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Research Highlights on Characterization of Briquettes Produced from *Gmelina arborea* Sawdust and Different Binders

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ABSTRACT

Background and Objective: Characterization refers to processes used to collect information on the qualities of a substance or product, such as briquettes. Briquettes are products of materials subjected to varying process conditions and properties and therefore require characterization. This study comparatively investigates the characteristics of briquettes produced from torrefied and fermented sawdust and three different binders in varying proportions. **Materials and Methods:** *Gmelina arborea* sawdust collected was sorted. Some samples were subjected to fermentation at different soaking times of 12, 24, 36 and 48 hrs, while others were to torrefaction at residence times of 30, 45 and 60 min, respectively. Each sawdust sample products were treated with used print office paper, newsprints and montmorillonite clay binders. The physical, chemical, mechanical and combustion characteristics of each product were evaluated. Data were analyzed using descriptive statistics and ANOVA at $\alpha_{0.05}$. **Results:** The physical characteristics of untreated sawdust determined are similar to those reported in literature as suitable for quality briquette production. The most significant physical changes observed in the pretreated samples were colour and weight changes with significant changes observed in torrefied sawdust dependent on the severity (duration) of torrefaction. Quality characteristics of torrefied sawdust were evaluated by percentage weight loss, mass yield and energy yield. Weight loss and mass yields decreased with an increase in torrefaction time, while the energy yield increased with an increase in torrefaction time. Torrefied briquettes had least thermal efficiencies, but possessed higher thermal energies and required less quantity to boil water. The mean Specific Fuel Consumption (SFC) does not significantly differ, but variations noticed are due to an increase in binder proportions, torrefaction time and fermentation time. The consumption rate FCR significantly influenced the optimization of stove performance. **Conclusion:** Binder proportions, binder type and torrefaction had a significant effect on the performance characteristics of briquettes produced. Fermentation methods used have no significant effects on the performance characteristics of briquettes produced.

KEYWORDS

Gmelina arborea sawdust, torrefaction, briquettes, binders, fermentations methods, consumption rate

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INTRODUCTION

Briquetting otherwise referred to as densification, entails compressing materials into compact shapes (briquettes) with or without the use of additives or binders with or without pressure application[1]. In general, biomass densification employs one of such agglomeration technologies for the conversion of loose agro-forest residues into solid fuel in low-pressure and some medium-pressure applications[2,3]. Binder use in briquetting is common, while binderless briquetting requires high-pressure compaction and external heating as applicable to some medium-pressure briquetting[4]. Many researchers have reported different binders that have competing uses and are relatively inexpensive[2,5]. Research studies on binders focused on the development of more sustainable, combustible, better performing and cheaper binders, with diverse improved effects on briquette quality[6,7], therefore, there is a need to explore the potentials of other non-edible binders such as paper and clay.

Pretreatment of biomass for briquetting has been recognized for a long time[8]. A literature search suggested torrefaction and fermentation as more attractive and less expensive processes for sawdust pretreatment for briquetting. The process of torrefaction involves roasting feedstock in an atmosphere that is nearly inert (oxygen-free) between 159 and 300°C to improve its combustion characteristics and heating value[9,10]. The conversion of raw biomass into a high-energy-density, hydrophobic and grindable material through torrefaction is thought to be a suitable and workable method for commercial and residential heating applications[9,10].

Fermentation is another pretreatment process in which, biomass is soaked in a liquid media for a while to lower the volatile matter concentration while preserving the cellulose and hemicellulose structure. Numerous existing fermentation techniques, each with unique contrasting benefits for the energy contained product, ease of processing and material applicability for further processing, improved miscibility with liquid fuels, higher octane ratings and reduced volatility[11]. The main objective of this paper was to highlight and make comparisons on physical, mechanical and combustion characteristics of untreated, torrefied and fermented briquettes produced from sawdust of *Gmelina arborea* and three binders (used print paper, newspaper and clay).

MATERIALS AND METHODS

Study area and duration: The experimental study location is Ishiagu, Ebonyi State, Nigeria reputed for its massive production of wood waste and clay. The duration of the experiment was thirty-two months, from January, 2020 to October, 2022.

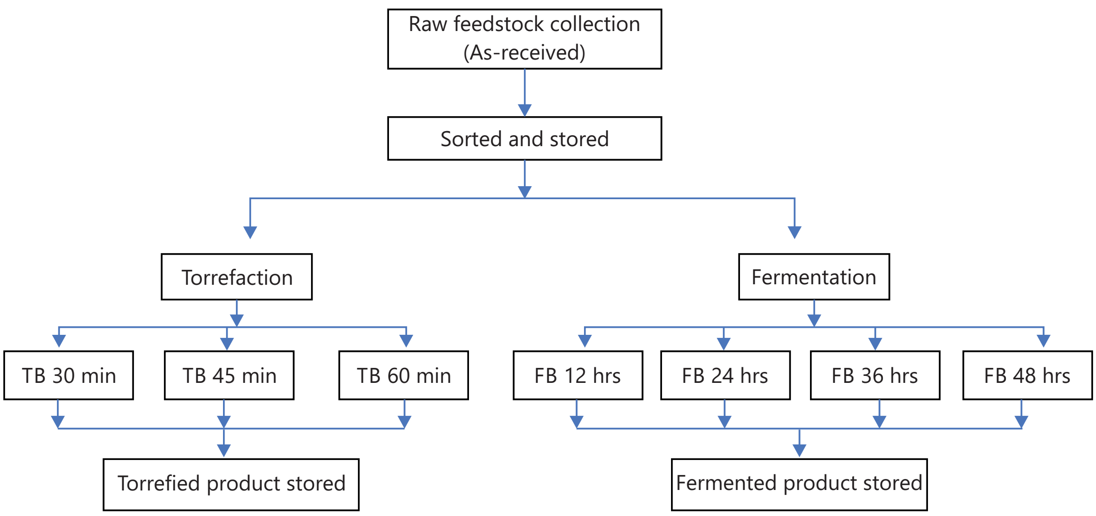

Fig. 1: Process flow diagram of the feedstock pretreatments

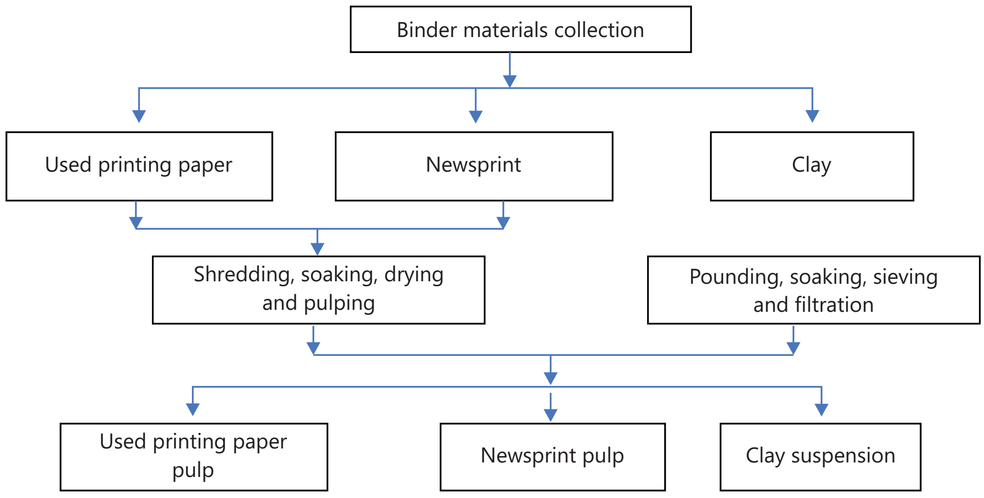

Fig. 2: Process flow diagram of the binder processing

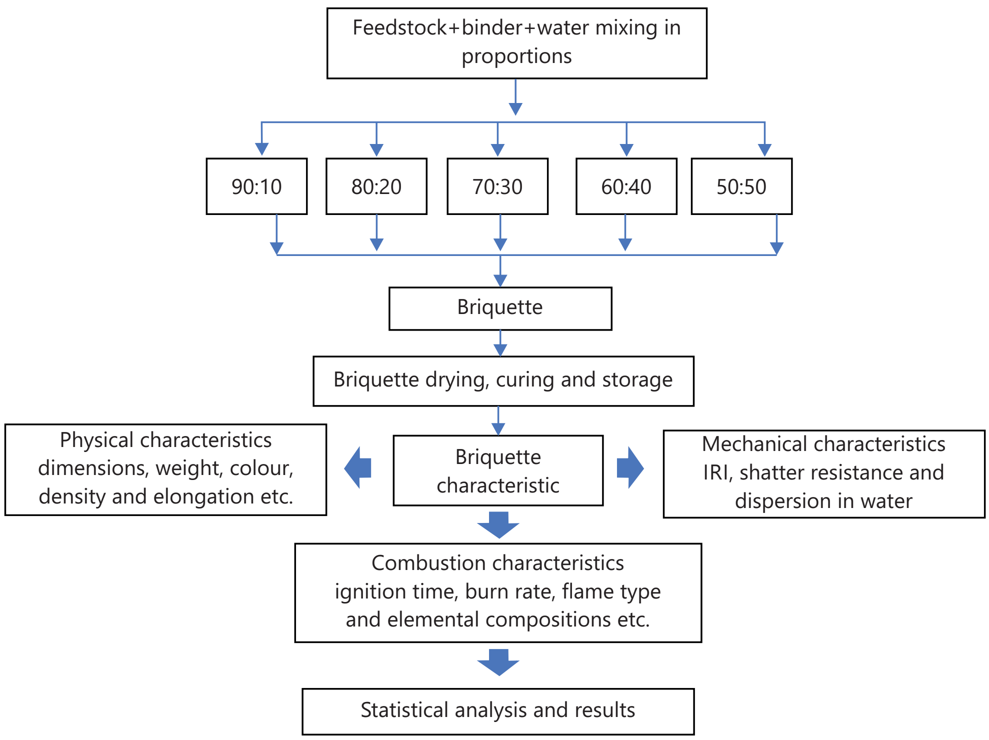

Fig. 3: Process flow diagram of briquette production

Material selection and preparation: Sawdust of *Gmelina arborea*, wood was selected based on availability within the experimental area and energy content, waste paper (used office print and newspaper) and clay (Montmorillonite) were selected as binders based on comparative advantages compared to other organic and inorganic materials. Materials collected from sawmills were prepared according to standard procedures (Fig. 1). Samples of sawdust were pretreated by torrefaction (Fig. 1) at three torrefaction times of 30, 45 and 60 min using batch reactor and fermentation by soaking raw sawdust in plastic tanks to ferment at 12, 24, 36 and 48 hrs using fermentation tanks. Each binder was prepared as shown in Fig. 2.

Yazdani and Ali[12], procedures were employed to determine the mixing ratios of feedstock and binder proportions (in grams) (i.e., 90:10, 80:20, 70:30, 60:40 and 50:50). Briquette production was carried out using a hand-operated 4-piston hydraulic briquetting machine. The physical, mechanical, chemical and combustion characteristics of briquettes were performed in three replicate samples and mean data obtained for each treatment was analysed to determine the briquette characteristics (Fig. 3).

Statistical analysis: Analysis of variance (ANOVA), correlation and regression analysis tools were used in the characterization experiments at significance level.

RESULTS AND DISCUSSION

Characterisation of untreated *G. arborea* sawdust: The summary of particle-size distribution, particle length and mean particle lengths determined are shown in Table 1. This classification was similar to that of Maharani *et al.*[13] and Bergström *et al.*[14].

Physical properties of untreated, torrefied and fermented sawdust: The most significant physical changes observed in the untreated and pretreated samples were colour and weight changes (Table 2). There were no noticeable colour changes in fermented products, however, there are observed changes in torrefied products from light brown to golden brown with specks of black at 30 min (mild torrefaction) to darkish brown at 45 min and finally to dark colour at 60 min (severe torrefaction). Weight losses for torrefied sawdust increased with an increase in the severity of torrefaction. The percentage loss could be explained by the amounts of volatiles and other compounds vapourized. Weight losses for fermented sawdust increased slightly with an increase in soaking time. Similar trends were observed with a density of feedstock used in each of the experiments.

Quality characteristics of torrefied sawdust were evaluated in the percentage weight loss, mass yield and energy yield[15]. The solid mass yield decreased appreciably with an increase in torrefaction time, while the energy yield increased with an increase in torrefaction time. The Energy Densification Ratio (EDR) increased with an increase in torrefaction time and consequently increased the energy yield. The weight loss was associated with volatile matter decomposition as well as moisture. These observations were similar to results obtained by Nhuchhen and Afzal[16] in the thermal pretreatment of cylindrical-shaped poplar wood and loblolly pine samples respectively.

Characteristics of binder materials: From comparative evaluation of relevant literatures on physical, optical and strength characteristics of the papers, the used print paper has a greater comparative advantage of producing better quality briquettes over newspaper in terms of durability and combustion characteristics. Table 3 presents a summary of clay analysis values obtained from this study in comparison with literature values. The results showed some similarity in some properties with negligible differences in others.

Briquette physical characteristics: Parameters measured to fully describe the physical characteristics of briquettes produced and a summary of results are presented in Table 4. These characteristics include briquette colour changes, hydroscopicity, hygroscopicity and stability (measured by relaxation ratio and dimensional changes). Pretreatment method and binder colours influenced colour changes in all briquettes. Torrefied and newspaper briquettes are greyish and black in colour, while the untreated and clay briquettes are brownish in colour. The used printing and fermented briquettes are greyish in colour. Briquette tendency to absorb or lose water was measured by its hygroscopicity and hydroscopicity. Paper briquettes have good hygroscopic, but poor hydroscopic properties and vice versa. Clay briquettes have poor hygroscopic properties, but good hydroscopic properties. All briquettes were stable, however, the extent of stability measured by relaxation ratios varied with binder type and concentrations. All the 90:10% paper briquettes are unstable and easily disintegrate under slight pressures. All other used printing paper briquettes are stable; the newsprint briquettes are slightly stable but susceptible to mechanical damage.

Table 1: Particle-size distribution of *G. arborea* sawdust

Sieve mesh	Description	Particle size (mm)	Particle length (mm)	Mean particle length, standard deviation
#8	Oversize (OS)	2.38	<10.67	8.57 mm, 4.594 at a 95% confidence interval
#12	Coarse pin size (CPS)	1.70	<9.98	
#20	Coarse pin particle (CPP)	0.85	<8.64	
#35	Fine pin particles (FPP)	0.50	<4.5	
>#40	Fine pin size (FPS)	0.40	<2.07	

Table 2: Physical characteristics of torrefied and fermented sawdust

Indicators	Untreated	Torrefied	Fermented
Colour	Light brown	• 30 min: Golden brown with black specks • 45 min: Dark brown • 60 min: Dark (severe torrefaction)	12, 24, 36 and 48 hrs: • No changes in colour at different soaking time • Changes in soaking water colour from colorless to wine red • Colour increased with soaking time
Moisture content (%)	9.41	7.50-9.50	7.50-9.50
Hydrophobicity	Hydrophobic	Hygroscopic	Hydrophobic
Grindability	Non-grindable	Grindable	Non-grindable
Weight	-	Percentage weight losses increased with torrefaction time	No significant changes in weight loss at different soaking times
Density	159±0.02	Decreased depending on severity of torrefaction	Slightly increased with increase in soaking time

Table 3: Properties of the clay sample (local 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
ÓCake thickness (inch)	1/32	1/32
Specific gravity	1.06	1.06
Viscosity (cp)	4.50	1461.5 mPa.s

*Udeagbara *et al.*[17] and **Experimental value

Table 4: Physical characteristics of different briquettes

Briquettes	Untreated	Fermented	Torrefied
Colour changes			
Used printing paper	Light brown to grey	Light brown to grey	Shades of black and brownish
Newsprints	Dark to light grey	Dark to light grey	Shades of black and brownish
Clay	Light to deep brown	Light to deep brown	Light yellowish to darken
Hygroscopicity			
Used printing paper	Good	Good	Moderate
Newsprints	Good	Good	Moderate
Clay	Poor	Poor	Poor
Hydroscopicity			
Used printing paper	Poor	Poor	Moderate
Newsprints	Poor	Poor	Moderate
Clay	Good	Good	Good
Stability (measured by relaxation ratios (increased with binder concentration for all briquettes)			
Used printing paper	Stable	Stable	Stable
Newsprints	Less stable	Less stable	Less stable
Clay	Very stable	Very stable	Very stable
Stability (mean external, internal and height dimensional changes measured by percentage elongation)			
Used printing paper	Slight elongations		
Newsprints	Highest elongations		
Clay	Least elongation		
Gravimetric changes	Depended on binder type, concentration and type of treatment		

The clay briquettes are all very stable. The relaxation ratio for used printing paper and fermented briquettes increased as the binder concentration increased, but the ratio for fermented clay briquettes decreased with the increase in binder concentration. Torrefied paper briquettes, on the other hand, had lower relaxation ratios, which decreased as the binder concentration increased. Relaxation ratios of fermented clay briquettes were significantly influenced by binder type and percentage concentration with high coefficient of determination (>0.97-0.99) with negative slope coefficients. This implied that clay shrinks the briquettes rather than increasing (swelling) their size.

Dimensional changes measured by percentage elongation revealed that briquettes with low binder contents elongate most readily along both axes (diametric and axial axes), whereas high binder content briquettes experienced less expansion along both axes. This showed that clay briquettes are more stable than used printing and newsprint briquettes and those higher-binder briquettes are more stable than low-binder briquettes. Low binder briquettes experienced reduced elongation than the high binder briquettes, implying that elongation decreased with an increase in binder concentration. Binder type has more stabilizing effects on torrefied briquettes while binder concentration has a strong influence on fermented briquette stability.

Gravimetric changes: An essential gravimetric property that determines briquette quality is density, measured directly after production (compressed density) and 30 days after production according to ISO 3131 standards[18]. The mean compressed and relaxed densities as well as the relaxation ratios measured are shown in Table 5.

Influence of binder and concentration on compressed density: Compressed density increased with an increase in binder content for used print paper and torrefied sawdust, with high positive correlation coefficients of determination R^2 = 0.8495, 0.8611 and 0.695, at ($p<0.05$), while low positive correlations were reported for fermented briquettes produced with the same types of binder. Similar trends were observed with clay binders of the same materials with high positive correlation coefficients. However, there occurred low positive correlations (R^2 = 0.4826, 0.1422 and 0.6321, for briquettes produced with newspaper binder and sawdust torrefied for 30, 45 and 60 min, respectively. The effects of binder ratio on compressed density were significant at ($p<0.05$). These findings supported the assertion by Mani *et al.*[19] that binder ratio and type have a substantial impact on compression density. The compressed density of fermented briquettes was significantly affected ($\alpha>0.05$) by binder type, binder concentration and treatment conditions separately, but not by briquettes made from torrefied sawdust.

Influence of binder and concentration on relaxed density: The binder and blend ratio had a positive strong significant impact on relaxed densities of newspaper and used print paper briquettes and $\alpha>0.01$ (2-tailed) on compressed densities of clay briquettes, according to the correlation findings. With positive Pearson's coefficient ($r>0.500$), implies a corresponding increase in relaxed density as the binder ratio increases. Similar trends in the relationship occurred between compressed density and binder proportions reported by Davies and Davies[20] that increased binder proportion resulted in an increased compressed density of briquettes, consequently, on relaxed density as contrary to literature reports stating otherwise according to Sotannde *et al.*[21], thereby validating the resulting outcome. Multiple regression analysis tests showed a significant difference ($\alpha<0.05$) in the mean briquette relaxed density with the highest positive interactions for torrefied briquettes.

Briquette mechanical characteristics: Briquette mechanical characteristic was measured by its durability when dropped on a hard floor and when immersed in water. Table 6 presents a summary of briquette's mechanical performance.

Table 5: Densities of untreated, torrefied and fermented briquettes

	Density (g/cm^3)					
	UPP		NP		CL	
Time	Compressed	Relaxed	Compressed	Relaxed	Compressed	Relaxed
Untreated						
	0.67	0.21	0.61	0.20	0.61	0.20
Torrefied						
30 min	0.64	0.22	0.65	0.19	0.72	0.40
45 min	0.62	0.20	0.63	0.19	0.72	0.39
60 min	0.64	0.22	0.61	0.19	0.77	0.42
Fermented						
12 hrs	0.80	0.24	0.65	0.21	0.74	0.47
24 hrs	0.81	0.23	0.67	0.20	0.84	0.47
36 hrs	0.82	0.23	0.72	0.20	0.88	0.53
48 hrs	0.81	0.23	0.61	0.20	0.82	0.55

Briquettes shatter index and shatter resistance: Untreated newsprint briquettes have higher weight losses when dropped on a hard surface while untreated clay briquettes have a lower shatter index, which implies weaker briquettes than used printing paper and clay briquettes. Higher weight losses occurred in low binder briquettes and decreased as binder concentration increased. Fermented printing paper briquettes had a very low shatter index compared with newsprint and clay briquettes. Shatter index in torrefied used printing paper and newsprint briquettes was significantly higher at lower binder concentrations, implying that weight losses decreased with an increase in binder concentration. Low-binder torrefied briquettes have a high shatter index and low shatter resistances. Clay briquettes exhibited least weight losses at lower binder concentrations compared to other briquettes. Shatter index for fermented UPP briquettes increased as fermentation time increased and decreased with a decrease in binder concentration, implying that low-binder briquettes are more susceptible to impact damage than higher-binder briquettes. Torrefaction time showed no significant effects on shatter index.

The shatter resistance (Table 6) increased with an increase in binder concentration for torrefied briquettes. Clay-bonded briquettes have the higher shatter resistance due to the inter-particle adhesion between clay particles and sawdust and the high coefficient of friction, hence displaying a significantly lower shatter index over those of used paper and newsprint briquettes.

Impact resistance index (IRI): The ability of a briquette to withstand unforeseen loads was measured by the impact resistance index (IRI). Briquettes produced showed an increased impact resistance index as binder concentration increased (Table 7). Similarly, as binder concentration increased, the number of shattered pieces per drop from a height of two meters decreased. After dropping each briquette for a maximum of nine drops, the briquettes with higher binder ratios maintained some bits that made up more than 5% of the initial briquette mass. The mean impact resistance index of untreated briquettes varied from (150-162%) for untreated briquettes to (97-157%) for torrefied briquettes and (99-185%) for untreated clay briquettes, respectively.

Briquette combustion characteristics: The summary table for combustion characteristics and performances in stoves is represented in Table 8.

Briquette ignition and smokiness: Untreated and fermented briquettes produced significant sooty smoke at ignition, which reduced during phase burning and produced no smoke at burnout. This is due to higher percentages of volatile ingredients. Untreated clay briquettes had poor ignition and phase burning, burned essentially by char combustion and did not produce smoke. Smokiness reduces for all

Table 6: Shatter and resistance index for briquettes

Untreated+UPP		Torrefied+UPP			Fermented+UPP		
Shatter index	Shatter resistance	Time	Shatter index	Shatter resistance	Time	Shatter index	Shatter resistance
18.41	81.59	30 min	42.92	56.95	12 hrs	2.98	84.31
		45 min	38.61	54.68	24 hrs	7.02	97.02
		60 min	41.20	55.08	36 hrs	15.69	77.44
					48 hrs	22.68	92.96
Untreated+NP		Torrefied+NP			Fermented+NP		
Shatter index	Shatter resistance	Time	Shatter index	Shatter resistance	Time	Shatter index	Shatter resistance
22.3	77.7	30 min	61.84	38.16	12 hrs	38.22	61.77
		45 min	62.72	37.28	24 hrs	40.14	59.86
		60 min	51.88	47.68	36 hrs	31.24	68.76
					48 hrs	36.33	63.67
Untreated+CL		Torrefied+CL			Fermented+CL		
Shatter index	Shatter resistance	Time	Shatter index	Shatter resistance	Time	Shatter index	Shatter resistance
12.39	87.61	30 min	45.39	54.61	12 hrs	35.68	64.32
		45 min	43.15	56.85	24 hrs	41.02	59.67
		60 min	44.72	55.28	36 hrs	35.05	64.95
					48 hrs	33.13	66.88

Table 7: Impact resistance index (IRI) for untreated, torrefied and fermented briquettes

Briquette	Untreated+UPP			Untreated+NP			Untreated+CL		
	Drops	Pieces >5%	IRI	Drops	Pieces >5%	IRI	Drops	Pieces >5%	IRI
	3	4	150	3	4	149	3	3	162
Briquette	Torrefied+UPP			Torrefied+NP			Torrefied+CL		
Time	Drops	Pieces >5%	IRI	Drops	Pieces >5%	IRI	Drops	Pieces >5%	IRI
30 min	5	5	134	3	5	56	6	3	200
45 min	4	7	91	3	5	65	5	4	178
60 min	4	6	117	4	5	97	5	4	157
Briquette	Fermented+UPP			Fermented+NP			Fermented+CL		
Time	Drops	Pieces >5%	IRI	Drops	Pieces >5%	IRI	Drops	Pieces >5%	IRI
12 hrs	5	4	137	4	6	80	5	5	113
24 hrs	5	3	230	5	6	85	5	4	140
36 hrs	6	4	202	5	7	79	5	5	116
48 hrs	5	4	185	5	6	99	6	5	135

Table 8: Briquette combustion characteristics and stove performance

Combustion characteristics	Untreated UPP	Untreated NP	Torrefied UPP	Torrefied NP	Fermented UPP	Fermented NP
Ignition time (min)	3-5	3-4	3-5	3-5	2-3	2-3
Smokiness	Sooty	Sooty	Mild	Less smoky	Smoky	Smoky
Flame height (cm)	20 to 25	20 to 25	20 to 25	20 to 25	20 to 25	20 to 25
Burn rate	0.500	0.54	0.463	0.402	0.503	0.558
Time to burn out 200 g fuel (min)	6	6	4	4	5	5
Stove performance						
Thermal efficiency (%)	33.2	34.55	29.26	25.15	31.58	33.92
Time to cook 206 g of rice (min)	29-35		27-35		30-38	
Time to cook 157 g of yam (min)	33-38		33		38	
SFC	0.581	0.575	0.620	0.589	0.570	0.579
FCR	0.28	0.29	0.25	0.28	0.26	0.28

SFC: Specific fuel consumption and FCR: Fuel consumption rate torrefied briquettes at ignition, with considerable reduction at flaming stage. Smokiness in torrefied briquette reduced with torrefaction time while the increase in binder concentration slightly increased smokiness.

Briquette flame propagation and burning duration: Used printing and newsprint briquettes have good flame propagation, reaching a height of 20 to 25 cm and it took approximately 14.46 min to burn out 137.33 g of torrefied used printing paper and newsprint briquettes in raising the temperature of 1.4 kg water from 30 to 90°C. Clay briquettes have prolonged ignition time and no flame propagation, but burn majorly by char combustion. The average time taken to completely burn a unit of each briquette in open-air ranges from 4 to 6 min.

Stove thermal efficiency (%): The stove thermal efficiency during the water boiling experiment ranges from (31.47 to 39.89%) for untreated briquettes, (17.13 to 38.52%) for torrefied briquettes and (23.84 to 39.89%) for fermented briquettes[22]. Thermal efficiencies of stoves in burning untreated and fermented briquettes are higher than torrefied briquettes, implying that a higher quantity of untreated and fermented briquettes are required to raise water to boil compared with torrefied briquettes. The practical significance is that torrefied briquettes developed higher energies and required less quantity to boil water. These ranges of results were similar to studies carried out by Sotannde *et al.*[21] and Egwim *et al.*[23].

Briquette burning time during cooking: Untreated UPP and NP briquettes took 29-35 min to cook 206 g of rice, torrefied briquettes took 27-35 min, while it took 30-38 min to boil the same amount of food with fermented briquettes. Cooking rice on a biomass stove took less time than cooking the same amount of yam; for example, cooking 0.157 kg of yam with torrefied briquette took 33 min, while cooking the same amount of yam with fermented briquette took approximately 38 min[2,24]. For all briquettes burned in the stove, the time required to cook 1 kg of yam and rice does not differ significantly (minimum 0.53/0.31 hrs) and (maximum 0.62/0.34 hrs). In practice, this means that few numbers of briquettes will cook same amount of food. Total time taken to burn 200 g-weight of briquettes ranged from 32 to 39 min.

Specific Fuel Consumption (SFC): The mean Specific Fuel Consumption (SFC) in cooking rice and white yam did not significantly differ, but variations occurred due to an increase in binder proportions, torrefaction time and fermentation time.

Fuel consumption rate (SFR): The fuel consumption rates are slightly reduced for fermented UPP briquettes compared to untreated briquettes, but are slightly higher than torrefied briquettes. The consumption rate increased with binder concentration. This implied that high binder concentrations have a significant effect on the optimization of briquette quality and consequently on stove performance. Furthermore, the binder type and treatment method showed a negligible effect on the fuel consumption rate.

CONCLUSION

Gmelina arborea sawdust is a suitable feedstock material for briquette production without grinding. Selected binders have good binding properties; however, clay has poor combustion characteristics even at the least binder concentration (10%). In excess of 10% binder, the briquette failed to ignite. All briquettes produced are structurally stable and satisfy quality characteristics of briquettes. Clay briquettes are more stable. Untreated and fermented briquettes exhibited low combustion characteristics and produced considerable smoke, while torrefied briquettes had the best combustion characteristics (energy value, smoke generation, flame propagation and burn rate, etc.) with an acceptable level of smokiness. Binder proportions, binder type and torrefaction had a significant effect on the performance characteristics of briquettes produced. Fermentation methods used have no significant effects on the performance characteristics of briquettes produced.

SIGNIFICANCE STATEMENT

Three significant factors influencing briquette quality and performance include binder type, binder concentration and feedstock pretreatment method. Each of these factors varied based on the conditions under which they operate. This paper reported significant highlights on the comparative characterization of three types of briquettes produced from *Gmelina arborea* sawdust, three types of binders and two pretreatment methods (torrefaction and fermentation). This work investigates the physical, chemical, mechanical and combustion characteristics of products obtained from untreated sawdust, torrefied sawdust and fermented sawdust. Essential parts of this research had been reported in scholarly journals, as appropriately referenced.

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