

Effects of Binder Concentrations and Soaking Time on Combustion Characteristics of Briquettes Produced from Fermented *Gmelina Arborea* (Roxb) Sawdust and Used Print Paper

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Abstract

Low-density briquettes are known for having several undesirable characteristics, such as an intense yellow flame and smokiness that are too high for domestic applications. The pretreatment of feedstock has been identified as a tool for addressing these issues; however, process costs and variability conditions has significant impact on the selection and performance of these methods. Consequent on these, fermentation method was employed to investigate the effects of binder concentration and soaking time on briquettes produced from fermented *G. arborea* sawdust and used print paper binder in this work. Untreated sawdust samples were collected from sawmill's dumpsite and soaked for 12, 24, 36, and 48 hours under mesophilic and anaerobic conditions while used print paper were converted into pulped fiber. Briquette mix ratio by percentage weight proportions varied from (10:90-50:50) % dry basis. A statistical analysis of briquette densities revealed a significant positive correlation between the densities of fermented briquettes and the binder concentration at ($p < 0.05$). Thermal efficiency decreased with increase in binder concentration with no significant difference in fermentation time, while the specific fuel consumption increased with increase in binder concentration. Fermentation time and binder concentration slightly improved the combustion characteristics of briquettes. Economic analysis suggested economic viability of the process.

Introduction

Sustainable biomass resources development for energy purposes requires adequate knowledge of biomass quality, which has potential towards forest-based bioenergy sector development, resulting in its increased and efficient utilization (Álvarez-Álvarez, et al., 2018). As society becomes more mindful of their influence on the environment and looks into eco-friendly and more efficient alternatives, wood biomass gradually become one of the fastest-growing affordable renewable technology material sources, with an estimated $4.39 \times 10^6 \text{ m}^3$ of log split and plywood processed annually in Nigeria between 2010 and 2015,

which translates to about 42 tonnes of sawdust generated from every 100 tonnes of timber (Ohunakin, 2010; Tokan *et al.*, 2014; Kiss and Alexa, 2015; Onuora et al, 2015). Improvement in the properties of these abundant materials through pretreatment and densification is an effective and productive way of converting them to useful forms. Among the renewable energy resources, biomass is considered a feasible option for sustainable energy development due to its carbon neutrality, sustainability and vast abundance. Research reports have shown that utilization of cheap and abundant lignocellulosic biomass such as sawdust has become a promising alternative to the edible environmentally and economically beneficial feedstock

(Perlack et al., 2005). These lignocellulosic materials are complex due to the presence of water, lignin, volatile matter, extractives, ash etc. that poses combustion limitations to the final product quality when densified (Wyman et al., 2005).

Despite the positive attributes of biomass, there are limitations to their utilization as a direct feedstock for power generation and limit their replacement as fossil fuels for energy production (Nhuchhen, 2016). These limitations include smoke generation above acceptable levels in domestic applications, yellow flames, high particle moistures, low energy density, hydrophobicity, high oxygen contents among others (Matali et al., 2016). In addition, lignocellulosic biomass possesses firm and fibrous nature, and its grindability pose a challenge requiring high-energy consumption during fuel preparation (Liu and Han, 2015). To overcome these undesirable properties, an appropriate technological solution is required which this study is set to accomplish through pretreatment of feedstock prior to densification.

Pretreatment of lignocellulosic materials for biomass-to-fuel conversion have been recognized and in use for a long time (Kumar et al., 2009). Several methods of pretreatment have been developed to pretreat lignocellulosic material (Mosier et al., 2005), however, to considerably optimize their performance in bioenergy applications, process selection and cost considerations are key factors (Moral and Nawsher, 2004). Fermentation processes have been developed with different comparative advantages in energy contents of product, process simplicity, suitability for domestic applications and less volatility (Shi et al., 2012, Gautam and Martin, 2000).

Fermentation is the process of soaking biomass in liquid medium for a period of time with the purposes of reducing the volatile matter content and retaining the cellulose and hemicellulose structure and was viewed as the cheapest pretreatment method from the point of view of equipment cost and process complexity. This research therefore significantly provided opportunity to investigate the physical, chemical and combustion characteristics of briquettes produced from fermented sawdust of *Gmelina arborea* soaked in water at four soaking time of 12hrs, 24hrs, 36hrs and 48hrs. The research hypothesis seek to produce briquettes with improved combustion performance and acceptable level of smoke emissions than untreated briquettes.

Materials and Methods

Materials

Sawdust of *Gmelina arborea*, being an energy wood, widely distributed and available in large quantities within the study area was selected for experimentation. Based on combustion characteristics and economic cost considerations, used office print paper (UPP) was selected as binder. Pretreatment

apparatus include 4 fermentation tanks of 20 lts capacity for soaking, a hydraulic press for briquette production and a biomass stove for combustion tests.

The fermentation experiment was conducted under mesophilic and anaerobic conditions. The fermentation tanks are transparent 20lts plastic containers with a lid cover to provide a controlled environment to allow mesophilic reactions takes place around 37-41°C (98.6-101.6°F) temperature through anaerobic fermentation (Plate 3.3b). An equal amount of dried feedstock material is poured into each labelled tank and water added to completely saturate the material and then covered. The setup was left to ferment for the designated duration of time of 12h, 24h, 36h and 48h respectively. At the end of each time, the water was drained, the material rinsed with clean water and sundried ready for binder mixing for briquetting.

The experimental briquetting apparatus is a four-piston hydraulic press installed with a two-pocket spring balance symmetrically positioned beside the hydraulic jack to measure the load applied by the jack to the piston. The major components of the machine include the frame constructed of angle iron, a 5-tonne hydraulic jack, a square pressure plate and four split-cylindrical moulds with locking devices, a water drain chute, and a 4-piston assembly (Plate 3.4). The briquette combustion apparatus used was a developed biomass stove with clay lining. The stove consists of two compartments; the combustion chamber (firebox where the briquettes are burnt) with clay lining and the ash collection compartment

Experimental Methodologies

Material Samples and Preparation

Raw or untreated samples of sawdust produced from a tablesaw machine with a 4-inch, 1-TPI blade was obtained from Uche sawmill located along Okue road in Ishiagu. The materials were used as received, requiring no size reduction. The untreated material was sorted for foreign matters and the particle distribution analysis carried out on representative sample using a sieve shaker. Measured samples of the untreated samples were then introduced to the 20lts plastic containers, and water was added to soak at ambient conditions for 12hrs, 24hrs, 36hrs and 48hrs. The fermented contents from each tank were rinsed with water after the soaking period and sun dried to moisture contents of 8-10%, then stored for densification.

Samples of 70gm wt. of used office print paper (UPP) were shredded into random small pieces using hand and scissors, and soaked in water at room temperature for several days to pulp, then excess water was a drained, mechanically stirred to a homogenous pulp. Subsequently, drained by compaction it in a polystyrene woven bag in a hydraulic press, and then thoroughly sundried to about (8-10) % moisture content (MC) to prevent biological degradation. The dried pulp

was ground in a burr mill to isolate clogged fibers and then stored for briquetting.

Material mix ratios was determined considering material breakdown time and concentration/proportion (Chaney, 2010; Amin et al., 2017). The proportions of feedstock mix to binder material ratios were based on percentage weight proportion i.e., 90:10%, 80:20%, 70:30%, 60:40% and 50:50% (dry basis) respectively. The mix ratio was determined by measuring out proportions (in grams) of *Gmelina* sawdust and each binder to give the percentage ratio of biomass-binder mix according to Yazdani and Ali, (2015). Two operating conditions considered during briquette production include residence time and operating pressure. A residence time of 5 minutes was allowed for the compressed material to remain under compressive axial load of 45kg was and a corresponding pressure of 169.80 kPa was selected for briquette production.

Sawdust Characterization Experiments

Characterization experiments performed include particle size distribution, density, geometric mean sizes, and particle moisture. The particle size distribution was determined by particle size evaluation was determined using ASAE Standard S319.4 test procedures (Karunanithy, et al., 2012) by placing weighed samples in stacked sieves arranged in decreasing order of sieve openings (2.36, 1.70, 0.085, 0.05 and 0.04) mm on the vibrating block of the sieve shaker to obtain retained mass samples on each sieve. The geometric mean diameter was determined according to ASAE S319.4 test procedure (Karunanithy et al., 2012). Mass to volume ratio relationship was used to determine the untreated and fermented sawdust particle densities using the mean values of three (3) replicate samples according to ASTM D7481-09 (2009) standard. The binder characterization experiments were performed at the hydraulics laboratory of the Federal College of Agriculture Ishiagu to determine the fiber length.

Briquette Characterization Experiments

The characterization of briquette produced was performed using scientific standard testing methods and analysis. Some of these tests include: Briquettes impact and water resistance tests (i.e. durability) performed according to (Ajayi and Lawal, 1995; Yaman et al., 2001). The equilibrium moisture content (EMC) determined 30 days after production. Oven-drying method was used by placing initially measured sample weights (W_1) of briquette in the oven set at 103 °C for 24 hours. The samples were thereafter cooled in desiccators, then reweighed (W_2). The equilibrium moisture content was evaluated using equation (1) given by Maharani et al., (2010):

$$EMC = \frac{W_1 - W_2}{W_1} \times 100\% \quad (1)$$

Where: W_1 = initial sample mass before drying, W_2 = final sample mass after drying

The proximate and ultimate analysis experiments were carried out according to the procedures presented by Nhuchhen and Afzal (2017), water boiling test and control cooking test. The effects of various process variables such as ignition time, burn rate, flame propagation etc. were determined by burning each briquette in free air and in stove respectively. Free air burning was achieved by burning each briquette on a steel wire mesh placed on a hollow dish which allowed free airflow under and around the briquette when lighted.

Experimental Variables Evaluated

The variables evaluated in this study include percentage mass of *Gmelina* and binder in the blends (concentration, %) and residence/soaking time (fixed) for briquetting. The response variables (dependent variables) measured include compressed density of the briquettes (i.e. density measured immediately after extrusion from the mould) and relaxed density (i.e. density measured after 30 days of curing), chemical (volatile matter, ash content, fixed carbon content, calorific value (HHV)) and combustion (ignition time, burn rate, specific fuel consumption, thermal efficiency) characteristics respectively (Bangboye and Bolufawi, 2008, Olorunnisola, 2007). The stove thermal efficiency was evaluated by burning known quantity of briquette samples in the stove and measuring the temperature change, duration and briquette heat capacity in raising water to 100°C during water boiling test.

The effects of the interactions between each variable were estimated as the variances between the mean for each level of interaction and total average response according to Muazu & Stegemann, (2015). IBM SPSS PC Version 20.0 Software was used as statistical tools and four statistical models; descriptive statistics, analysis of variance (ANOVA), correlation and multiple linear regression analysis were used in analysing data obtained from the experiments.

Results and Discussions

Characterization of Untreated and Fermented *G. Arborea* Sawdust

Characterization was performed to determine particle size distribution, geometric mean length, particle density and particle moisture of untreated sawdust. The particle size analysis showed the proportions of particle sizes which help classified the *G. arborea* sawdust samples into four fractional sizes: oversized (OS), coarse size (CPS), coarse pin (CPP) and fine pin particles (FPP) with a significant amount of specks of dust. The analysis showed the following sizes: oversized (2.38mm), coarse (1.70mm), coarse pin (0.85mm), fine size (0.50mm) and fine particle size

(0.40mm) similar to Rizki et al., (2010). The geometric mean particle length measured on the sieves is 8.57mm and the mean standard deviation obtained was 4.594 with a maximum standard error of 2.27 at a 95% confidence interval. These attributes were considered suitable for briquetting according to Rizki et al., (2010). The mean untreated particle density determined at mean moisture content of 9.41% was $159 \pm 0.02 \text{ kg/m}^3$ which is within the range of values of (124 – 240 kg/m^3) reported by Rizki et al., (2010).

Physical examination of fermented sawdust revealed that the soaking water showed increased colour concentration from colourless to wine red as the soaking duration increased. This implied that some chemical components of the volatile matter and extractive constituents might have drained into the water. It was also observed that foam bubbles appeared more on the 48 hours fermentation tank than the other tanks, suggesting increasing enzymatic reactions with an increase in soaking time, leading to biogas emissions. This could have some significant effect on the adhesive bonding of some materials and binder activity during densification and some probable effects on combustion characteristics. In addition, colour changes in the dried fermented samples were not significantly different, suggesting that soaking does not affect colour variations.

Chemical Composition of Sawdust Sample

The proximate analysis of untreated “as received” *Gmelina arborea* sawdust sample at approximately 7.78% moisture content showed that the untreated *Gmelina arborea* sawdust has low ash (2.19%) and carbon (17.10%), and high volatile matter (72.93%) contents. These values fell within, and in good agreement with other values reported in research outcomes (Mohamed et al., 2019; Bhatti and Chouhan (2016); Srinath and Goli (2011)). In addition, it was observed that the variations in the material variables are largely dependent on the differences in the percentage moisture contents of samples used (Mohamed et al., 2019). There is a slight reduction in the percentage values of elemental compositions; ash (2.07%), carbon

(22.80%), and high volatile matter (75.13%) contents obtained for fermented sawdust samples. Although the observed mean values of the proximate analysis of the fermented briquette samples do not significantly differ from those of the untreated briquette sample, at various soaking times, their effects on smokiness and flame burning may be significant.

Briquette Physical Characteristics

Briquettes produced (Figure 1) 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. The colour of briquettes produced varied from golden yellow to grayish yellow as the binder concentration increases, however, there is no significant variation in color as the soaking time increased. The representative samples of untreated and fermented briquettes obtained are stable, with exemptions of samples from 90:10% wt/wt binder concentration which are fragile and easily disintegrate under slight pressures. The percentage diametral and height elongations for untreated and fermented briquettes varied from (1.27-1.68) % and (1.08-2.80) % respectively. Low binder briquettes have the higher elongations at both axis while the expansion decreased with increase in binder content. Fermented sawdust at different fermentation times and binder concentrations showed stability as regard changes in height. From this results, it can be inferred that binder concentrations significantly affect briquette quality, stability, and consequently the combustion characteristics (Oyedemi, 2012).

Briquette Compressed and Relaxed Density

The mean maximum compressed densities (i.e. density determined immediately after production) for different pretreatment conditions varied from 560 kg/m^3 for 90:10 wt/wt binder concentration to 795 kg/m^3 for 50:50 wt/wt binder concentration for untreated briquettes, and varied from 622 kg/m^3 to 720 kg/m^3 for 90:10 wt/wt binder concentration. The compressed density for fermented briquettes increased



Figure 1. Briquette samples produced from fermented sawdust.

with an increase in binder ratio (Figure 2) while it decreased for untreated briquettes with low positive correlations at ($P < 0.05$). This implied that binder ratio has significant effects on the compressed density however, the values of compressed densities are higher than the recommended minimum density value (600 kg/m^3) for efficient transportation and safe storage (Mani et al., 2006) for low-density briquettes. This implied that the briquettes can adequately withstand transportation stress without damage. Analysis of variance (ANOVA) performed showed a multiple coefficient of determination R^2 (0.810) and the adjusted R square ($adj. R^2=23.9\%$) and the root mean square error 13.80, for the ANOVA model indicated the variation proportions explained by the regression model. The analysis of variance (ANOVA) indicated that individually, binder type, binder concentration and treatment conditions without any interaction had significant effects ($p < 0.05$) on the compressed density of fermented briquettes.

The relaxed densities decreased with increase in binder concentration for all briquettes with maximum values higher than the value of 200 kg/m^3 recommended by Mani et al. (2004) and Gilbert et al. (2009) for efficient transportation and safe storage. This implied that the type of binder used and binder ratios influences relaxed density and briquettes' dimensional stability as reported by Okia et al., (2016) that dimensionally stable briquettes were produced at higher relaxed densities. It can be inferred that this report disagreed with the conclusions of Sotande et al. (2010) that binder type and mix ratio had no significant influence on relaxed density.

Briquette Chemical Characteristics

Briquettes Equilibrium Moisture Content (EMC)

The mean range of EMC values for untreated briquettes are (7.86-12.28 %) and the values of mean

equilibrium moisture contents for fermented briquettes are between (7.81-12.83 %). There was an increase in equilibrium moisture content as the binder concentration increases, with maximum at 50% binder concentration. The values obtained for untreated and fermented briquettes fell within the recommended equilibrium moisture content of $<18\%$ for good storability (Wamukonya and Jenkins, 1995; Olorunnisola, (2007; Oroka and Thelma, 2013). For instance Wamukonya and Jenkins (1995) recommended 7.7–15.1%, the wet basis for sawdust briquettes, Olorunnisola, (2007) reported equilibrium moisture content for coconut husk and paper binder briquette between 5.4 % and 13.3. These range of values indicated that the briquettes are capable of being transported without loss.

Briquettes Proximate Analysis

The proximate analysis of untreated briquettes produced (Table 1) shows a high concentration of non-combustible materials and low fixed carbon and calorific values. These results are higher than those obtained by Majumder et al., (2008). The ash content produced from sample briquettes was an indication of the quantity of unburnt material left after burning. The values for fermented briquettes varied from (10.39-11.57) %. Higher values of ash contents were reported for briquettes with 50% binder levels. These values are higher than 4.03 - 4.08% values obtained for untreated *Gmelina* sawdust briquettes produced in this study. These variations in results compared to other literature values be explained by the variations in binder type, concentration, feedstock material and the species of the feedstock. However, the values obtained are favourably comparable with good quality briquettes reported in literature (Guusu et al., 2021). Due to the extraction of some percentages of extraneous materials by soaking, there is a slight increase in volatile matter contents of the fermented briquettes (69.03%) compared with

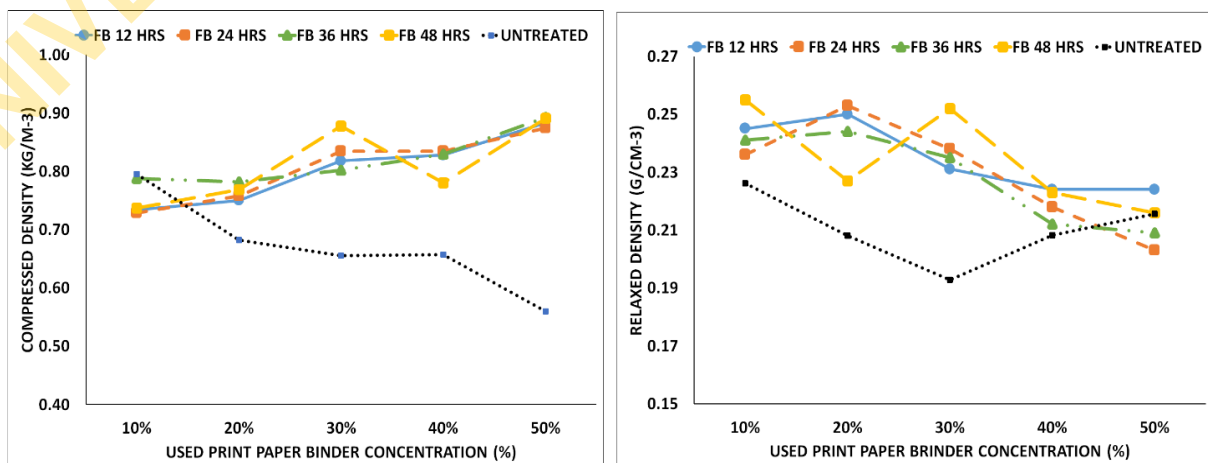


Figure 2. Compressed and relaxed densities of untreated and fermented briquettes.

Table 1. Mean values of proximate analysis performed on briquettes

Briquette	Proximate analysis					Fuel ratio
	%Ash	%VM	%FC	%MC	HHV (MJ/kg)	
Untreated	12.67	67.74	9.83	9.76	13.93	0.15
12 HRS FB	12.67	69.94	9.53	7.85	14.18	0.14
24 HRS FB	12.50	68.97	10.00	8.53	14.19	0.15
36 HRS FB	11.67	69.82	8.87	9.63	13.90	0.13
48 HRS FB	11.66	69.63	7.91	10.81	13.55	0.11

(67.74%) of the untreated briquettes. The volatile matter contents of fermented tends to increase with increase in soaking time.

The fixed carbon content of any fuel explains the available solid carbon for combustion which also signifies the proportion of char that remained after devolatilization phase which influences its heating value (Efomah and Gbabo, 2015). The fixed carbon contents of fermented briquettes are slightly lower than the untreated briquettes and decreased with increase in binder concentration. This gives an indication of higher energy value generation by fermented briquettes. This observation could possibly be explained by the fact that binder and feedstock materials are products of woody biomass. These outcomes compared favourably with the reports of Raju et al., (2014).

The heating value (HHV) of any fuel indicates the maximum amount of energy potential available in definite fuel mass therefore, fuels with higher heating values produced extra energy above fuel of same mass from other products. This inferred that fermented briquette with slightly higher heating values compared to untreated briquettes have higher energy potentials. A general review of proximate constituents and calorific values for all categories of briquettes revealed that volatile matter negatively affects calorific value of briquette while the fixed carbon increased the HHV. This observation was in good agreement with the report of Onuegbu et al (2012a), which can be justified by the fact that burning low volatile matter requires less energy.

To further justify the quality of briquettes produced, the fuel ratio (the ratio of fixed carbon to volatile matter content) was suggested by Nhuchhen and Afzal, (2017) was evaluated. From the results presented in Table 2, it can be seen that the fuel ratio decreased with increase in fermentation time. Observed response of each briquette with change in binder concentration revealed that the fuel ratios of low binder contents are higher than those of high binder contents. From experimental point of view, lower fuel ratios portray higher reactivity of fermented feedstock with binder, which implied an increase in fixed carbon content, resulting in increased fuel ratio of untreated

briquettes and consequently a better combustion performance.

Briquettes Ultimate Analysis

The values of elemental components obtained from untreated briquettes (C=37.08, H=4.71, O=35.23) % are higher than those of fermented briquettes (C=36.72-38.69) %. The elemental compositions of all fermented briquettes increased with fermentation time and binder concentration. This implied that briquettes have higher elemental compositions than the untreated briquettes. The H/C and O/C atomic ratios obtained for untreated briquettes (0.15) and (0.95) are within the range of values obtained for fermented briquettes (0.11-0.15) and (0.95-0.97) respectively. These values were in same range with values obtained by Nhuchhen, (2016). The atomic ratios (H/C and O/C) values predict the capability of each fuel to produce heat. This signifies that there are no significant effects of fermentation treatments on the briquettes produced when compared with untreated briquettes. Therefore, the impacts of H/C and O/C ratios on the HHV values of both briquettes are not very significant.

Briquette Combustion Characteristics

Ignition Time

Observed self-ignition time for untreated and fermented briquettes was between 3-4 minutes. Material pretreatment and binder concentration have no significant effects on self-ignition time and flame propagation. However, self-ignition time slightly increased with increase in binder concentration for all briquettes while fermented briquettes exhibited lower self-ignition time. This could be explained by increase in briquette density as the binder concentration increased. All the briquettes burn with rapidly propagating flame for a period of 10-15min before reaching decomposition stage (Figure 3). The observed rapid flame propagation and short durations of burning in this work was justified by Oyelaran et al., (2015) who reported that flame

Table 2. Mean values of ultimate analysis performed on briquettes

Briquette	C	H	O	H/C	O/C
Untreated	37.08	4.71	35.23	0.13	0.95
12 HRS FB	37.90	4.83	36.19	0.13	0.95
24 HRS FB	37.75	4.80	35.87	0.15	0.95
36 HRS FB	37.42	4.79	35.93	0.13	0.96
48 HRS FB	36.72	4.73	35.55	0.11	0.97

**Figure 3.** Stages of flame propagation and burning of briquettes in free air (a) Kerosene supported ignition phase (yellow flame), (b) flaming phases, (c) char combustion (decomposition) phase.

propagation in briquette depend on feedstock material properties and briquette density.

Briquette Mass Reduction

Figure 4 showed the mass reduction plotted against time during phase burning of untreated and fermented briquettes. It was observed that at 5% level of significance, Fermented briquettes have higher mass reduction as binder concentration increases than those of untreated briquettes. In addition, mass reduction rate was higher for low binder briquettes with an exponential (decay) curve than at higher binder ratios. The coefficient of determination (R^2) of each normalized curve were found to be higher than 0.81 which indicated that briquette mass and binder concentration could explain more than 81% of mass reduction experienced by each briquette therefore confirming the report of Chaney, (2010) that the quantity of briquettes burn does not affect the rate of briquettes mass reduction. Furthermore, it can be inferred that fermentation had little effect on the briquettes' behaviour during mass reduction. These reports were in agreement with the report of Chaney 2010. These implied that the higher density briquettes have lower specific fuel consumption values than lower density briquettes. To predict the interactions between mass reductions for briquettes, the following exponential functions and R^2 values

provided a satisfactory fit and can be used in optimization of briquette combustion performance.

Untreated briquettes:

$$\text{Mass reduction} = 0.6294e^{-0.062x} \quad R^2 = 0.872$$

Fermented briquettes:

$$\text{Mass reduction} = 0.5634e^{-0.279x} \quad R^2 = 0.889$$

Briquette Smokiness

From the experimental reports, untreated used paper briquettes burn with substantial smoke at ignition, which subsequently reduced during the phase burning, then dispersed at burnout. Smokiness of fermented briquettes reduced with increase in soaking time and binder ratios. The extent of smokiness of briquettes depended principally on the amount of volatile matter contents, oxygen and hydrogen contents. Briquettes with high volatile matter and oxygen contents tends to produce more smoke than those with low volatile contents. Therefore, fermentation treatments have slightly significant effects on smokiness at different binder concentrations compared with untreated briquettes. Fermented briquettes produced less observable smoke than the untreated briquettes and smokiness reduced with increase in binder concentration. In addition, the thick black smoke produced from untreated briquettes were eliminated in fermented briquettes. This provide a

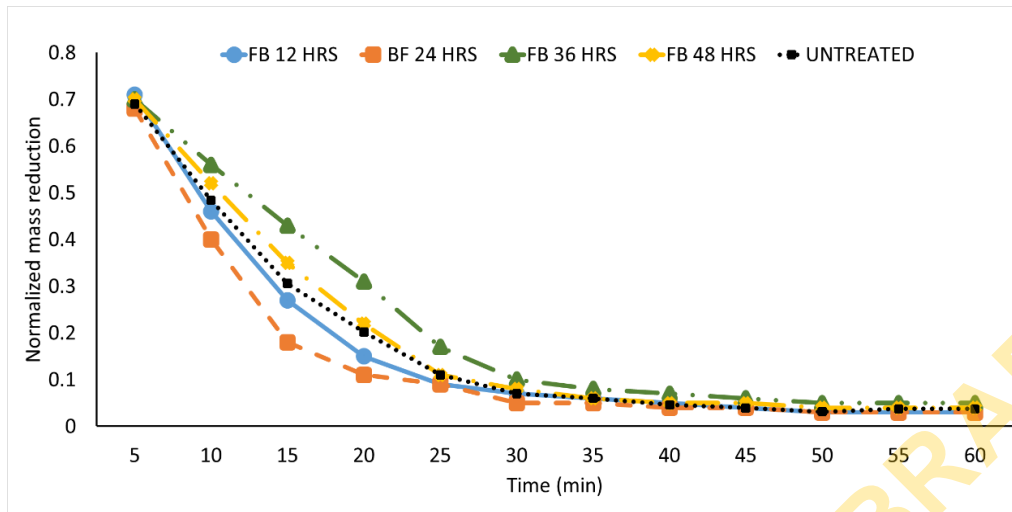


Figure 4. Normalized mass decrease for untreated and fermented briquettes.

confirmation that fermentation does not significantly eliminate smoke in briquette but mildly reduced it.

Briquette Burn Rate

To determine the burn rates for untreated and fermented briquettes at different binder concentrations, established equation used by Onuegbu et al., (2012b) was adopted. A graphical representation of the values response is shown in Figure 5. These charts provide an overview of the effects of binder ratios and treatments on briquette burn rates. Fermented briquettes produced lower burn rates (0.457-0.523) kg/hr at lower binder concentrations (10-20%) with significant increase in burn-rates as the concentration increases. It was observed that burn rate increased with increase in binder concentrations for all categories of briquettes. The range of values obtained for untreated briquettes (0.488-0.520) kg/hr significantly differs from 0.8kg/hr obtained by Oyedemi (2012).

To investigate the effects of density on burn rates and predict briquette performance, an exponential fitted trend line of normalized burn rates against binder concentrations was plotted and the following exponential expressions gave a satisfactory fit between the normalized burn rates and briquette density (x).

Untreated briquettes:

$$NBR = 0.4753e^{0.0158x} \quad R^2 = 0.8591$$

Fermented briquettes:

$$NBR = 0.435e^{0.049x} \quad R^2 = 0.9726$$

Briquette Performance in Stove

Stove Thermal Efficiency

The thermal efficiency values in burning untreated and fermented briquettes were represented in Figure 6 at different binder concentrations. The minimum and maximum values of thermal efficiencies obtained for untreated briquettes were 48.07% and 79.78%

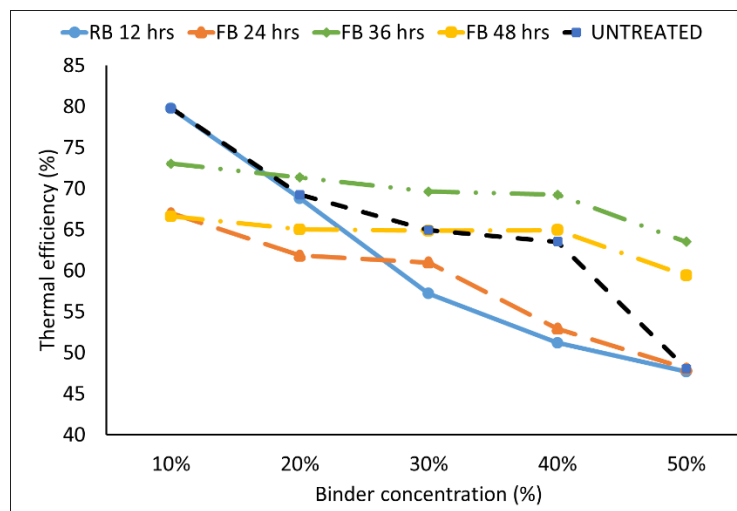


Figure 5. Burn rate for untreated and fermented briquettes.

respectively. The mean thermal efficiency values for fermented briquettes decreased with increase in binder concentration. From these results, it was evident that thermal efficiency was significantly affected by binder concentration. The minimum and maximum values obtained for each briquettes falls within the values obtained by other researches such as (Sotande et al, 2010).

Specific Fuel Consumption

The values of SFC for untreated briquettes increased as the binder concentration increases. Similar trends were observed for all fermented briquettes (Figure 7). The mean values of the specific fuel consumption (SFC) of the stove burning untreated and fermented briquettes while cooking 0.206 kg of rice and 0.175 kg of yam (*D. rotundata*). The stove specific fuel consumption (SFC) values increased with increase in binder concentration. At lower binder concentrations, there were no significant differences in SFC values which implied that the decrease in SFC value could only be attributed to the high binder contents which increased the lignin content which could led to reduction in the

volatile matter content of fuel consequential on higher fuel consumption per unit time. From these observations, it can be inferred that binder concentration affects the SFC of fuel briquette more than fermentation time. The practical inference of this result is that lesser quantities briquettes would be required to cook known quantity of food using the briquette stove. Hence if untreated, torrefied and fermented briquettes were to be subjected similar competitive market, 45 min torrefied UPP briquettes will be more preferred for its economics of production, smokiness and SFC characteristics. This observation was similar to the situation described by Olugbade et al., 2019 in the comprehensive review of combustion characteristics of some agricultural biomass and sawdust.

Fuel Consumption Rate

The fuel consumption rate increased with increase in binder contents (Figure 8). It was equally evident that type of binder and treatment does not significantly affected the FCR, however, fermented briquettes showed slight variations with untreated briquettes. The

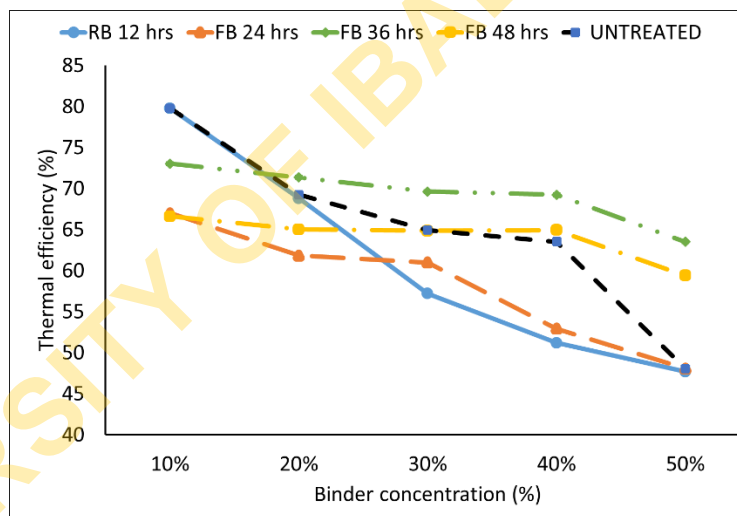


Figure 6. Thermal efficiency of briquettes in stove during water boiling test.

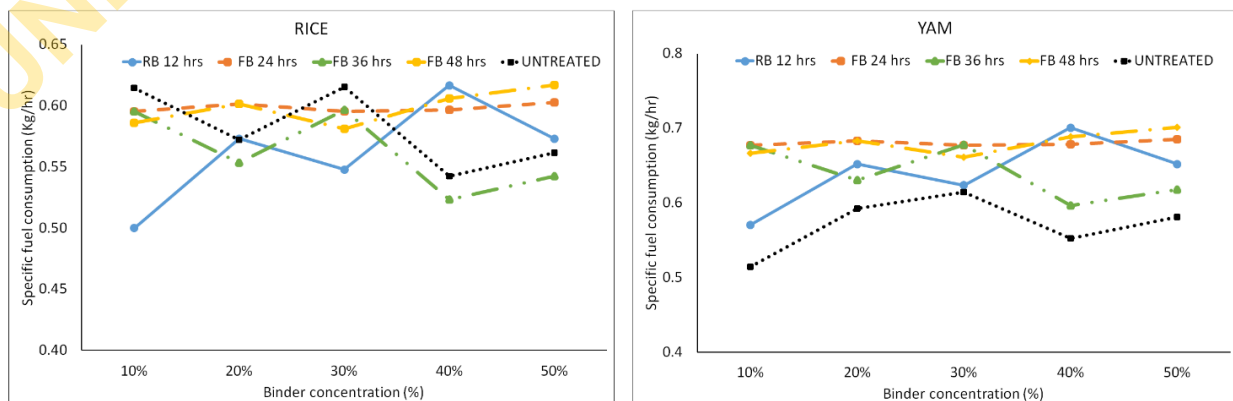


Figure 7. Specific fuel consumption (SFC) of stove in cooking rice and yam.

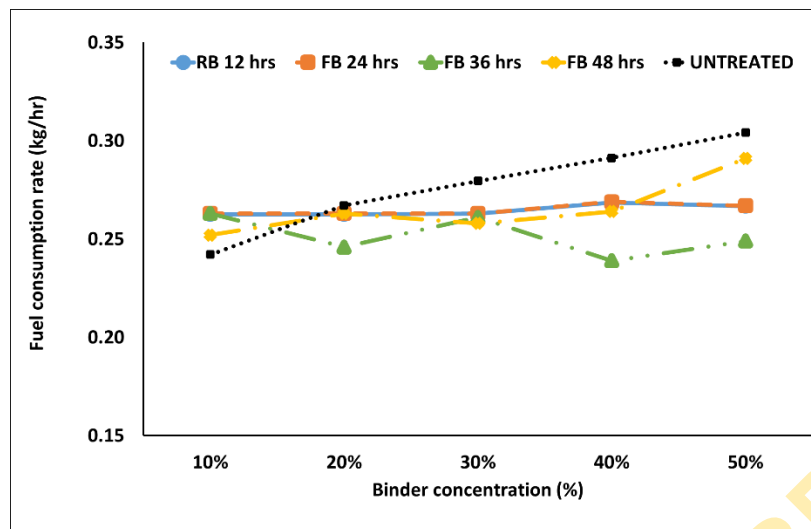


Figure 8. Fuel consumption rate (FCR) for cooking rice and yam in stove.

fuel consumption rates are slightly lower in fermented briquettes compared to untreated briquettes at different binder concentrations. This observation could be explained by the presence of extraneous contents in untreated sawdust, which might have been removed by fermentation. In addition, fuel consumption rates increased with increase in binder level for all briquettes.

Economic analysis

Cost evaluation of the entire process and the financial advantages of the product are included in economic analysis. This was demonstrated by evaluating the costs of the entire process relative to costs of material input, apparatus, and material process.

Cost Valuation

The project is not capital intensive, and the production cost remained relatively low given that the feedstock and binder materials are wastes from the wood industry and offices are freely available. Institutional laboratories and workshops already have the necessary tools and equipment. Low level investments were needed for the pulping, fermentation, and product handling processes.

Economic benefits

When the project's advantages were considered, the project produced improved products with greater economic values than the raw materials, which suggested the project as being economically viable.

Conclusions

From the experimental procedures and comparing the outcomes of this study with results of untreated briquettes, the following conclusions are made.

1. Fermentation time slightly reduced the volatile matter contents of feedstock, thereby reducing the briquettes smokiness.
2. Increase in binder concentration improves the combustion characteristics of fermented briquettes and reduced smokiness. Untreated briquettes are smokier when compared with fermented briquettes.
3. Self-ignition time and flame propagation were not affected by fermentation while smokiness reduced with increase in binder concentration and length of fermentation time.
4. Thermal efficiency decreased with increase in binder concentration with no significant difference in respect to fermentation time, while the specific fuel consumption (SFC) increased with increase in binder concentration.
5. Fermentation time and binder concentration slightly improved the combustion characteristics of briquettes.

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