respond to handling, transportation, storage and weather conditions.

### **Shatter and impact resistance**

Table 6 shows the results of shatter index and shatter resistance. The mean percentage shatter index of 3 replicate samples showed that maximum weight losses occurred at lower binder concentrations and decreased as the binder concentration increases, while the shatter resistance increased with increase in binder concentration which inferred that low binder concentration does not adversely affect the durability of briquettes while higher binder concentration reduced the impact losses in briquette. However, all briquettes

**Table 5.** ANOVA test for briquettes compressed and relaxed density

		ANOVA				
Model	Sum of Squares	Do	Mean Square	F	Sig.	
<b>Compressed density</b>						
2	Regression	968.550	3	322.850	10.265	.225 <sup>b</sup>
	Residual	31.450	1	31.450		
	Total	1000.000	4			
2	Regression	1000.000	4	250.000	.	.
	Residual	.000	0	.		
	Total	1000.000	4			
<b>Relaxed density</b>						
2	Regression	999.084	3	333.028	363.449	.039 <sup>c</sup>
	Residual	.916	1	.916		
	Total	1000.000	4			
2	Regression	1000.000	4	250.000	.	.
	Residual	.000	0	.		
	Total	1000.000	4			

a. Dependent Variable: Binder ratio (%), b. Predictors: (Constant), compressed density, c. Predictors: (Constant), relaxed density (%),

exhibited high shatter resistance which by implication suggest that all briquettes produced from clay binder has better impact and shock resistance in transportation and storage. Impact resistance index (IRI) value indicated the capability of a briquette to withstand sudden loads. The impact resistance values obtained (Table 6) showed an increase in impact resistance index as the binder concentration increases. The interactions between impact resistance index and binder concentration values (Figure 5) showed linear relationship with strong coefficient of determination  $R^2$  (0.8857). This implied that binder concentration had significant effects on impact resistance index of briquettes at ( $p < 0.05$ ).

Briquette water resistance test was conducted to know the extent to which water and humidity could affect the quality of briquettes. Two parameters; percentage water absorption (PWA) and water resistance capacity (WRC) were evaluated and results shown in Table 7.

The percentage water absorption (PWA) slightly increased and then decreased as binder concentration increases while the water resistance capacity (WRC) decreased, then increased in same proportion as binder concentration increases. In addition, it was observed from the table that clay briquettes experienced slow water absorption but low resistance to disintegration in water after immersion, especially for binder concentrations higher than 20%, hence became highly unstable with poor hygroscopicity.

The interactive effects of these parameters on briquette durability are presented graphically in Figure 6. From these figures, the low coefficient of determination ( $R^2 = 0.0213$ ), is an indication that binder concentration does not significantly affects clay briquette durability and hygroscopicity at  $p > 0.05$  (Davies & Davies, 2013).

### **Briquette combustion characteristics**

#### ***Briquette ignition and burning characteristics***

Observed self-ignition time for each briquette varied between (7-10) minutes. The 10% bonded briquettes were able to be ignited with visible flame not sustained beyond 2-3 minutes before extinction, however the briquette continued to glow (i.e. burn by char combustion) for about 40 minutes. The observed delayed ignition time could only be adduced to the non-combustibility of clay properties that filled the biomass matrix which eliminated oxygen required to supports burning. This observation implied that clay briquettes are not suitable for low thermal applications like domestic cooking but suggested for use in industrial heating applications such as furnace heating.

#### ***Flame combustion and smokiness***

Considering the three stage phase-burning of briquettes: ignition phase (1), steady-state flaming combustion phase (2) where volatile matters are burn off, and the decomposition phase (3) where char combustion takes place, the low-content (90:10)% clay briquettes have prolonged ignition time (7-10min), produced yellow flame with poor propagation (10-15)cm, which rapidly depleted after a short time of burning. Higher binder concentration briquettes (80:20, 70:30, 60:40 and 50:50) failed to either ignite, propagate or decomposed. Smokiness observed during flame burning was due to initial pre-ignition support-burning with 3-5mls of kerosene added to initiate burning.

#### ***Briquette mass reduction***

The mass reduction of each briquette in free air (Figure 7) showed that at  $p > 0.05$  significance, there was relatively small variations in mass reduction for 10% binder concentrations. Furthermore, the prolonged char combustion time and observed non-disintegration of briquette suggested its preferred utilization in industrial furnace than domestic cooking. At higher binder concentrations, the briquettes failed to ignite, even when supported with supplemental 3-5ml kerosene doses.

#### ***Stove performance***

Briquette combustion performance in stove could not be achieved due to poor flame propagation within the combustion chamber. Attempts at supplemental ignition failed, thus preventing water boiling and controlled cooking tests experiments. To validate this result, the briquettes were subjected to supported burning in a gas cooker flame (Figure 8) for about 40 minutes. There was no flammable combustion, rather there was char combustion. This further validate the claim that clay briquettes are not suitable for low thermal applications, but could be efficient in furnace and other high-thermal applications.

#### ***Research economic analysis***

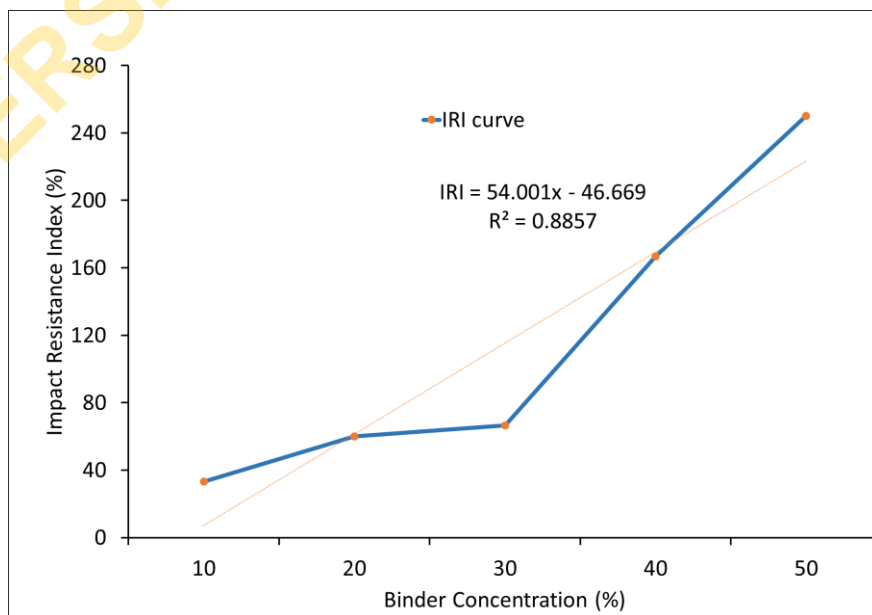
Economic analysis was evaluated based on material and process cost valuations, and economic importance of the research outcome. The cost implications of sourcing the feedstock material, binder clay and transportation including processing cost per unit production of eight (8) briquettes in unit operation is relatively low (approx. NGN80.00 per kg). The sawdust and clay extracted from dug pits are freely available while institutional laboratories and workshops already have the necessary tools and equipment. Evaluation of unit costs of briquette compared with the cost of buying firewood (NGN200.00 per kg), kerosene (NGN800.00 per ltr.) or gas (NGN850.00 per kg), made briquettes more economically viable.

**Table 6.** Shatter and impact resistance index for briquettes

Binder mix ratio (%w/w)	Shatter index (K)	Shatter resistance (%)	IRI
90:10	23.36	76.64	33.33
80:20	19.04	80.96	60.00
70:30	13.22	86.78	66.67
60:40	4.63	95.37	166.67
50:50	1.70	98.30	250.00

**Table 7.** Percentage water absorption and resistance capacity of briquettes

Binder mix ratio (%w/w)	Shatter index (K)					PWA (%)	WRC (%)
	Initial	15 min	30 min	45 min	60 min		
90:10	5.40	16.70	20.40	12.10	8.70	1.24	98.76
80:20	5.40	20.30	22.80	12.10	7.50	1.24	98.76
70:30	5.30	22.70	22.60	14.00	6.60	1.64	98.36
60:40	5.40	22.30	21.50	12.60	6.50	1.33	98.67
50:50	5.50	25.10	21.70	12.50	7.70	1.27	98.73

**Figure 5.** Impact resistance index curve for briquettes.

**Conclusions**

The following conclusions can be drawn from the results of tests and analysis on the viability of using clay as binder in the production of coal briquettes.

a. Clay exhibited good binding characteristics, even at the least binder concentration of 10% investigated.

b. Binder concentration have significant effects on the physical, mechanical and combustion characteristics of briquettes

c. Clay is a non-viable binder in briquetting due to its poor combustion characteristics, long pre-ignition time, failed visible flame propagation and char combustion with high ash contents.

d. Considering the above, clay briquettes are not viable fuel for domestic applications.

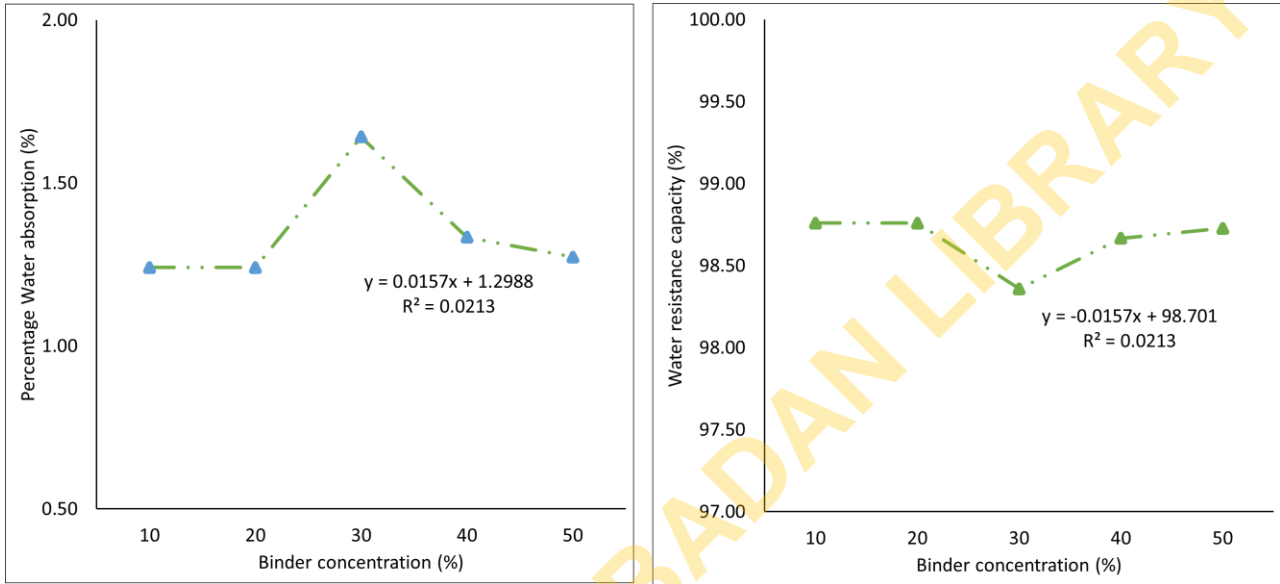


Figure 6. Percentage water absorption and resistance capacity of briquettes.

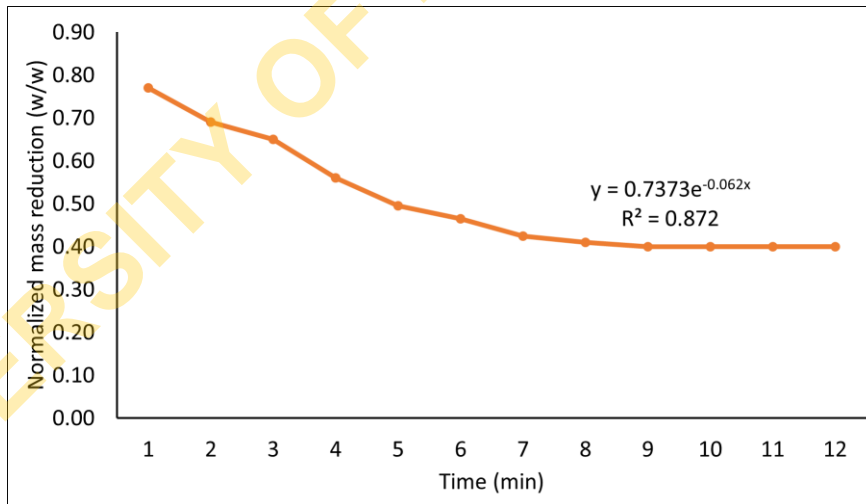


Figure 7. Normalised mass decrease for 10% binder briquettes.



Figure 8. Gas assisted phase burning and decomposition.

## Ethical Statement

Not applicable

## Funding Information

Not applicable

## Author Contributions

First Author: Conceptualization, Formal Analysis, Investigation, and Writing -original draft;

Second Author: Conceptualization, Methodology, Visualization and;

Third Author: Project administration, Writing - review and editing; and

Fourth Author: Supervision

## Conflict of Interest

The author(s) declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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