Natural Resources Conservation and Research 2024, 7(1), 5292.
https://doi.org/10.24294/nrcr.v7i1.5292

Article

Effects of feedstock pretreatment and binder selection on briquette characterization

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CITATION

Bello RS, Olorunnisola AO, Omoniyi TE, Onilude MA. Effects of feedstock pretreatment and binder selection on briquette characterization. Natural Resources Conservation and Research. 2024; 7(1): 5292. https://doi.org/10.24294/nrcr.v7i1.5292

ARTICLE INFO

Received: 18 March 2024
Accepted: 29 March 2024
Available online: 19 April 2024

Abstract: Briquettes from raw biomass exhibit smokiness and emits irritant gases. Technical solutions were found in feedstock pretreatment and appropriate binder selection, which this study investigated. Torrefaction and fermentation pretreatments and used printing paper (UPP), newsprint (Np), and clay (C) were selected for experimentation. Samples of *Gmelina arborea* sawdust (GaS) collected from sawmills were characterized using the ASTM standards. Hollow briquettes were produced at 10:90%, 20:80%, 30:70%, 40:60%, and 50:50% feedstock/binder mixes. Data were analyzed using descriptive statistics and ANOVA at $\alpha_{0.05}$. Results showed that torrefaction yield increased with torrefaction time, particle density increased with fermentation time but decreased with torrefaction time. Proximate values significantly differ for torrefied and fermented GaS, while heating value (HHV) increased with residence for torrefied and fermented briquettes. Torrefied UPP briquettes produced non-luminous flame and less smoke. Clay briquettes, however, had charred combustion. Fuel consumption increased with binder concentration but decreased with an increase in residence time.

Keywords: pretreatment; *Gmelina arborea* sawdust; torrefaction; briquettes; characterization; binder

1. Introduction

The current energy insecurity and unsustainable environmental consequences are surmountable through energy resource diversification. The global supply of biomass from different sources was estimated at approximately 220 billion tons per year, with an estimated two-thirds consumed in developing nations in household cooking [1]. Out of the country's total energy consumption, 85.9% comes from biofuels and wastes, while fossil fuel accounts for 9%, natural gas for 3.3%, and electricity for 1.8% [2]. Apart from fuelwood, the global biomass resources largely revolve around wastes generated from forestry residue, agricultural and industrial/domestic wastes.

Despite the advantages of biomass, there are restrictions on its use as a primary feedstock for energy production; it is limited due to luminous yellow flame, excessive moisture contents, poor energy per unit volume, hydrophilic properties, high oxygen content resulting in smoky burning [3]. These constraints make transportation, processing, preservation, and conversion operations difficult and limits their replacement as fossil fuels for energy production [4]. Biomass densification employs briquetting agglomeration technology for the conversion of loose agro-forest residues into solid fuel, increase energy density and improve fuel consumption. Depending on the extent of pressure application, briquetting is classified either as low-pressure or high-pressure compaction, otherwise referred to as binder-based and binderless briquetting processes [5]. Different starchy binders from cassava, maize and other food crops are relatively expensive since they have other competing uses [6]. Therefore, there is need to explore the potentials of other non-edible binders such as paper and clay.

Pretreatment of biomass for briquetting has been recognised for a long time [7]. A literature search suggested torrefaction and fermentation as more attractive and less expensive processes for sawdust pretreatment for briquetting. Torrefaction is the roasting of feedstock in near inert (oxygen-free environment) atmosphere between 159–300 ℃ temperature range to increase the heating value, hydrophobicity and improve its combustion characteristics [8,9]. Conversion of raw biomass into a high-energy-density, hydrophobic and grindable material through torrefaction is considered an appropriate practical method for commercial and household heating applications [8,9].

According to Zanzi et al. [10], torrefaction occurs during the first heating at temperatures lower than 160 ℃ and is followed by additional heating at temperatures above 160 ℃, which removes more water and produces CO_2. Hemicellulose degrades at 180–270 ℃, causing the biomass to break down and release moisture, volatile gasses, and low-energy molecules that turn brown instead of yellow [10]. Torrefaction turns completely exothermic at 280°C, producing more gas and causing the synthesis of other heavy compounds and extraneous gases [11]. Biomass and any type of wood or grass can be torrefied, and appropriate in use for the production of pellets, briquettes, and as a coal replacement in thermal power plants and metalworking processes due to its potentials in the creation of high-quality feedstock [12]. Torrefied biomass tends to be hydrophobic, brittle and easily grindable with significant energy and market potentials [4,8,9]. However, existing large-scale torrefaction reactors are usually very costly.

Fermentation process, 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 energy contained product, ease of processing, and material applicability for further processing, improved miscibility with liquid fuels, higher octane ratings, and reduced volatility [13]. Therefore, the main objective of this study was to investigate the effects of torrefaction, fermentation and binders on the physical, mechanical and combustion characteristics of briquettes produced from sawdust of *Gmelina arborea*. To achieve this, a laboratory-scale direct heating torrefaction batch reactor, a hydraulic piston briquetting machine, and a briquette stove were developed.

2. Techniques and preparations

Sourcing of untreated sawdust and characterization: *Gmelina arborea* sawdust acquired from different sawmills in Ishiagu, Ebonyi State, Nigeria was sorted to remove foreign matters such as stone pebbles, leaves, visible bark, etc. The feedstock after sieve analysis requires no size reduction and therefore used as received.

Particle-size distribution analysis were performed using ASAE Standard S319.4 test [14,15] to determine the particle size of sawdust in three replicates. Particle size distribution performed in a Rupson mechanical sieve shaker (manufactured by Fritsch® Germany) with stacked sieves of American Society for Testing and Materials (ASTM) mesh numbers #8, #12, #20, #35, and #40 with aperture sizes: 2.360 mm, 1.700 mm, 0.850 mm, 0.500 mm, and 0.425 mm respectively). Particle geometric mean diameter was evaluated using ASAE S319.4 test [14,15]. ASTM D2395-17 test protocol was used to obtain the particle mean diameter [15,16]. ASTM D7481-09 [17] standard was used to evaluate the biomass density.

2.1. Feedstock pretreatment and binder preparation

Feedstock pretreatment: A direct-heating torrefaction batch reactor was used for torrefaction, accomplished between 250–300 ℃ with limited air supply at three residence times of 30, 45, and 60 min [18,19]. Fermentation experiment was carried out in 20 L. transparent anaerobic plastic fermentation tanks with their lids covered to provide controlled environment for mesophilic reactions. Fermentation process involves soaking feedstock in water or solvent for 12, 24, 36, and 48 h, respectively to ferment at temperature range 37 to 41 ℃ [20,21]. After soaking, each fermented materials were drained at the end of fermentation time and the material rinsed with clean water and sun-dried to 9%–10% moisture content before being stored for briquetting. Products obtained from each process is shown in **Figure 1**.

Figure 1. Samples of untreated, torrefied and fermented sawdust produced.

Binder preparation: Binder selection was based on material cost and combustion properties. Two types of binders considered include waste papers (combustible) and clay (non-combustible). Waste papers (used printing paper (UPP) and newsprint (NP)) sourced locally were torn to pieces with hands and scissors, each stock was shred, soaked in plastic water jars at room temperature for days to pulp. After draining the water, the material was stirred into homogeneous pulp. The pulp was pressed with hydraulic press to the extract water. The pulp was then sun-dried to stop biological deterioration. To separate the individual fibers, the dried pulp was ground in a burr mill before storing it for briquetting. Fiber length and characterization were carried out at bioinstrumentation laboratory, Federal College of Agriculture Ishiagu.

The clay (montmorillonite) sample obtained from earthen pot site in Ishiagu was pound with a wooden rammer, dissolved in water and sieved using a 400-micron sieve mesh to remove sand and organic matter residues. The fine filtrate was allowed to settle for 3–5 days before being decanted to get a clayey suspension. The clayey suspension was sundried to produce clay cakes, which were ground and sieved to produce fine clay powder (about 125 microns), which was then stored in polythene (to prevent moisture absorption) before being used in briquette manufacture. API RP-13B standard procedures using NDJ-S8 type digital viscometer manufactured by Ningbo Movel Scientific Instrument Co., Ltd. China was used to determine clay rheological properties.

Feedstock and binder materials by weight were measured (**Table 1**) and mixed in proportions (90%:10%, 80%:20%, 70%:30%, 60%:40%, and 50%:50%) for briquette production. Briquettes were produced using a 4-piston Hydraulic Briquetting Press (HBP) [22]. The mould cups and piston plates were greased with SAE 90 lubricant prior to manufacture to reduce material friction during production. Per unit operation, four sets of twin briquettes (marked as AR1-8 for untreated, TB1-8 for torrefied briquettes, and FB1-8 for fermented briquettes) were produced.

Table 1. Weight of binder proportions used in briquette production.

Binder ratio (%w/w)	**Weight (g)**		
	G. sawdust	**Paper/newsprint**	**Clay**
90:10	374.5	41.7	175.1
80:20	327.9	43.3	375.6
70:30	291.9	124.9	437.0
60:40	249.7	166.5	655.5
50:50	208.1	208.1	874.0

2.2. Briquette characterization

Briquette characterization tests carried out included physical, mechanical and combustion tests. Measured variables include; density, durability, water absorptivity, shattering resistance, proximate and ultimate analysis, ignition, flame characteristics and performance in stove. Physical characteristics determined included briquette colour, weight, equilibrium moisture content (MC), and stability. Mechanical properties include Impact Resistance Test (IRT), shatter index test, and water resistance test. Proximate and ultimate analysis were performed using bomb calorimeter following [23] procedures, while the ultimate analysis was based on model Equations (1)–(3) developed by Parikh et al. [24], estimated at a 95% confidence level.

$$C = 0.637F_\mathrm{c} + 0.455V_\mathrm{m} \tag{1}$$

$$H = 0.052F_\mathrm{c} + 0.062V_\mathrm{m} \tag{2}$$

$$O = 0.304F_\mathrm{c} + 0.476V_\mathrm{m} \tag{3}$$

Water boiling test (WBT) and controlled cooking test (CCT) boiling rice (Oryza sativa) and yam (Discorea rotundata) with briquette samples were used to evaluate briquette combustion properties in the stove. A clay-lined biomass-burning stove was used in briquette burning to determine combustion characteristics.

Statistical analysis: Statistical analysis tools used in this study include Descriptive statistics to describe and establish relationships between dependent and independent variables, analysis of variance (ANOVA) to determine the effects of particle size, material density, residence time on sample performance [7]. Correlation was used to establish relationships between the dependent and independent variables while multiple linear regression analysis establishes the effects of material pretreatment, binder, and binder ratio on briquettes' dependent variables (density, moisture content, volatile matter, fixed carbon, ash, heating value), and independent variables (material density, particle size, and moisture) [25].

3. Results

3.1. Feedstock and binder characteristics

Physical properties of untreated and treated sawdust: The colour (**Figure 1**) and weight alterations in the torrefied samples were the most notable physical features. The colour of the untreated sawdust changed during the course of the roasting process at 250 ℃ for 30, 45, and 60 min in the batch reactor. At 30 min, it was light brown with black specks; at 45 min, it was dark brown; and at 60 min, it was dark brown (severe torrefaction). The colour typically turned black after 60 min of residence, producing char products. These colour changes are consistent with Sundqvist [26] findings that mild torrefaction occurs after 30 min, severe torrefaction occurs after 60 min, and blackness is related to a rise in carbon contents.

Colour changes in fermented sawdust were not significantly notable, however the physical examination of the soaking water revealed colour change from colorless to wine red, and that the colour deepened with increase in soaking time. This suggested that some of the extractive and volatile matter's chemical constituents might have filtered into the water. Additionally, it was found that the 48-hour fermentation tank produced more foam bubbles than the other tanks, which suggests increased enzymatic action that resulted in biogas emissions [27]. This might significantly affect materials' ability to join binders during densification, and possibly affect even the combustion characteristics. Additionally, the dried fermented samples' colour changes were not noticeably different among the fermented samples at different soaking duration, indicating that soaking did not influence colour alterations.

Binder characteristics: **Figure 2** showed samples of different binders used. Characteristics determined for paper binders include opacity, colour, and weight, ash-content and fiber length of the paper pulps. The opacity of used printing paper was lower, while the newsprint had better surface roughness and porosity. The used printing paper also had more brightness and greater basis weight compared to newsprint. The density of the used printing paper varied from 0.5 to 0.7 g/cm^3, while that of newspaper was ~0.4 g/cm^3. The used printing paper had higher ash content (35%) than the newspaper (12%). Newsprints pulp contained residue with shorter fiber length (~0.2–0.6) mm compared with used printing paper (~0.6–1.5) mm.

Figure 2. Samples of the three types of binder used in the experiment, **(a)** used printing paper pulp; **(b)** newsprint pulp; **(c)** clay suspension [28].

Table 2 present a summary of clay analysis values obtained from this study with values obtained by Udeagbara et al. [29] within the same experimental vicinity in Ebonyi state. The results showed some similarity in some properties with negligible differences in others. The difference could be explained from the viewpoint of instrumentation and experimental conditions.

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

Properties	***Local clay**	****Sample 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 (g/cm^3)	1.06	1.06
Viscosity (cp)	4.50	1461.5 mPa.s

*Udeagbara et al. [29], **Experimental value.

Briquette samples: **Figure 3** showed the briquette samples produced at 1.67 kPa found suitable for low-pressure briquettes production [30]. After ejection, the briquette required drying to lower its moisture content to an equilibrium state for stability, storage, and evaluation. Drying the briquettes in the open air after production was quite challenging due to the fluctuating weather conditions of the drying environment, especially between different batches of briquettes produced as the temperature and humidity changed. However, the conditions were carefully managed and the moisture was reduced to equilibrium moisture of <8%, then stored in sealed polyethylene bags for evaluation.

Figure 3. Briquette stack after 19 days of curing.

3.2. Briquette characteristics

Physical characteristics: The briquette colours varied for different binders, binder concentration and treatment conditions. The colours varied from deep brown colours (for higher clay concentration) to light brown for untreated and fermented clay briquettes to dark for torrefied briquettes. The colour variations are largely influenced by binder type, binder concentration, and material treatment method. A subjective visual observation revealed that the higher the binder concentration, the more attractive the briquettes. The mean external and internal dimensions of all categories of briquettes (**Figure 4**) did not vary significantly, with minimal reduction in the internal diameters from (0.04–0.11) mm and increased external diameter between 1.4 mm and 2.16 mm. The mean external (*D*) and internal (*d*) diameters of all treatments varied from 79.72 mm, 79.84 mm and 80.23 mm and 14.85 mm, 14.78 mm to 15.16 mm for untreated, fermented and torrefied respectively.

Briquette gravimetric characteristics described by compressed weights and relaxed weights after drying for 30 days for untreated and fermented briquettes is not significantly different. Torrefied briquettes have the least dry/relaxed weights irrespective of percentage binder concentrations and resident time, while clay briquettes have the highest dry weight values. The mean heights of compressed briquettes slightly increased with an increase in binder level, while the relaxed heights after 30 days slightly decreased with negligible ±0.10 mm variations.

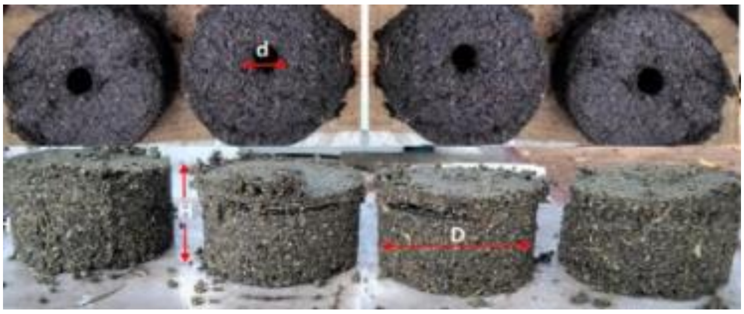

Figure 4. Briquette essential dimensions.

D = External diameter, *d* = internal diameter, *H* = height.

Briquette produced have a noticeable tendency of expansion in the diametral axis. Clay briquettes have the least elongation along the diametral axis 1.27%–1.68% and axial elongations 1.08%–2.80% respectively while the newsprint has the highest diametral and axial elongations. Briquettes with a low binder content elongate most readily along both axes, whereas other 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 that higher-binder briquette are more stable than low-binder briquettes. The average compressed density for untreated UPP varied from 560 to 795 kg/m^3, untreated NP (536 to 658 kg/m^3), and untreated CL (471 to 558 kg/m^3) respectively. The relaxed densities varied from untreated UPP (193 to 226 kg/m^3), untreated NP (184 to 206 kg/m^3), and untreated CL (209 to 226 kg/m^3) respectively. Compressed and relaxed densities for torrefied UPP briquettes varied from (622 to 549 kg/m^3) and (267 to 186 kg/m^3); and (699 to 205 kg/m^3) for newsprint binders, while the values for clay ranged from (894 to 596 kg/m^3)

respectively. The compressed and relaxed densities of fermented UPP briquettes varied from 720 kg/m^3 to 622 kg/m^3 and 224 to 285 kg/m^3, while values obtained for Newsprint binders varied from 787 to 217 kg/m^3 and those obtained for clay are 769 to 654 kg/m^3 and 852 to 316 kg/m^3 respectively. These values are higher than the untreated briquette density.

Mechanical characteristics: Briquettes durability were evaluated based on percentage weight loss/shatter index (toughness, %), the impact resistance index (IRI) and water absorption capacity. The shatter index evaluates the strength of briquettes directly for conveyance, handling, and storage. Untreated newsprint briquettes have higher weight losses when dropped on a hard surface while untreated clay briquettes have the least weight loss, which implies that untreated newsprint briquettes suffered more losses and hence were weaker than used printing paper and clay briquettes. Higher weight losses occurred in low binder briquettes and decreased as binder concentration increases. The shatter index decreased with an increase in binder concentration. Untreated newspaper briquettes at low binder concentration had the highest weight losses, while untreated clay briquettes had the least weight loss. Similar responses were observed for torrefied and fermented briquettes. In addition, high shatter indices were observed for torrefied briquettes with low binder concentrations, which decreased with increase in binder concentrations. Evidently, torrefied briquettes with 10% wt/wt binder concentration recorded the highest shatter indices while 50% torrefied binder briquettes have the least shatter indices. The higher the value of the shatter index, the lower the quality of the briquette, which is representative of poor durability at gravitational fall and wear. The shatter resistance increased with increase in binder concentration.

The ability of a briquette to withstand unforeseen loads was measured by the impact resistance index (IRI). Briquettes at different binder ratios for untreated, torrefied, and fermented conditions showed that the impact resistance index increased as binder concentration increases. Similarly, as binder concentration increased, the quantity 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 impact resistance index of untreated briquettes varied from 25%–400% for untreated used printing paper, 14.29%–400% for untreated newsprint briquettes, and 33.33%–400% for untreated clay briquettes respectively. Considering the effects of different treatments, torrefied briquettes have the least impact resistance index, while newsprint briquettes have the least impact resistance index. The impact resistance index lower than 90% has a greater tendency to break on impact according to Borowski [31] report. The interactions between impact resistance index and binder concentration showed strong linear relationships. The impact resistance index decreased as torrefaction time increases from 30 min to 60 min, which suggested that, the addition of a higher binder percentage to torrefied sawdust could improve its impact resistance index. All torrefied and fermented briquettes showed high positive correlations with binder concentration which implied that an increase in binder concentration increases the impact resistance index of the briquette, with practical implications that binder concentrations above 10% binder levels using any of the treatments and binders are adequate for desirable briquette durability [6].

Briquette water absorption capacity and dispersion resistance: The weight gain for untreated, torrefied, and fermented briquettes in water increased in the order: used printing paper, clay, and newsprint for untreated briquettes while it decreased with increase in binder concentration. Untreated clay briquettes dissolves in water after 15 min of immersion, while untreated used printing paper and untreated clay remained undissolved through the 60 min of immersion. Torrefied and fermented briquettes gained weights at immersion but dissolved after 15 min of immersion in water. The percentage water absorption of used printing paper and newsprint briquettes rapidly increased from the initial weight of ~5 g to over 25 g within 15 min of immersion and slightly absorbed moisture for 60 min. However, clay briquettes gained less weight within 15 min of immersion and subsequently dispersed in water. Furthermore, an increase in binder concentration resulted in increased weight gain for all briquettes.

The water absorption capacity of untreated briquette samples was very low, disintegrating rapidly in water. The water absorption capacity of torrefied newsprint briquettes per unit of time was higher than clay briquette samples. Fermented paper briquette samples exhibited similar dispersion characteristics as the untreated samples. Fermented clay binder briquettes had the least resistance to disintegration in water, hence remaining highly unstable after immersion and soluble in water, especially at higher binder concentrations from 20%. This implied that clay-bonded briquettes have relatively high-water absorption characteristics and poor hygroscopicity. These findings suggest that the type and concentration of binder have a considerable impact on briquette hygroscopicity. UPP torrefied briquettes exhibit a high affinity for water, sometimes reaching 100% saturation in less than one hour and hence, good water absorptivity while clay briquette exhibits poor water absorptivity and hence poor durability in water. In addition, the water dispersion characteristics of the briquette are not affected by the fermentation process or time.

Clay briquettes disintegrated after some time in the water, while paper briquettes with 50% binder concentrations sank in the water. These results implied that increasing the binder ratio improves water resistance to dispersion.

Briquette chemical characteristics: Proximate and ultimate analysis tests were used to evaluate the percentage compositions of the chemical elements in each briquette. The ultimate (elemental composition), and HHV of untreated and treated briquette samples are shown in **Figures 5–7**. Comparing the proximate percentage values (ash, VM, FC) of torrefied and fermented briquettes, torrefied used printing paper briquettes have lower VM and higher FC than the newsprint briquettes while fermented briquettes had higher VM and ash contents than torrefied briquettes.

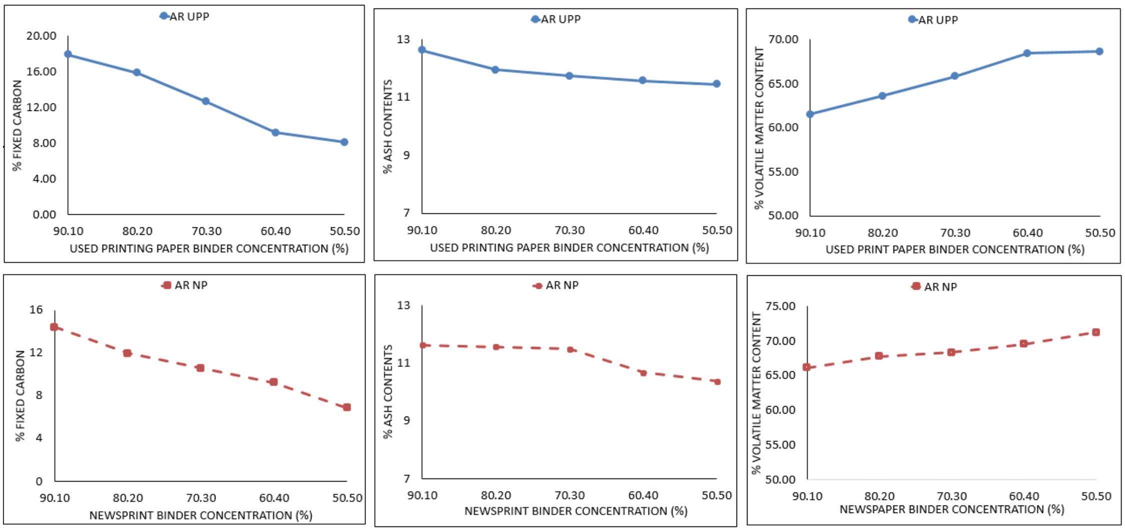

Figure 5. Proximate analysis of untreated, used printing paper (UPP) and newsprint (NP) briquettes.

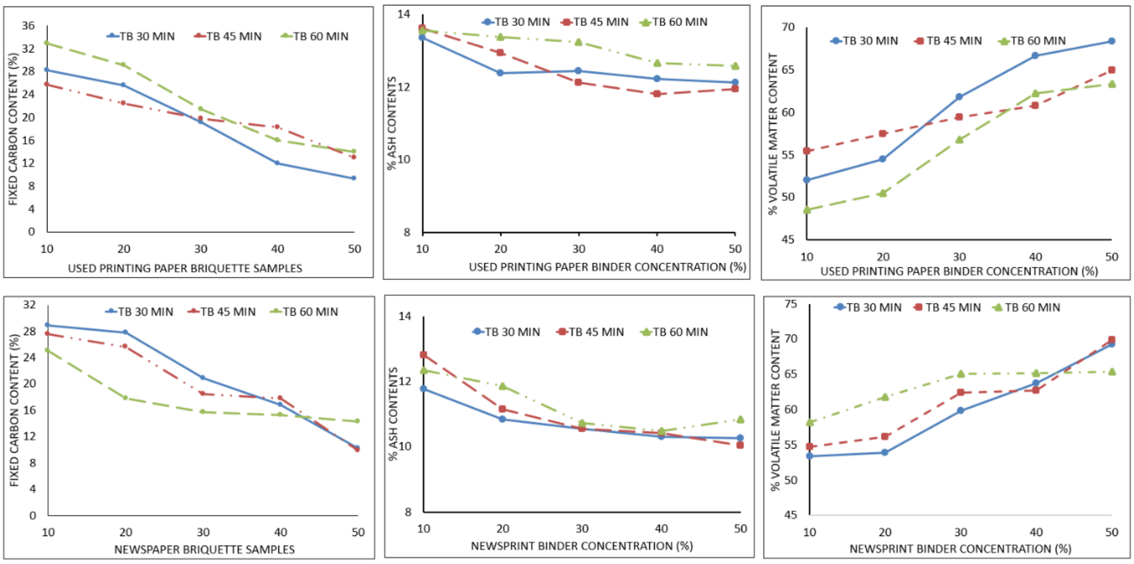

Figure 6. Proximate analysis of torrefied briquette samples.

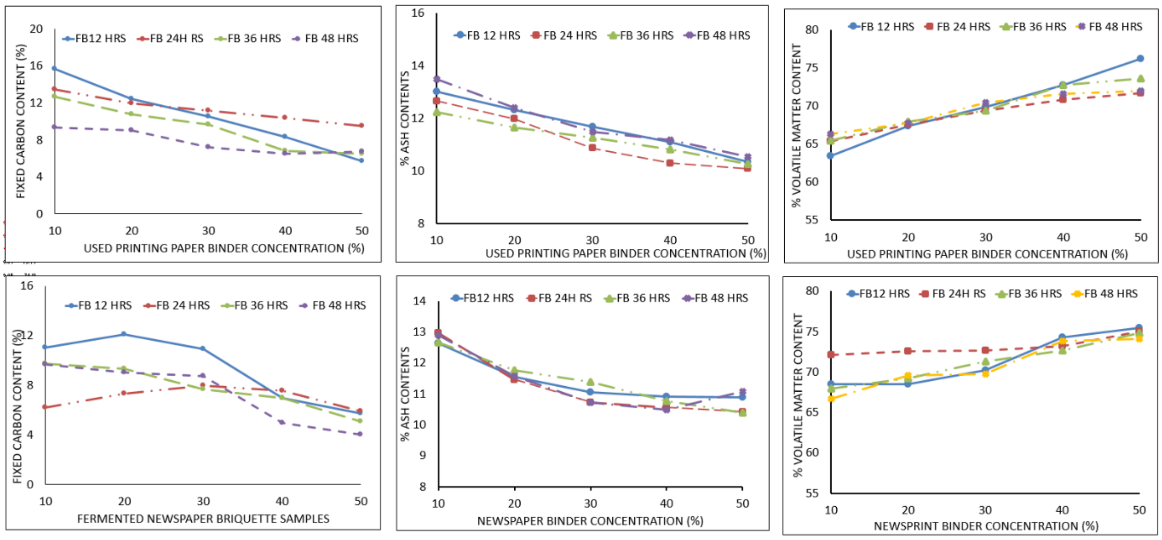

Figure 7. Proximate analysis of fermented used printing paper (UPP) and newsprint (NP) briquettes.

Atomic ratio (O/C and H/C): The capacity of each fuel to generate heat was predicted using the atomic ratios (H/C and O/C). For torrefied briquettes, the H/C and O/C was between 0.11 and 0.15, and 0.95 and 0.98, respectively. These values matched Nhuchhen [4] values. In contrast to TB, the atomic ratios of FB showed a distinct decline. Lower ratios indicated higher energy content [32]. Balogun et al. [33] reported a comparable decrease from >0.6 to ≤0.3 for O/C atomic ratio for woody and non-woody biomass. These ratios were observed to be lower than other types of fuels [18,32,34]. Because the HHV range of values tends to be constant for fermented briquettes, it is difficult to see how the atomic ratios affect the HHV. This finding is at variance with Ajimotokan et al [32] observations of increased O/C atomic ratio, while biomass HHV decreased. However, comparable findings are possible when evaluating biomass without binder addition.

Combustion characteristics of the briquettes: The observed self-ignition duration ranged from 3 to 5 min for all categories of briquettes, whereas clay briquettes took a longer time (7–10 min), burn with a steady flame for 10 to 15 min before decomposition stage [35]. The non-combustibility of tiny clay particles that filled the biomass matrix caused the observed delay in clay briquette ignition, eliminating oxygen, which is necessary to support burning. According to this discovery, briquettes with low clay content could be utilized for large-scale industrial heating but are not recommended for use in residential cooking.

The observed flame propagation and burning stages correlate to the three briquette phase-burning stages. Smouldering occurred within the central hole as the flame extended around the briquettes, expanding into a mixture of bright yellow flame at the perimeter and spinning non-luminous blue flame around the core hole, resulting in a rapid increase in flame height. The flame propagated into a dazzling white flame at the height of burning as the briquette disintegrated, then transitioned into a glowing flame around the briquette. As the volatile elements burnt, the flame quickly degenerated into char combustion and burnout. Except for clay briquettes, all briquettes made from used printing paper and newsprint possessed these characteristics.

The mass reduction was performed to determine the rate at which each briquette mass decayed as it burned. Each briquette was ignited in free air and the mass reduction was recorded until the briquette mass had been reduced to between 3%–5% of its initial weight. At the 5% level of significance, it was found that newsprint had the greatest mass reduction while clay briquettes had the lowest mass reduction across all treatments [28]. The fermented used printing paper briquettes have higher mass reduction than those of other briquettes as binder concentration increases. Additionally, the exponential (decay) curve for the rate of mass reduction in lower binder briquettes was greater than in higher binder ratios. Newsprint briquettes exhibit slightly greater mass reduction than used printing paper briquettes for all treatments.

Untreated used printing paper and newsprint briquettes burn with considerable quantities of smoke during ignition, then lesser smoke during phase burning, and finally no smoke at burnout. Used printing paper briquettes have lower VM and oxygen contents than the newsprint briquettes; hence, their smokiness was reduced during the experiment compared with newsprint. Untreated clay briquettes had poor ignition and phase burning, but burn essentially by char combustion therefore, the smokiness cannot be evaluated substantially.

All torrefied briquettes (used printing paper and newsprint) produced visible smoke at the ignition, with a considerable reduction in smokiness at the flaming stage as the entire outer surfaces were engulfed completely in flame, then the smoke vanished. The extent of the smokiness of each briquette reduced with torrefaction time (i.e., the TB30 MIN > TB-45 MIN > TB-60 MIN) while an increase in binder concentration showed a slight increase in briquette smokiness. The Smokiness of high binder torrefied briquettes was not significant compared with fermented briquettes of least binder concentration. The smoke produced from untreated sawdust was the highest at all binder concentrations. Observed smokiness of torrefied used printing papers reduced significantly and tolerable than torrefied newsprint briquettes with unpleasant darker smoke with noticeable carcinogenic sensation when inhaled. This effect could be adduced to binder material, concentration, and torrefaction time for *G. arborea* sawdust. According to these observations, TB-60 MIN used printing paper briquettes emitted the least smoke; however, from an economic standpoint, 45 min used printing paper torrefied briquettes (TB-45 MIN) outperform TB-30 MIN and TB-30 MIN briquettes in the three main variables evaluated (i.e., pretreatment conditions, binder type, and concentration).

All fermented briquettes produced substantial smoke, however, at higher binder ratios and increased fermentation time; there was a significant reduction in smokiness. In comparison to treatment, fermentation have less observable influence on smokiness. Based on binder type, fermented used printing paper briquettes produced less observable smoke than newsprint; smokiness decreased as binder concentration increases. These findings show that when compared to untreated briquettes, fermented briquettes generated significantly less heavy, black smoke. This demonstrates that fermentation only slightly reduces, rather than substantially eliminates smoke in briquettes. Drawing conclusions from all briquette performances, the most significant pretreatment approach that significantly minimizes briquette smokiness is a combination of moderate torrefaction (i.e., 45 min) and used printing paper.

Briquette combustion characteristics: The performance of the briquettes was examined by burning them (water boiling test, WBT) in a constructed biomass stove to determine the burn rate and thermal efficiency of the stove. The time required to heat water to 100 ℃ was compared using WBT) [36]. The thermal efficiency values obtained for untreated used print paper and newspaper briquettes are 33.20% and 34.55% respectively, respectively. The thermal efficiencies obtained for torrefied briquettes at 30, 45 and 60-minute torrefaction are: used printing paper torrefied 28.40%, 29.93%, and 29.46%, and newsprint torrefied 25.96%, 24.84%, and 24.66%, respectively. For fermented briquettes, the mean values are; used printing paper 30.46%, 29.08%, 34.68%, 32.08, and newsprint 34.01%, 34.20%, 33.00%, 34.55% for 12, 24, 36 and 48 h respectively. From these results, untreated newsprint briquettes have the highest thermal efficiencies due to their highly volatile contents. The stove thermal efficiency increased with an increase in binder concentration and decreased with torrefaction time. Thermal efficiencies of fermented do not differ significantly from untreated briquettes. The results of range of thermal efficiencies for untreated briquettes (31.47% and 39.89%), torrefied briquettes (17.13% and 38.52%), and fermented briquettes (23.84% and 39.89%) are generally within the range of results reported from other studies [6,37,38]. It is clear from the aforementioned that torrefaction period had a significant influence on the variations in stove thermal efficiency. Furthermore, the differences in thermal values for untreated and fermented briquettes exhibited a minor variation as binder content increased. These findings demonstrated that treatment, binder type, and concentration had major impacts on thermal efficiency.

Control cooking tests (CCT): Rice and white yam were used in the control-coking test (CCT,) to evaluate the performance of each briquette using a biomass stove. The time taken to burn 200 g weight of briquettes ranged from 32 to 39 minutes. 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 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. For all briquettes burned in the stove, the length of time required cooking 1 km of yam and rice does not differ significantly (minimum 0.53/0.31 h) and (maximum 0.62/0.34 h) for torrefied briquettes. In practice, this means that a smaller number of torrefied briquettes will cook the same amount of food as untreated or fermented briquettes.

Specific fuel consumption (SFC): The stove means specific fuel consumption (SFC) in heating 206 g of rice and 175 g of white yam with untreated and torrefied, and untreated and fermented briquettes. With increasing binder concentration, the stove-specific fuel consumption (SFC) for each briquette increased. Untreated newsprint briquettes have the highest mean SFC values of 0.718–0.745 and 0.714–0.748 for cooking rice and yam respectively, torrefied briquettes have the least SFC values among the three treatments with the highest mean value of 0.581 for used printing paper and 0.575 for newsprint briquettes cooking rice respectively.

When the specific fuel consumption (SFC) values were compared to the binder concentrations, the SFC values for all torrefied used printing paper and newsprint briquettes decreased; however, at there were no significant difference in the SFC values at higher binder concentrations. The increase in binder concentration and lignin content and volatile matter content decrease could be consequential decrease in the SFC. The SFC values obtained for untreated briquettes increased with increase in binder contents. For all fermented briquettes, similar patterns were seen (**Figure 8**). Additionally, the fermented used printing paper has higher SFC values than fermented newsprint briquettes. The high volatile matter contents of both materials, which are in line with literature reports, could explain this observation. These findings suggest that binder concentration, rather than fermentation time, has a greater impact on the SFC of fuel briquettes. The specific fuel consumption values obtained in this experiment for untreated and fermented fuel are greater than the values of 0.48 reported by Olorunnisola [39] and 0.4 reported by Oyedemi [6], but the SFC values obtained for torrefied briquettes falls between 0.5 and 0.6.

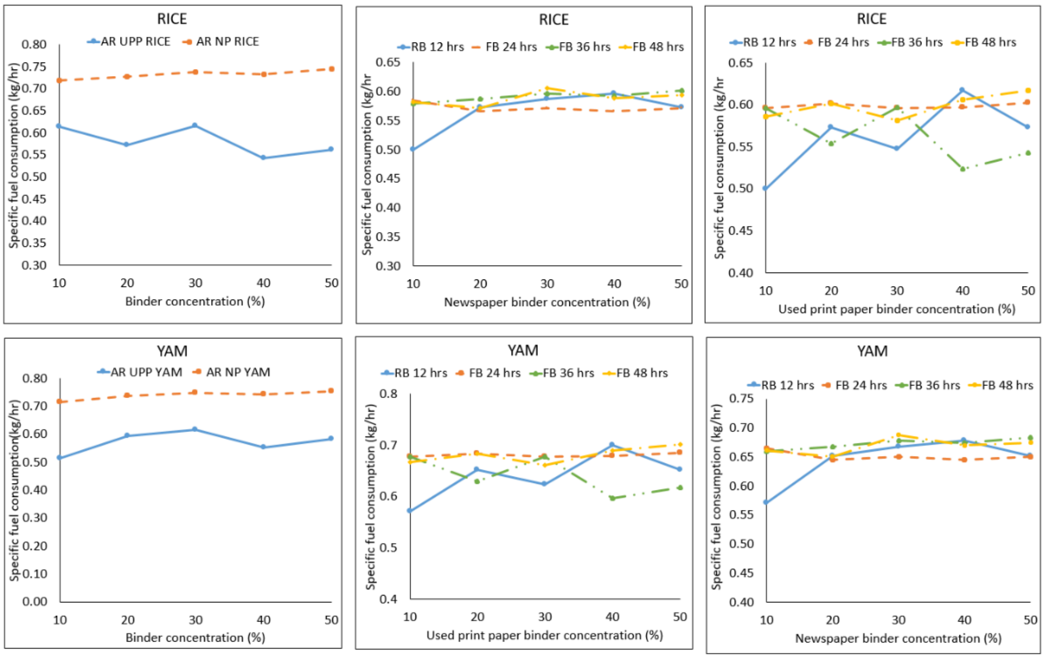

Figure 8. Specific fuel consumption of untreated and fermented briquettes.

The direct effect of this is that less briquettes are needed to boil a predetermined amount of food on the stove. Torrefied used printing paper briquettes would therefore be favoured if untreated, torrefied, and fermented briquettes were put in a comparable competitive market because of their favourable production costs, decreased smokiness, and favourable specific fuel consumption characteristics. This result was consistent with what Olugbade et al. [40], who conducted a thorough investigation into the combustion properties of several agricultural wastes, had stated as the scenario.

Fuel consumption rate (FCR): The number of briquettes burned in a given amount of time to cook a given amount of food is indicated by the fuel consumption rate. For every sample briquette, the fuel consumption rate for cooking 206 kg of rice was assessed; the findings are displayed graphically in **Figure 9**. The consumption rate of the three fuels increased with binder contents. Furthermore, the binder type and treatment method showed a negligible effect on the rate at which fuel was consumed; with slight variations demonstrated by torrefied and fermented briquettes. Furthermore, at lower binder concentrations, a minor increase was found for used printing paper and newsprint torrefied briquettes, which increased significantly, as binder concentration increased.

The 60-minute torrefied briquettes had lower fuel consumption rates, while the 30 min torrefied briquettes had the highest rates, implying that more 30 min torrefied briquettes were consumed in cooking, and less 60 min torrefied briquettes were consumed for cooking the same amount of food. 45 min used printing paper torrefied briquettes consume more fuel than newspaper torrefied briquettes, but at higher binder ratios, their rate of consumption is equivalent. This meant that the consumption rates of both fuels were comparable. According to these findings, 45-minute torrefied briquettes are just as good as 60-minute torrefied briquettes. By inference, 45 min torrefied used printing paper briquettes are economically preferred due to timesaving in material processing.

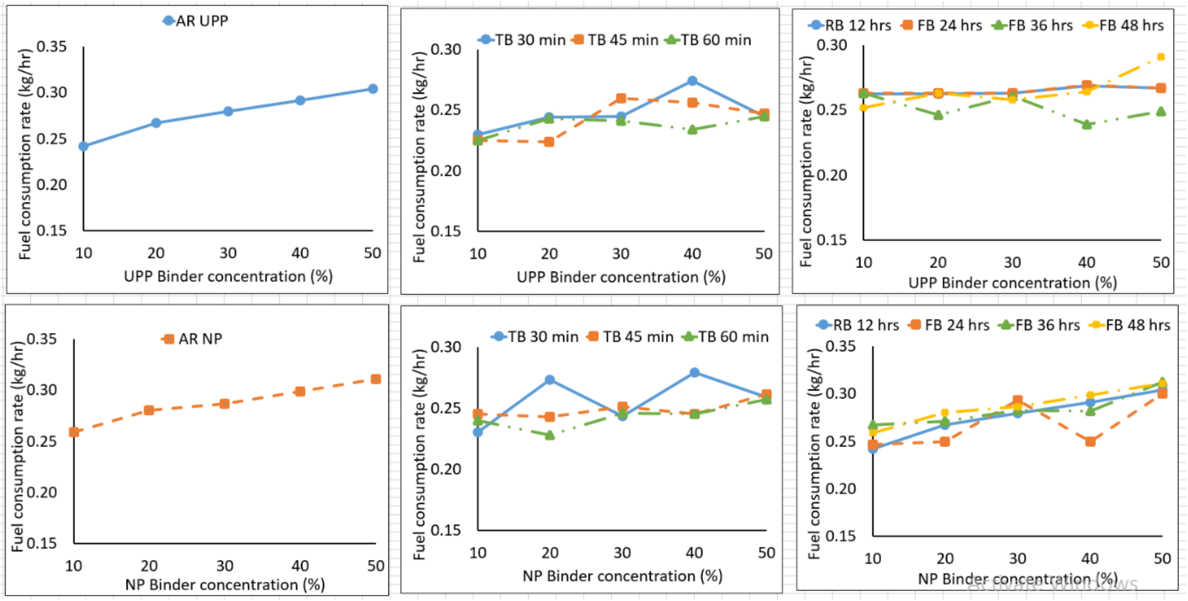

Figure 9. Fuel consumption rate (FCR) of untreated and treated briquettes.

For fermented briquettes, the fuel consumption rates are slightly lower compared to untreated briquettes but slightly higher than torrefied briquettes with different quantities of binder. The extraneous components in untreated sawdust eliminated by fermentation and torrefaction, could explain this outcome. Similarly, for all briquettes, the FCR increased binder concentration increases. This implied that high binder concentrations had a substantial effect on briquette performance in briquetting, which is consistent with the findings of Nikiema et al. [41] on the optimization of corncob briquettes.

4. Conclusion

The influences of torrefaction, fermentation, and binders on combustion related attributes of briquettes produced were evaluated according to the objectives of this study. The feedstock material selection, preparation, briquette production, products characterization, and combustion performances of different products obtained in this experimental study were discussed with the following conclusions established.

1) The *Gmelina arborea* sawdust with mean material particle density for the replicate samples value of 159.30 ± 0.02 kg/m^3 is within the range of values found in literature is suitable for production of good quality briquette.
2) Torrefied sawdust colour varied significantly with increase in torrefaction time and energy yield, there were no significant visible differences in colours of fermented sawdust at different soaking times. Torrefaction time of 45 min is suitable to produce torrefied sawdust without consequences of energy or economic losses.
3) Judging from the observed characteristics, the used printing paper has greater comparative advantage of producing better quality briquettes over newspaper in terms of durability and combustion characteristics.
4) Used printing paper and newsprint binders have similar binding characteristics;

however, used printing paper has longer fiber characteristics, readily available, and is less expensive compare with newsprint, therefore more suitable for briquetting. Clay has good binding properties but poor combustion characteristics.

5) The briquette samples are structurally stable and satisfied quality characteristics of briquette. Fermented used printing paper briquettes have better mechanical characteristics compared with torrefied briquettes. Torrefied briquettes have better combustion characteristics than other briquettes. Used printing paper and newsprint briquettes burned with luminous flames while clay briquettes burn by char combustion.

Recommendations

In accordance with the findings, following recommendations were made for future research study.

1) Further studies on the environmental impact assessment and economic viability of the torrefaction and briquetting process.
2) Additional research works on the torrefaction of other energy woods to expand torrefaction knowledge.
3) Optimization studies required on torrefied sawdust produced at 40, 45 and 50 min torrefaction time using appropriate optimization tools.

Author contributions: Conceptualization, RSB and AOO; methodology, RSB; software, RSB; validation, AOO, TEO and MAO; formal analysis, RSB; investigation, RSB; resources, RSB; data curation, RSB; writing—original draft preparation, RSB; writing—review and editing, AOO, TEO; visualization, RSB; supervision, AOO, TEO and MAO; project administration, AOO; funding acquisition, RSB. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: I wish to express my profound appreciations to Olorunnisola A. O., Omoniyi T. E., and Onilude M. A., for providing unwavering and invaluable supports towards the conception and experimentation of this work. I equally appreciate the efforts of Adewole N. A., Department of Wood Products Engineering, for providing enabling environment during the research work. I thank the entire staff of the Technical Support Unit (TSU), University of Ibadan for technical supports during the laboratory work.

Conflict of interest: The authors declare no conflict of interest.

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