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Effect of Residence Time on Characteristics of Torrefied Sawdust Produced from *Gmelina arborea* (Roxb) Wood

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ABSTRACT

Background and Objective: Biomass feedstock remains a critical ingredient in all densification studies and the process conditions under which these materials were produced are significant to its performance. Conventionally, feedstocks are utilized in briquetting without major technological processing which is consequential on product characteristics. In this study, sawdust of *Gmelina arborea* subjected to thermochemical pre-treatment conditions was analysed and characteristics were compared with untreated material. **Materials and Methods:** Untreated sawdust of *Gmelina arborea* wood obtained from a sawmill in Ishiagu was torrefied at three residence times of 30 min, 45 and 60 min at a temperature of 250°C in a batch reactor and the products were characterized to determine their physical and chemical characteristics. **Results:** The particle-size distribution of untreated sawdust showed greater proportions of coarse and fine pin particles (58.03%) and (38.00%), respectively, requiring no grind with a mean particle density of 159.30±0.02. The proximate analysis of untreated sawdust at 7.78% moisture content revealed a volatile matter content of 72.93, 2.19% ash content and 17.10% carbon content. The proximate analysis of torrefied samples revealed a significant loss in volatile matter contents to 21.02% as residence time increased to 60 min, the fixed carbon increased from 17.10-65.38% and calorific values from 17.38 MJ kg^{-1} for raw sawdust to 26.28 MJ kg^{-1} as residence time increases. Reduction in volatile matter contents increased the energy values of torrefied sawdust. **Conclusion:** Thermochemical pretreatment of the feedstock significantly increase the material fixed carbon content and energy values of the Torrefied sample, reduced the volatile matter-the smoke-generating component of sawdust considerably and improved the product's characteristics in briquetting.

KEYWORDS

Gmelina arborea, torrefaction, residence time, reactor, characterization, smokiness

INTRODUCTION

Energy remained a critical socio-economic determinant of the quality of life of the people, however, the rising cost of fossil fuel, non-availability in rural areas and pollution has made biomass suitable alternative energy due to its availability in large quantity and energy contents. Economic growth, urbanization,

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population and energy needs increase in Nigeria have led to overdependence and increased demands on the use of fossil fuels, which consequently had contributed to the outrageous increases in fuel prices[1]. As society becomes more mindful of its 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 in Nigeria. The Nigeria biofuel policy which seeks to cut down on fossil fuel use to achieve non-reliance on fossil fuels, create a commercially viable sector and sustainable domestic green jobs and integrate the agricultural sector with the downstream petroleum sector provided a boost to alternative bio-energy sources such as biomass[2].

Despite the positive attributes of biomass, there are limitations to its utilization as a direct feedstock for power generation. These limitations include excessive smoke, yellow flames high moisture content, low energy density, hydrophilic behaviour and high oxygen content, which makes it susceptible to biological attack and biodegradation[3]. In addition, lignocellulosic biomass possesses firm and fibrous nature and its grind ability poses a challenge requiring high-energy consumption during fuel preparation[4]. These limitations create difficulties in transportation, handling, storage and conversion processes and limit their replacement as fossil fuels for energy production.

To overcome these undesirable properties, an appropriate technological solution is required which this study is to accomplish through preliminary treatment before utilization in densification and thermochemical conversion process. Pretreatment of biomass was introduced to improve biomass properties by decomposition of hemicellulose, lignin and cellulose materials, while the biomass retains most of its energy and removes volatile matter contents to improve their combustion characteristics. Pretreatment of lignocellulosic materials for biomass-to-fuel conversion has been recognized and in use for a long time and includes chipping, palletisation, torrefaction and physicochemical, chemical and pyrolysis pretreatment[5]. However, identifying an efficient and appropriate pretreatment method has been difficult due to the diverse nature of the lignocellulosic biomass[6] and the hazardous nature of most of these pretreatment methods, which require corrosion-resistant reactors and thus make the pre-treatment process very expensive. A literature search of related works on different pretreatment methods and suitability to associated materials, suggested pretreatment by torrefaction as the more attractive process for sawdust pretreatment and briquetting, which will be considered in this research.

Torrefaction is a mild pyrolysis biomass process in which feedstock is roasted in a near inert (oxygen-free environment) atmosphere within a narrow temperature range of 159-300°C[7,8] to increase the heating value, hydrophobicity and improve its combustion characteristics. Biomass torrefaction is a practicable process for the conversion of raw biomass into high-energy-density, hydrophobic, compactable, grindable and lower Oxygen-Carbon (O/C) ratio solid suitable for commercial and residential heating applications. During torrefaction, drying takes place at the initial heating, followed by further heating at over 160°C during which more water is removed and also results in the formation of CO_2[9]. Degradation of hemicellulose takes place between 180 and 270°C, during which the biomass begins to turn brown and give off moisture, carbon dioxide and low energy compounds[9]. At about 280°C, the reaction becomes entirely exothermic and gas production increases, resulting in the formation of carbon monoxide, hydrocarbons like phenols and cresols and other, heavier products[9].

Torrefaction can be applied to all types of wood, grasses and other types of biomass resulting in a uniform commodity fuel. Due to its potential applications in the production of high-quality feedstock, it is suitable for use in producing pellets, briquettes and as a substitute for coal in thermal power plants and metallurgical processes[10]. Torrefied biomass is hydrophobic, brittle and easily grindable with significant energy and market potentials[7,8]. Torrefied products' performance is affected by several operating parameters such as type of biomass, torrefaction temperature and residence time. Several other researchers gave good accounts of works already done in this area[10-15]. However, there are limited research efforts made in this area in Nigeria, therefore this work seeks to investigate the effects of torrefaction time on the physical and combustion characteristics of torrefied sawdust of *Gmelina arborea* pretreated at three torrefaction time and the performance of sample briquettes produced with the used print paper binder.

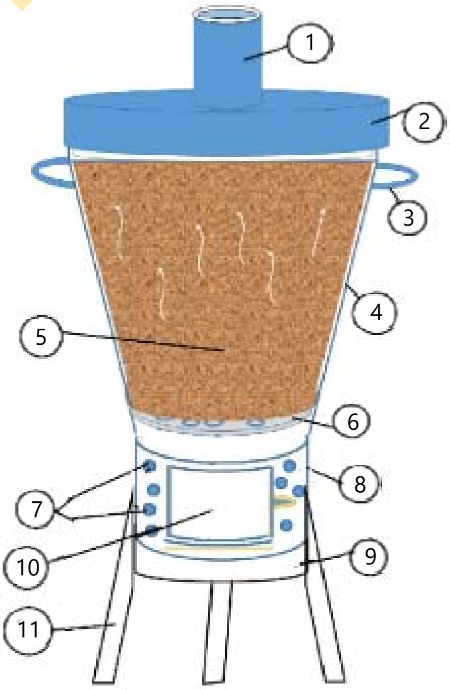
MATERIALS AND METHODS

Study area: The experiment was conducted at Ishiagu, located between latitudes 5°40' and 6°45' North of the Equator and longitudes 7°30' and 8°30' East of the Greenwich Meridian, Ebonyi State Nigeria. The duration of the experiment lasted for 8 months from April, 2021 and October, 2021.

Feedstock material selection: The lignocellulose material considered for experimentation is sawdust of *Gmelina arborea* species, derived from primary wood conversion processes in sawmills located in Ishiagu Ebonyi State, Nigeria. *Gmelina arborea*, being an energy wood was solely selected due to its wide distribution and availability in large quantities within the study area and the wide range of binder materials, pre-treatment conditions and binder concentrations to be an investigated.

Particle-size distribution apparatus: The material particle-size distribution experiment requires a precision electronic weighing scale (SF-400, capacity 5000 g×1 g/177 oz×0.1 oz) and a mechanical sieve shaker (Fritsch®, Germany) to determine the weight and relative proportions of different particle sizes, respectively.

Torrefaction reactor: Installed torrefied reactors are not readily available for this experiment due to the complexity of the technologies and costs. However, the concept of co-firing in the pulverised coal-fired stove was used to develop a simple direct-heating torrefaction batch reactor in Fig. 1 used for the experiment[16]. The reactor is comprised of two chambers (the heating chamber and the torrefaction chamber), a chimney and a cover. The torrefaction chamber is a 30 L capacity with the featured secondary air inlet created by a removable chimney on top. The heating chamber is a 5 L capacity ventilated circular



1. Flue vent
2. Reactor cover
3. Handle
4. Reactor chamber
5. Biomass
6. Screen
7. Heating chamber
8. Air vents
9. Reactor base
10. Gate
11. Tripod stand

Fig. 1: Experimental torrefaction reactor

casing with an adjustable gate to regulate air exchange. The primary air intake section opens to a perforating metal base with several vents and equally opens at the upper segment of the reactor. The charcoal fuel when kindled with a fire torch ignites the feedstock with supplemental primary air inlet vents. A metal gate controls the rate of air intake into the combustion chamber for heat generation for torrefaction. The heat supply was managed by adjusting the metal gate to control hot air intake through the holes into the torrefaction chamber.

Experimental methodologies

Sample collection: The sawdust of *Gmelina arborea* (Roxb) was obtained from a table saw and a CD 4 band saw machine with speciality teeth and 4-inch, 1-TPI blades respectively from the Uche sawmill located along Okue road in Ishiagu, Ebonyi State. The materials after being sorted for foreign matter contents were used as received (untreated), requiring no size reduction.

Feedstock material drying: The materials obtained at high moisture contents have to be sundried to reduce the moisture content to 8-10% dry basis, reported as favourable for the production of stable briquettes and also reduce the cost of energy utilization in torrefaction according to ASTM Standard D3173-03. To determine the material moisture content, a 10 g weight sample was oven-dried for 24 hrs at 105.3°C to obtain constant weight. The Moisture Content (MC) on a percentage dry basis was determined using the expression:

$$\text{MC (\%)} = \frac{(W_1 + W_2) - W_3}{W_3 - W_1} \times 100 \quad (1)$$

Where:

W_1 = Dish weight (g)
W_2 = Dish+sample weight before drying (g)
W_3 = Dish weight+sample after drying (g)

Torrefaction experiment: The upper chamber of the batch reactor was filled to the top level with Gmelina sawdust and weighted. Charcoal fuel was fed into the lower chamber and ignited. Dried biomass was fed into the pre-heated torrefaction reactor, while the air supply to the heating chamber was controlled by a metal gate and air vents around the chamber. At ignition, a digital temperature probe installed above the lower chamber was used to monitor the temperature within the upper chamber. Heat radiated from charcoal passed into the upper chamber to roast the sawdust in a limited air supply. The sawdust was heated at torrefaction temperature maintained between a range not exceeding 200 and 300°C, for predetermined resident times of 30, 45 and 60 min[17,18]. At a certain torrefaction resident time, the reactor cover was removed to release a portion of the volatile matter in form of light gases and small amounts of condensable organic compounds visible as condensates on the cover. Subsequently, at the end of residence time, the remaining solid material containing increased fixed carbon content and the less volatile matter was removed from the reactor. After torrefaction, the char obtained was stored in bags for densification.

Characterization experiments

Raw material characterization: Characterisation experiments carried out on Gmelina sawdust include the determination of the particle size distribution, density, geometric mean sizes and particle moisture. Due to the heterogeneous nature of the sawdust samples, the samples were classified into Oversized Sizes (OS), coarse sizes, pin sizes and fine fractional sizes. The particle size characteristics important to briquette quality determination, which include particle size distribution, particle geometric mean sizes and particle density, were determined using ASAE Standard S319.4 test procedures[19,20] in three replicates for analytics.

Binder materials characterization: Binder characterization experiments were carried out at the hydraulics laboratory of the Federal College of Agriculture Ishiagu. The fibre length of the sample pulp used was measured using sieve analysis.

Proximate and ultimate analysis: The proximate analysis experiment was carried out according to the procedures and elemental compositions determined by equations presented by Alizadeh *et al.*[17].

Statistical analysis: Statistical analysis using IBM SPSS PC Version 20.0 (IBM Software Incorporation, New York, United States of America) was performed to compare the effects of the binder and process variables on the briquette properties. The statistical effects of the variables and their interactions on the responses were evaluated based on the individual replicates.

RESULTS AND DISCUSSION

Characterization of untreated *Gmelina arborea* sawdust: To clearly define the effects of feedstock physical characteristics on briquettes quality, characterization was performed to determine the particle size distribution, geometric mean length, particle density and particle moisture. The results of each of these characteristics are presented and discussed in the following subsections.

Characterization of untreated *Gmelina arborea* sawdust

***Gmelina arborea* particle size analysis:** Particle size distribution analysis performed classified the *Gmelina arborea* sawdust samples into four fractional sizes: Oversized (OS) size< #8 mesh, coarse size (CPS) #12 mesh, Coarse Pin (CPP) size for #20 mesh and Fine Pin Particles (FPP) for #35 mesh with a significant amount of specks of dust. The analysis showed classifications similar to the research of Maharani *et al.*[21], corresponding with oversized (2.38 mm), coarse (1.70 mm), coarse pin (0.85 mm), fine size (0.50 mm) and Fine Particle Size (FPS) for >#40 mesh (0.40mm). The particle-size distribution pattern in Fig. 2 showed that a greater proportion (53.89%) of the particles were retained on a 0.85 mm (#20) sieve, which corresponds with coarse pin (CPP) size. In addition, the percentage mass retained on sieves #8 (2.68%) and #12 (1.11%), respectively are very low compared to other sieves, indicating a lower percentage of coarse particles, while the average percentage mass retained on sieves #35 (28.19%) and #40 (13.9%) are significantly high compared with percentage retained on sieve #20, indicating a high cumulative fine particle size proportions (42.09%) in the feedstock. It has been reported by Maharani *et al.*[21] that a portion of fine to medium particle

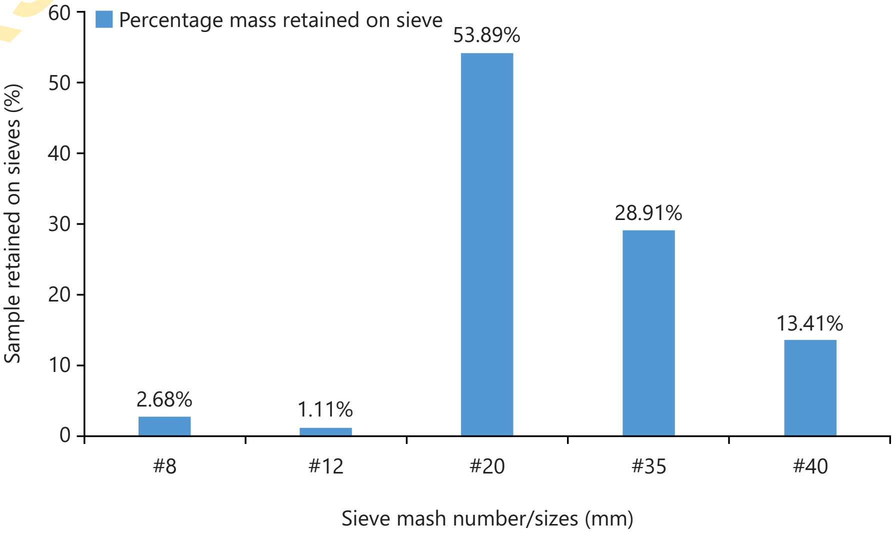


Fig. 2: Mean particle size distribution of three replicate sawdust samples

Table 1: Density distribution of *Gmelina arborea* sawdust samples

Replicate samples	Moisture contents (%)	Sample mass W_s (g)	Sample vol. V_o (cm^3)	Density (g cm^{-3})
1	9.85	155.20	1000	0.155
2	10.52	152.30	1000	0.152
3	7.87	101.10	600	0.168
Mean	9.41	121.73	770	0.159

Table 2: Mean particle moisture of sawdust used as determined at the mixing stage

Sample replicate	Dish+sample (g)	Dish+final sample (g)	Moisture content (%)
1	24.5	22.4	21.4
2	24.2	23.3	21.6
3	24.4	22.8	22.3
Mean	24.37	22.83	21.77

(15-20%) was required for good briquette quality, which implied that the sawdust as received without grinding required sieving to be suitable for briquetting. The material was then sieved with the #40 sieve size to remove a greater proportion of fines from the feedstock.

Geometric mean particle length and standard deviation: Geometric mean particle length and the standard deviation were determined to know the suitability of the material in the densification process without grinding. The particle lengths determined from each class were OS (10.67), CPS (9.98 mm), CPP (8.64 mm), FPP (4.5 mm) and FPS (2.07 mm). The mean measured particle length 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[21] and this further implied that the material does not require grinding before briquetting. In addition, Lisowski *et al.*[22], reported the suitability of size distribution and physicochemical properties of pellets produced from the mixture of straw and hay. These results were in agreement with Olugbade *et al.*[23] and showed that the feedstock will produce good products (briquettes) and required no size reduction before densification.

Gmelina arborea sawdust particle density: The mass-to-volume ratio relationship was used to determine the sawdust particle density using the mean values of three replicate samples as shown in Table 1. The mean material particle density determined at the mean moisture content of 9.41% showed a similar range of values for the three replicate sample tests with a minimum value of 152.30±0.02 and maximum value of 168.50±0.02, respectively and a mean average value of 159± 0.02. These values were within the range of values at 10% moisture content as reported by Olugbade *et al.*[23]. Maharani *et al.*[21], reported (0.22+0.02-0.32+0.11 g cm^{-3}) particle density range for sawdust from five different wood species from different mills and showed an average±SD values with 10-15% moisture range. These reports validated the results obtained for the feedstock.

Sawdust moisture content at mixing state: Material moisture played a significant role in briquetting by acting as a natural bond initiator, as well as a lubricant during densification. However, the amount of particle moisture at the mixing state could affect the even distribution of binder in the mix and consequently the quality of briquette. Table 2 shows the mean moisture content (21.77%) of sample replicates. The mean moisture content determined (i.e., 21.77%) was found to be higher than the 10-12 percent moisture range suitable for briquetting, therefore the samples required sun-dying to reduce the moisture to the recommended standard moisture range suitable for briquetting. Selected material feedstock particle moisture considered in this work is (7.87 to ~10) %, which was characteristic of low moisture fuels ~6-16%[24].

Chemical composition of raw *Gmelina arborea* sawdust sample: The proximate analysis of untreated "as received" *Gmelina arborea* sawdust sample and other literature values (used for comparison) in the experiment were presented in Table 3. From the experimental results, the untreated *Gmelina arborea*

Table 3: Proximate analysis of untreated *Gmelina arborea* sawdust (wt % on a dry basis)

Moisture content (%)	Volatile matter (%)	Ash content (%)	Carbon content (%)	HHV (MJ kg^{-1})	Reference
9.40	87.55	2.75	10.52	32.79	Adegoke *et al.*[26]
7.78	72.93	2.19	17.10	17.38	Experimental
5.25	79.95	1.50	13.52	21.24	Okoroigwe *et al.*[27]
5.00	80.90	2.00	12.10	16.86	Bhatti and Chouhan[25]
4.52	81.79	1.58	12.11	17.01	Alizadeh *et al.*[17]

The heating value of raw *Gmelina arborea* sawdust sample

Table 4: Percentage weight loss, mass and energy yield of torrefied *Gmelina arborea* sawdust

Duration	Initial wt of sawdust (g)	Final wt of char (g)	wt loss (%)	Mass yield (%)	EDR*	Energy yield (%)
30 min	10.3	7.9	23.30	76.7	0.91	36.33
45 min	11.0	3.7	66.36	33.64	1.08	58.10
60 min	10.1	2.58	71.78	28.22	1.35	69.80

*EDR: Energy densification ratio

sawdust at approximately 7.78% moisture content has low ash and carbon contents (2.19%) and (17.10%), respectively and high volatile matter content (72.93%). These result values fell within and in good agreement with other values reported in research outcomes[17,25]. In addition, it was observed that the variations in the material variables are largely dependent on the differences in the percentage moisture contents of the samples used. It can therefore be inferred that the chemical compositions of *Gmelina arborea* sawdust are dependent on the percentage of moisture contents (wet basis). High volatile matter contents have been shown to contribute significantly to the reactivity of the material[25].

The calorific value of sawdust was estimated using a correlation model validated[28], with a good prediction accuracy within the error bar of ±10%. The calorific value of sawdust using the chemical variables obtained in Table 3 was 17.38 MJ kg^{-1}.

Characterization of torrefied sawdust

Physical characteristics of torrefied products: The most significant physical characteristics observed in the torrefied samples were colour and weight changes. As the raw sawdust was roasted at a torrefaction temperature of 250°C for 30 min, 45 and 60 min residence time in the batch reactor, the colour of the torrefied material changed 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). At residence times beyond 60 min, the colour turned mostly black, resulting in char products. These colour changes correspond with the observations of Nhuchhen and Afzal[28] associating torrefaction at 30 min with mild torrefaction and torrefaction at 60 min to severe torrefaction, with blackness associated with an increase in carbon contents. It was further observed that changes in colour and concluded that the formation of chromophoric compounds was largely responsible for colour changes during torrefaction[29]. Alizadeh *et al.*[17] reports of an increase in the black colour of the torrefied sawdust further adduced this to an indication of loss of volatile matters. Thus, it can be inferred that the torrefaction process increases the carbon content and reduces the volatile matter contents and consequently increased the quality of sawdust. These results were in good agreement with reported literature studies[17,29,30,31].

Quality characteristics of torrefied products: Torrefied product qualities were evaluated by three main factors which include weight loss, mass yield and energy yield[31]. Material weight loss explains the proportion of volatile matter contents that are removed from the torrefied sample during the torrefaction process. Mass and energy yields are evaluated based on residence time and temperature conditions[32], while the mass yield accounted for the solid products retained from the torrefaction process. Table 4 presented a summary of the results of three replicate experiments performed on torrefaction at three residence times of 30 min (mild torrefaction), 45 min (intermediate) and 60 min (severe torrefaction) and temperature of 250°C.

Table 5: Proximate of torrefied *Gmelina arborea* sawdust

	MC (%)	VM (%)	Ash (%)	FC (%)	Fuel ratio	HHV (MJ kg^{-1})	Torrefaction degree
Untreated							
Gmelina arborea	7.78	72.93	2.19	17.1	0.23	17.38	-
*TS 30 min	7.78	65.19	5.76	21.3	0.33	17.63	10.61
TS 45 min	7.75	47.92	5.76	38.57	0.80	21.02	34.29
TS 60 min	7.84	21.02	5.76	65.38	3.11	26.28	71.18

*TS: Torrefied sawdust

The range of measured weight loss for each product varied between 23.30% wt. for 30 min torrefied sawdust, 66.36% wt. for 45 min product and 71.78% wt. for 60 min product. From the results, the average weight loss in 60 min torrefied sawdust was higher than the percentage of weight loss in 30 min product, which could be explained by the amount of volatiles and other compounds vaporized. Similar observations were reported[32,33].

The mass yield of the products at 30 min, 45 min and 60 min varied from 76.7% wt. for 30 min to 33.64% wt. for 45 min and 28.22% wt. for 60 min, respectively. In similar work[34], the mass yield obtained for torrefied woody biomass at 30 min was 80% wt. while it was 50% wt. for non-wood torrefied biomass at a temperature of 240 and 300°C, respectively. The energy yield which described the energy contents of material retained after torrefaction increased with an increase in torrefaction time. These values are found within the limits of literature values of 55-93% wt. for energy woods[33,35].

Torrefaction degree was used to evaluate the ratio of volatile matter removed to the initial volatile content of the raw material on a dry-ash-free basis in the torrefaction process. The Torrefaction degree evaluated in Table 5 showed an increase with the duration of the process from 10.61% at 30 min (mild torrefaction) to 71.18% at 60 min (deep torrefaction), respectively. Torrefaction time was largely responsible for these differences in the degree of torrefaction since torrefaction was carried out at constant temperature.

Proximate analysis of raw and torrefied sawdust: The proximate and predicted ultimate analysis of untreated and torrefied sawdust at different torrefaction hold times and temperatures of 250°C was presented in Table 5. From this table, the chemical properties of the untreated *Gmelina arborea* sawdust were significantly affected by torrefaction. The fixed carbon and ash contents increased from 17.7% and 2.19-65.38% and 5.76%, respectively with the increase in torrefaction time from 30 to 60 min. For instance at 30 min torrefaction time, fixed carbon and percentage ash contents increased from 17.10-51.65% and 2.19-5.76%, respectively at an average moisture content of 7.75%.

Fixed carbon contents of the torrefied sawdust increased with torrefaction time from 17.1% for untreated sawdust to 21.3, 38.57 and 65.38% at 30, 45 and 60 min torrefaction time, respectively. These increases were similar for ash contents which also increased from 2.19% for untreated sawdust to 5.76, 5.76 and 5.76%, respectively for torrefied sawdust.

Figure 3 showed the trend of decrease in percentage volatile matter content as torrefaction time was increased. The percentage of volatile matter removed at 30 min torrefaction time was 34.81%, while 52.08% VM was removed at 45 min torrefaction time and 78.98% VM removed at 60 min torrefaction time respectively. Torrefaction time has significant effects on the fixed carbon and volatile matter contents removed, which was consequential on the product. For instance, at a constant mean temperature of 250°C, an increase in torrefaction time from 30-45 min increases the fixed carbon from 17.63-21.02% and reduced the volatile matter from 65.19-47.92%. This trend could be explained by the fact that sawdust is composed of a substantial amount of volatile and that oxygenated compounds were expelled from the hemicellulosic fractions through thermochemical reactions, hence a reduction in the volatile matter and

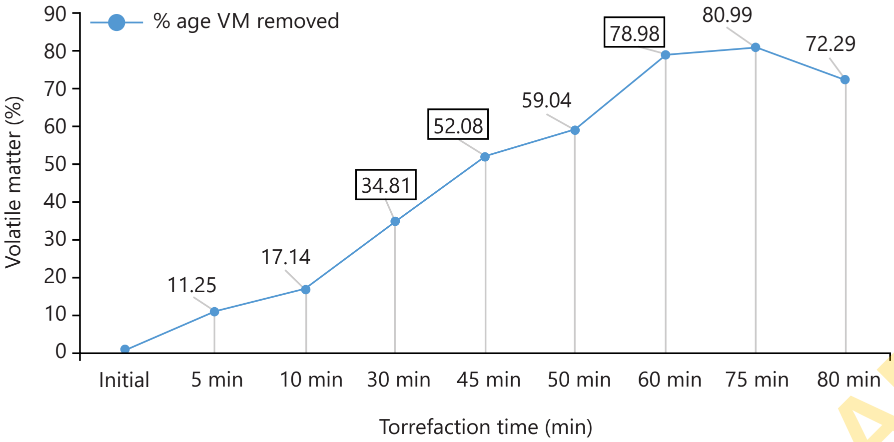


Fig. 3: Percentage weight of volatile matter removed during torrefaction

increase in the fixed carbon as torrefaction time increases. These observations were in agreement with the views of other researchers such as[17,36] in torrefying sawdust between 200-300°C and holding time of 20 min. This suggested that torrefaction time is critical to the significant reduction of volatile matter content during torrefaction.

Effects of Higher Heating Value (HHV) on other proximate parameters: The High Heating Value (HHV) of briquettes increased from 17.38 MJ kg^{-1} for untreated sawdust to 17.63 MJ kg^{-1} for torrefied sawdust at a residence time of 30 min, 21.02 MJ kg^{-1} at 45 min torrefaction time and 26.28 MJ kg^{-1} at 60 min residence time. From this result, the calorific value increased with an increase in torrefaction time, with a corresponding increase in fixed carbon content as the volatile matter content decreased. The ash content does not change significantly (2.19-5.76%) all through the torrefaction time. The volatility of the material decreased with an increase in fixed carbon content, resulting in increasing calorific value. The predicted heating values of untreated and torrefied sawdust showed that an increase in torrefaction time increased the HHV value and reduced the corresponding moisture contents. Consequently, it can be established that torrefaction negatively affects moisture content and positively affects the HHV content of *Gmelina arborea* sawdust[37].

For instance, from Table 5, the HHV of the raw sawdust increased from 17.23-26.28 kJ kg^{-1} at 60 min of torrefaction time. These observed results were in good agreement with reported study by Alizadeh *et al.*[17].

Ultimate analysis of torrefied sawdust: The results of the ultimate analysis in Table 6 showed that there was an increase in carbon content from 43.23-46.37 and 51.21% as torrefaction time increases from 30-45 and 60 min, respectively. The hydrogen contents experienced a reduction in value from 5.15-4.70% as torrefaction time increased while oxygen contents reduce from 37.51-29.88%, respectively. These results can be explained by the thermal conversion of a limited air supply. It can further be established that there exists a direct and inverse relationship between carbon contents and hydrogen/oxygen contents respectively with torrefaction time. This implied that as torrefaction time increases, the carbon content increases and hydrogen and oxygen contents decrease simultaneously. The practical implication of this is that removal of oxygen by torrefaction resulted in increased production of gases such as CO_2, CO and water and ultimately favourable higher energy values of the product.

Atomic behaviour of torrefied sawdust: The atomic behaviour of torrefied sawdust was evaluated by determining the H/C and O/C ratios. From the results, it can be observed that H/C decreased from (0.12 for untreated sawdust to 0.09 at T60 min, in the same manner, O/C decreased from 0.90 for untreated sawdust to 0.57 at T60 min, which implied a reduction in moisture content and an increase in

Table 6: Ultimate analysis of torrefied *Gmelina arborea* sawdust

	C	H	O	H/C	O/C
Untreated *Gmelina arborea*	44.08	5.41	39.91	0.12	0.91
*TS 30 min	43.23	5.15	37.51	0.12	0.87
TS 45 min	46.37	4.98	34.54	0.11	0.74
TS 60 min	51.21	4.70	29.88	0.09	0.58

*TS: Torrefied sawdust

fixed carbon and HHV values due to the direct correlation between the latter[31]. Adnan *et al.*[7] and Basu[8] reported that lower Oxygen-Carbon (O/C) ratio solid fuels are suitable for commercial and residential heating applications. Similar reports were obtained for biomass material torrefaction under different conditions[17].

CONCLUSION

Based on the outcomes of experimental procedures, results and discussions the following conclusions are made. The particle-size distribution of sawdust of Gmelina feedstock showed greater proportions of coarse pin (0.85 mm) and fine pin particle (0.5 mm) sizes (58.03%) and (38.00%), respectively, which were characteristics required for good quality briquette production, requiring no grind. The density and proximate characteristic analysis values of untreated sawdust were consistent with literature values. Torrefaction time has significant effects on colour, reduction in volatile matter contents, increase in calorific energy and fixed carbon contents of the three replicate samples. The mass-energy yield of the torrefied products increased with an increase in torrefaction time from 30-60 min. The percentage of weight loss increased with an increase in torrefaction time. The carbon contents increased from 17.10-65.38% and the HHV values increased from 17.38 MJ kg^{-1} for raw sawdust to 26.28 MJ kg^{-1} for TS 60 min. An increase in torrefaction time improves the physical and chemical characteristics of raw sawdust. Process optimization is required to improve reactor performance, with attention focused on effective temperature control, product discharge and heat regulation.

SIGNIFICANCE STATEMENT

Human survival is pivoted on energy production to meet the needs of food, shelter and comfort which conventional fossil fuels could not sustainably, therefore alternative energy sources such as biomass densification must be continuously harnessed as potential energy processes to meet these needs. However, the performances of raw feedstock are not satisfactorily due to smokiness and loose nature among other challenges. Therefore, the need for feedstock property optimization, which this study achieved. The study was conducted on preheating one of the extensively used energy woods in densification studies, *Gmelina arborea*. Torrefaction of sawdust of *Gmelina arborea* was carried out at three residence times of 30, 45 and 60 min and a constant temperature of 250°C . The physical, chemical and energy characteristics of torrefied products were investigated and reported. From the results, torrefied sawdust has to increase fixed carbon and higher calorific values, thereby having better characteristics than the densification of raw sawdust.

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