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INFLUENCE OF TORREFACTION ON LIGNOCELLULOSIC WOODY BIOMASS OF NIGERIAN ORIGIN

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ABSTRACT

Torrefaction process is a thermal treatment that can improve quality of lignocellulosic biomass into a carbon-rich and hydrophobic feedstock which is applicable as fuel and metallurgical reductant. Biomass (Melina and Teak wood) of Nigerian origin was subjected to mild (240°C) and severe (300°C) torrefaction treatment at different residence times (30 and 60 min) and particle sizes (+0.5 - 2 mm and +4 - 6.35 mm). Raw biomass and biochar from torrefaction were subjected to proximate, ultimate, higher heating value and SEM analyses. The mass yield obtained for mild treatment conditions for both biomass was in the range of 72 - 84 (wt. %) compared to 40 - 54 (wt. %) under severe treatment conditions. However, 33 - 56 % increment in higher hating value was observed for severe treatment conditions as against 11 - 17 % of mild treatment condition. This ultimately led to a 60 - 72 (wt. %) energy yield for severe treatment conditions and 73 - 94 (wt. %). The fixed carbon content increased from the range of 8 - 11 (wt. %) to 20 - 61 (wt. %) after torrefaction. The volatile matter content under mild condition was reduced by 7 - 10 % for both biomass as against 41 - 47 % under severe treatment condition. The fuel ratio increased from 0.11 and 0.15 for Melina and Teak woods respectively to a range of 0.22 - 0.25 for mild treatment conditions and 0.97 - 1.75 for severe treatment condition. The H/C and O/C atomic ratios of biochar were lowered towards that of sub-bituminous coal and peat. A honey-comb-like structure with cylindrical holes were observed for biochar compared to the fibrous and spongy nature of the raw biomass. Biomass of Nigerian origin were improved under torrefaction and thus can be suitable as feedstock in thermal or metallurgical applications.

Keywords: fuel ratio, biomass, torrefaction, teak, melina.

INTRODUCTION

One major determinant of development in any nation is the energy sector. This is also a critical factor that defines a nation as developed, developing or underdeveloped [1]. Nigeria as a developing nation struggles with epileptic power supply for her citizens. Apart from the oil and gas sector, several other energy sources are available in the country that can complement oil and gas. Biomass is one of these numerous sources. Obviously, biomass in Nigeria has earned little or no substantial research and industrial attention, thereby making it unexplored for sustainable energy application. The rate of consumption of woody products leads to generation of voluminous amount of waste which are often discarded and burnt in unhealthy way. Dosunmu and Ajayi [2] estimated the wood wastes generated in Lagos to be 267,436 ton annually while Kuye and Edeh [3] estimated the agro-forest waste generated annually in Nigeria to be 13 million tons. Biomass had been employed in several areas to develop environmentally friendly fuels that reduces the effect of global warming and substantially substitute the depleting petroleum resources. Feedstock to produce biofuel pellets [4 - 7] and co-firing with coal [8, 9] for power generation are examples of biomass utilization. It has also been attractive in the iron making sector in smelting process and as pulverized powder in tuyere of blast furnace along with coal [10]. Based on these huge advantages, it has become compelling for Nigeria and other developing nations to research into the suitability of biomass available within its domain for energy and metallurgical applications. Teak and Melina are two woody biomass species that attracts massive utilization in Nigeria, thereby contributing largely to wastes pile [11]. However, low bulk density, high oxygen content, low energy density and high moisture content (up to 60 %) are the limitations that must be overcome for biomass effective utilization [12, 13]. Torrefaction process had been employed to overcome these challenges [14-16]. It is a thermal treatment process where biomass is subjected to temperature range of 200 - 300°C in an inert or nitrogen environment. This process leads to removal of hydroxyl groups, thereby impacting hydrophobic condition, improve energy density and grindability of biomass [17]. Torrefaction degree of severity could be light (200 - 230°C), mild (240 - 260°C) or severe (260 - 300°C). Light torrefaction is treatment where hemicellulose is degraded leaving lignin and cellulose unaffected while cellulose is mildly affected under mild torrefaction. Severe torrefaction is characterized by depolymerisation of lignin, cellulose, as well as hemicellulose [18]. The influence of torrefaction treatment on biomass varies based on feedstock type, feedstock properties and origin among other factors [13, 18]. Literature on the influence of torrefaction process on biomass of Nigeria origin is still scarce. Therefore, the present study focused on torrefaction of biomass by understanding the influence of its mild and severe treatment on two woody species (Teak and Melina) for their suitability in co-densification which can be used as smelting process feedstock and in other applications.

EXPERIMENTAL

Materials

Lignocellulosic woody biomass used in this study were Teak (*Tectona grandis*-RTw) and Melina (*Gmelina arborea*-RMw) woods of Benin (Nigeria) origin (6° 20′ 17.34″ N, 5° 37′ 32.70″ E). Lumbers were converted into chips and fines using a saw wood cutting machine (Model No: CS33EB). The wood chips and fines were sun-dried for five days to remove surface and residual moisture at the National Metallurgical Laboratory, Jamshedpur, India. The wood chips were further pulverized and screened to particle sizes below 6.35 mm.

Torrefaction

Dried pulverized biomass (46g) was placed in a tubular furnace and torrefied under the following conditions: particle size; +0.5 - 2 mm (tagged as 2 mm) and +4 - 6.35 mm (tagged as 6 mm) sieve sizes, temperature; 240°C (mild) and 300°C (severe) and residence time; 30 and 60 minutes. Torrefaction was performed in an inert environment by a continuous nitrogen flow at the rate of 2L/min. For each treatment, mass yield and weight loss were calculated using the expressions in equations (1) and (2).

$$W_L = [(I_W - F_W)/I_W] \text{ x } 100 \text{ \%} \tag{1}$$

$$MY(\%) = 100 - W_L \tag{2}$$

where W_L is the weight loss (%), I_W is the initial weight of the sample (g), F_W is the final weight of the sample (g) and MY represents the mass yield. The energy yield (EY) after torrefaction in accordance with equations (3) and (4):

$$EY = EDR \text{ x } MY \tag{3}$$

$$EDR = HHV_{product}/HHV_{raw\ Mw} \tag{4}$$

where EDR is energy densification ratio and MY is the mass yield (%)

Characterization

Proximate analysis was carried out gravimetrically in duplicates and the average has been reported. The moisture content (MC) was determined according to ASTM E871-82 [19] standard in an Oven (Model No: OF-22G, JESO TECH, Korea). Volatile matter (VM) contents was determined in accordance with BS EN 15148 [20] standard. The ash content (AC) was carried out in a muffle furnace (Model No: CBFL518C, USA) in accordance with ASTM E1755-01 [21] standard. Fixed carbon (FC) content was obtained by positive difference between 100 and the sum of moisture, ash and volatile matter contents. Fuel ratio was evaluated as the ratio of fixed carbon to volatile matter [22]. Sample identification is based on condition during torrefaction, for example, Tor M/240/60/6 represent +4 - 6.35 mm Teak or Melina wood, torrefied at 240°C for 60 min residence time.

Higher heating value (HHV) analysis was carried out in a Parr 6200 Oxygen Bomb Calorimeter (Model No: A1290DDEE) using ASTM D5865-04 [23] standard. Oven-dried sample (0.5 g) was completely combusted under a pressurized (3.5 MPa) oxygen atmosphere. The analysis was carried out in duplicates and the average has been reported. The ultimate analysis was performed in a LECO-CHN628 Analyser (Model No: 622-000-000) and sulphur analysis was carried out in a LECO S - 144DR Sulphur Determinator (Model No:606-000-300, SN-477) using ASTM D4239-11 [24] standard. For comparison, the models in Equations (5 - 7) were adopted in predicting HHV from ultimate analysis; Yin [25] Sheng and Azevedo [26] and Boie [27] respectively.

$$\text{HHV (MJ/kg)} = 0.2949C + 0.825H \tag{5}$$

$$\text{HHV (MJ/kg)} = -1.3675 + 0.3137C + 0.7009H + 0.0318O \tag{6}$$

$$\text{HHV (MJ/kg)} = 0.3517C + 1.1626H + 0.1047S - 0.1110 \tag{7}$$

SEM analysis

Surface morphology examination of pulverized raw and torrefied samples was carried out in a Hitachi TM1000 Tabletop Scanning Electron Microscope (TM).

RESULTS AND DISCUSSION

Colour of raw biomass and biochar

The colours of raw Tw and Mw with some of the torrefied samples under different conditions are presented in Fig. 1. The biochar produced from torrefaction process were different in colour from the raw Tw and Mw. It is easy to predict which of the samples were exposed to severe and mild thermal treatment. Samples that were subjected to mild torrefaction irrespective of resident time and particle size changed from light brown to dark brown products while severely torrefied samples yielded black products. This implies that the loss of volatiles and moisture were high under severe torrefaction. The change in colour signals the degree of conversion of Tw and Mw. It is an indicator that thermal degradation has led to transformation of hemicellulose, cellulose and lignin [28]. The change in colour was also explained by Sundqvist [29] in his study. He treated biomass (wood) surface thermally with absorption, reflection and scattering phenomenon of visible light incident (380-800 nm). He concluded that formation of different chemophoric groups such as carbonyls, hydroxyls, methoxyls and phenolic compounds with the ability to

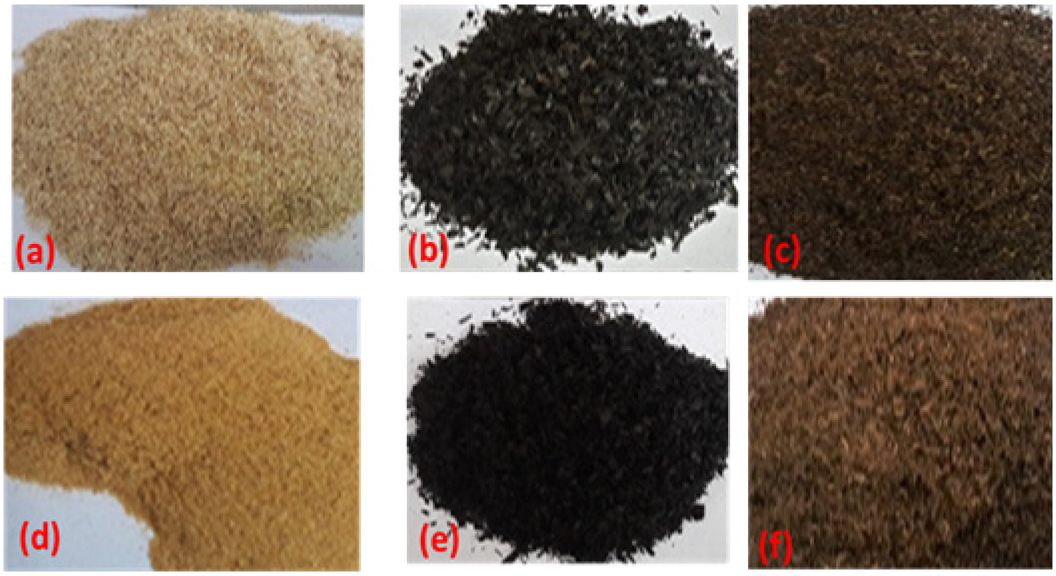

Fig. 1. Colours of (a) raw Mw (b) severely torrefied Mw (c) mildly torrefied Mw (d) raw Tw (e) severely torrefied Tw and (f) mildly torrefied Tw.

absorb visible light incident are responsible for the dark colour in biomass. It is therefore possible to understand the behaviour of biomass under heat treatment since these compounds will be formed under severe conditions treatment. The dark brown in colour of mildly torrefied Tw and Mw may also be as a result of the formation of aldehydes and phenols [30]. Severe torrefaction leads to destruction of intra- and inter- molecular C–O and C-H bonds and this directly results into loss of hydrophilic and oxygenated compounds, thus, formation of black hydrophobic compounds [31 - 33, 13].

Influence of mild and severe conditions on weight loss, mass yield and energy yield

The char (mass) and energy yields are important parameters to quantitatively measure the influence of torrefaction process on biomass [13]. Mass yield is the quantity of solid product that remains after torrefaction process while weight loss represents the portion of sample released as gas and volatiles. Fig. 2 represents the influence of torrefaction conditions on weight loss, mass yield and energy yield. The weight loss ranges from 15.85 to 59.75 wt. % which means that the mass yield ranges from 40.25 to 84.15 wt. % for both lignocellulosic biomass. It could be observed that the weight loss of Tw and Mw were higher under severe conditions than under mild conditions. This trend is similar to the results of Pimchuai et al. [34] where 67.25, 59.50 and 42 wt. % weight loss were obtained for sawdust while operating within severe thermal treatment conditions. Bridgeman et al. [35] also reported 61.50 % mass yield for Reed canary grass under severe treatment condition. Arteaga-Pérez et al. [36] reported a 58.14 wt. % mass yield for Eucalyptus wood. Lasode et al. [15] also reported an average solid yield (mass yield) of 80 wt. % and 50 wt. % for woody and non-wood biomass torrefied at a temperature of 240 and 300°C respectively. Weight loss in biomass has been attributed to loss of condensable compounds such as water, sugars, acids, furans, ketones, alcohol and poly-sugars [37]. Further loss of condensable lipids such as terpenes, phenols, tannins and fatty acids could also contribute. The release of

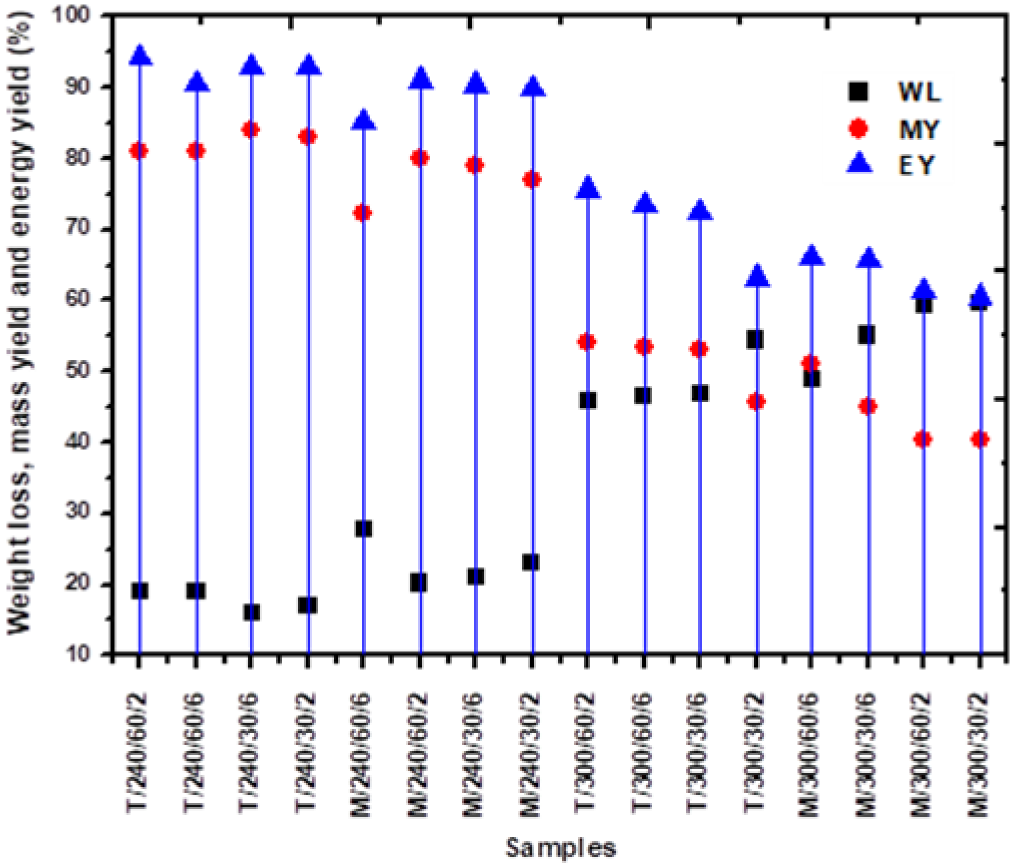

Fig. 2. Weight loss, mass yield and energy yield under mild and severe treatments.

non-condensable gases like CO_2, CO, CH_4, toluene and benzene are also responsible for weight loss during torrefaction with variations under mild and severe conditions [38, 39]. High weight loss may be desirable in biomass if energy yield is appropriate. The energy yield summarized the overall influence of torrefaction conditions on biomass feedstock. Nhuchhen et al. [13] described energy yield as the fraction of the original energy in the biomass retained after torrefaction. During torrefaction, some energy-lean components decomposed and were released with specific quantity of energy contents. The energy yield of biochar under severe conditions range from 60-79 wt. % while 89 - 94 wt. % range was obtained for mild conditions. Both are within range of 55 - 93 wt. % obtained for sawdust, pine and Birch wood [31, 34, 36]. Quality char within the range of 60 - 94 % energy yield as shown in Fig. 2 will be available for bio briquettes or other application when operating within the mild and severe torrefaction conditions.Properties of raw and torrefied biomass.

Elemental compositions

The average characteristic elemental compositions of raw and torrefied biomass are presented in Table 1. The carbon content of raw Tw and Mw are 47.84 and 47.09 wt. %, respectively. The value was enhanced by both mild and severe torrefaction conditions. The value is within the range of 47 - 51 wt. % reported for some other woody biomass [15, 42 - 44]. The range of carbon content for biochar produced under mild condition at various residence time and particle size is 52 - 56 wt. % while 63 - 72 wt. % was obtained under severe conditions. Hydrogen value for raw Tw and Mw was in the range of 6 - 7 % wt. %, however, it dropped to 4 - 5 % for biochar produced under both mild and severe torrefaction conditions. N and S contents remain in the range of 0.2 - 0.4 wt. % for both raw and torrefied biomass. This implied that biochar from torrefied product in similar manner to raw biomass will generate lower quantity of SO_x and NO_x emissions when utilized as fuel. The oxygen content of raw Tw and Mw are 43.69 and 43.54 wt. %, respectively. The range of oxygen content of biochar produced under mild conditions is 37 - 38 wt. % compared to 19 - 29 wt. % of biochar under severe conditions. High oxygen in biomass reduces its heating value, thereby making it an undesirable lean grade fuel [41]. Oxygen content of biochar produced under severe conditions is higher than 11.36 wt. % reported for bituminous coal by Gamgoum et al. [43] but at par with 29.59 wt.% of low volatile coal reported by Du et al. [41]. The reduction of oxygen within the elemental

Table 1. Elemental composition of raw and torrefied samples.

Samples	C (%)	H (%)	N (%)	S (%)	O (%)
RTw	47.84	6.09	0.39	0.26	43.69
RMw	47.09	6.65	0.38	0.24	43.54
T/240/60/6	54.67	6.01	0.36	0.21	37.28
M/240/60/6	55.53	5.92	0.27	0.22	36.26
T/240/60/2	54.78	5.95	0.36	0.22	37.11
M/240/60/2	53.86	6.03	0.18	0.20	38.35
T/240/30/6	53.29	6.06	0.35	0.20	38.98
M/240/30/6	52.41	5.95	0.25	0.20	39.79
T/240/30/2	53.94	5.92	0.25	0.21	38.12
M/240/30/2	54.87	5.92	0.22	0.21	37.25
M/300/60/6	63.19	5.62	0.28	0.19	29.08
T/300/60/6	63.02	5.26	0.42	0.19	29.24
T/300/60/2	63.99	5.29	0.35	0.22	27.51
M/300/60/2	72.04	4.74	0.33	0.20	19.67
T/300/30/6	64.23	5.31	0.44	0.19	27.88
M/300/30/6	69.54	5.09	0.30	0.20	22.84
T/300/30/2	67.73	4.80	0.46	0.23	23.70
M/300/30/2	70.24	4.86	0.38	0.22	22.08

matrix of biochar is as a result of dehydration reaction which gives room for the formation of water vapour and other light volatile organic compounds. Formation of CO and CO_2 at higher degree in severe condition compared with mild condition is also responsible for lower oxygen content [17]. Biochar produced from severe conditions has carbon and oxygen contents in the range of lean grade coal that make it a suitable feedstock to partially or totally substitute coal in thermal and metallurgical applications.

H/C and O/C atomic ratios

The ability to produce heat and electricity is what distinguish one fuel from one another [43]. A useful tool of comparison is the H/C and O/C atomic ratios diagram. The lower the respective ratios, the greater the energy content of such fuel feedstock [18]. H/C and O/C atomic ratios of Tw and Mw compared to various forms of solid fuel are illustrated in the van Krevelen diagram on Fig. 3. The H/C and O/C atomic ratios of Tw is slightly lower than that of Mw. Compared to Mw with 1.68 H/C and 0.69 O/C atomic ratios, the H/C and O/C atomic ratios of Tw are 1.52 and 0.69 respectively. These ratios were observed to be higher than other type of fuels [18, 44]. High hydrogen-carbon and oxygen-carbon atomic ratios lowered the heating value of Tw and Mw. This corresponds to the observation of Basu [18] on HHV of biomass reducing from 20.5 MJ/kg to 15 MJ/kg when the O/C atomic ratio increased to 1.03 from 0.86. Severe torrefaction conditions led to higher reduction in H/C and O/C atomic ratios compared to mild torrefaction condition as shown in Fig. 3. Oxygen content of Tw and Mw were reduced under different torrefaction conditions due to series of decomposition reactions. One of which is dehydration process that favours the formation of more C-C and C-H and destruction of C-O and H-O bonds as discussed in section 3.3.1. This can be observed in volatile loss and high weight loss during torrefaction process (Fig. 2). O/C atomic ratio for biochar from severe torrefaction condition is in the range of 0.23 - 0.39 while H/C is 0.76 - 1.27. The range of 0.45 - 0.58 O/C and 1.21 - 1.37 H/C atomic ratios were observed for mildly torrefied biomass. A similar reduction from > 0.6 to ≤ 0.3 was observed by Balogun [45] for O/C atomic ratio of different woody and non-woody biomass. It can be seen that biochar from severe treatment conditions towards lean grade coals properties (sub-bituminous and lignite). Thus, it can be adopted for thermal and metallurgical applications.

Proximate characteristics

Proximate analyses of raw biomass and biochar

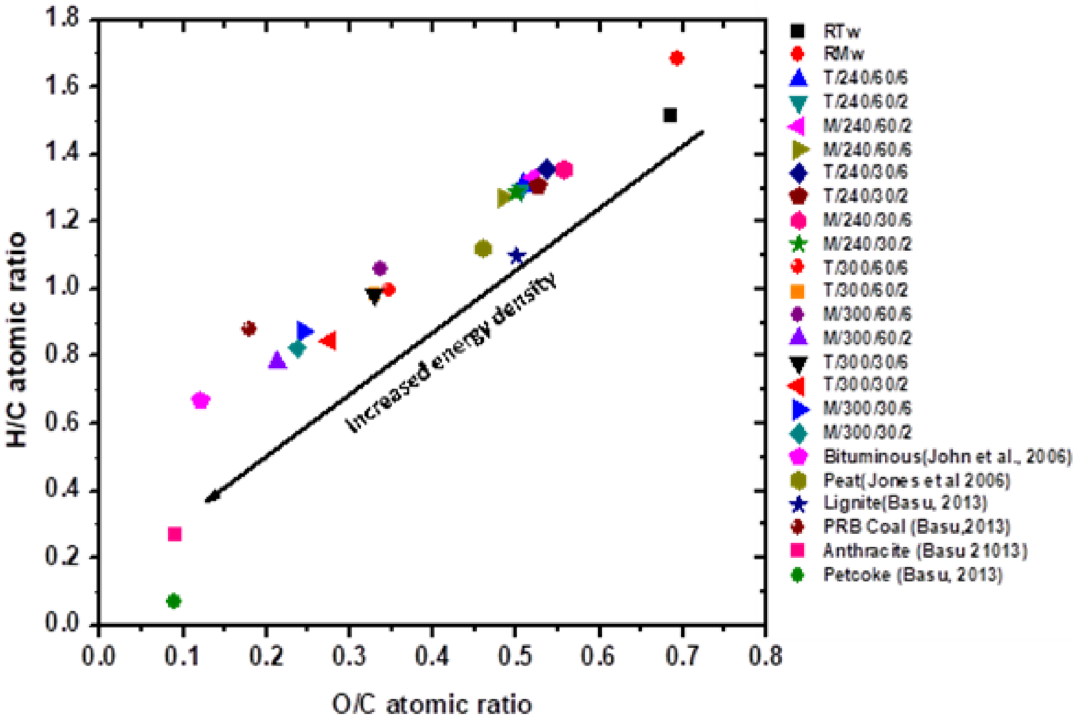

Fig. 3. H/C and O/C atomic ratios of raw and torrefied biomass with some other solid fossil fuels.

Table 2. Proximate characteristics of raw biomass and biochar.

Samples	MC (%)	VM (%)	Ash (%)	FC (%)
RTw	7.23	79.26	1.73	11.79
RMw	7.52	81.42	2.15	8.92
T/240/60/6	3.13	74.87	1.82	20.19
M/240/60/6	3.03	71.70	2.20	23.07
T/240/60/2	3.22	74.98	1.79	20.02
M/240/60/2	3.01	71.89	2.22	22.89
T/240/30/6	3.73	77.01	2.00	17.27
M/240/30/6	3.07	72.70	2.18	22.06
T/240/30/2	3.80	75.65	1.78	18.78
M/240/30/2	3.00	70.39	2.20	24.42
M/300/60/6	2.73	48.02	2.05	47.21
T/300/60/6	2.76	37.87	2.20	57.18
T/300/60/2	2.56	47.08	2.05	48.32
M/300/60/2	2.53	34.64	2.29	60.55
T/300/30/6	2.73	48.48	1.78	47.02
M/300/30/6	2.51	44.39	2.21	50.90
T/300/30/2	2.56	42.55	2.03	52.87
M/300/30/2	2.47	37.15	2.23	58.17

are presented in Table 2. The volatile matter (VM) on dry basis of Tw and Mw are 79.26 wt. % and 81.42 wt. %, respectively. Biomass generally contains high volatile matter as previous report for VM of some woody biomass showed 78.91 wt. % for Willow [40], 85.20 wt. % for Miscanthus [46], 77.71 wt. % for Pine [36], 82.30 wt. % for *Terminalia ivorensis* and 95.5 wt. % for Teak wood [15]. Different degree of reductions was observed in the VM of biochar based on the treatment conditions. The conversion of complex polymers into smaller monomers and that of smaller monomers into condensable and non-condensable volatile gases varied with treatment conditions. The range of VM of biochar produced from mild torrefaction condition is 70.39 - 77.01 % for both biomass. The results showed that Mw released more condensable and non-condensable products compared with Tw because it contained lower VM at every mild condition. A similar observation was made of biochar produced under severe treatment where the range of VM for Mw reduced to 34.64 - 44.39 wt. % against the 42.55 - 48.48 wt. % for Tw. Devolatization rate has direct implication on the fixed carbon of biochar. Higher fixed carbon (FC) was obtained for severely torrefied biomass with Mw having the highest value of 57 wt. %. An increase in fixed carbon hence denotes a decrease in VM. Increased fixed carbon is essential for biochar utilization in energy production [47]. The ash represents the mineral content of biomass and it is in the range of 1 - 3 wt. % for both raw biomass and biochar. Nhuchhen et al. [13] stated that ash as non-combustible material could remain constant or increase because it is not driven off via torrefaction. High ash is not desirable in biochar for utilization in gasifiers. It will cause decrease in operation throughput and increase operating cost. The ash content of biochar produced from woody biomass is lower compared to coal [48]. Moisture content of biochar reduced from the range of 7 - 8 wt. % to 2 - 3 wt. %. Moisture loss is due to dehydration and it contributes to the total weight loss of biomass. Based on the proximate analyses, biochar improved with high fixed carbon, low moisture and low volatile which implied that the fuel properties are better torrefaction with than the raw biomass.

Fuel ratio and higher heating value

Another useful parameter to measure improvement in fuel properties is fuel ratio. It is the ratio of fixed carbon to volatile matter content in biomass [49]. The

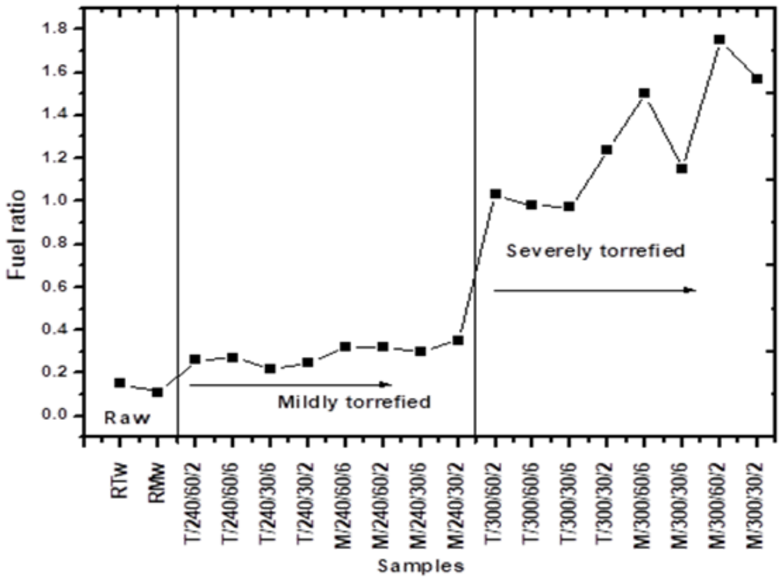

Fig. 4. Fuel ratio of raw and torrefied Teak and Melina woods.

fuel ratio of raw biomass and biochar are presented in Fig. 4. It can be observed that the fuel ratio of biochar is better under both severe and mild torrefaction conditions more than raw biomass. Mw has the highest fuel ratio of 1.75 under severe treatment compared to 0.11 of the raw biomass. Similarly, a fuel ratio of 1.24 was obtained for biochar of Tw compared to 0.15 of raw biomass. The lower fuel ratio depicts that raw biomass has higher reactivity than biochar. The increase in fixed carbon led to an increase in fuel ratio which implied that combustion of biochar will be stable than the raw biomass [22]. Fig. 5 represents the comparison of HHV obtained experimentally with some models developed based on ultimate characteristics as stated in equations (5 - 7). The HHV of biochar is in the range of 22 - 28 MJ/kg for severe conditions compared to 18.72 and

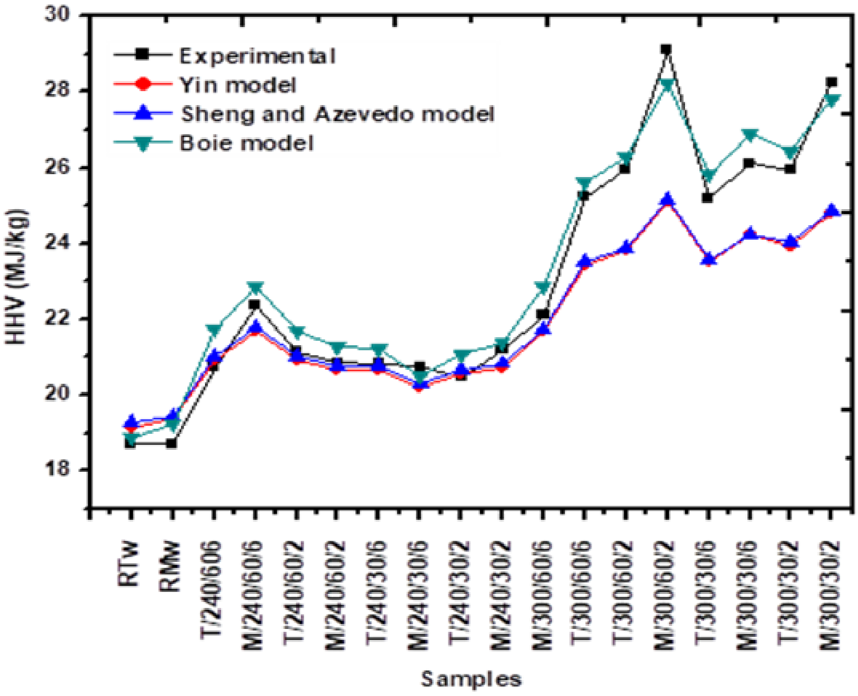

Fig. 5. Comparison between experimented and correlated value of HHV for raw and torrefied Tw and Mw.

18.39 MJ/kg of the raw Tw and Mw respectively. Mild conditions also improved the HHV to a range of 20 - 21 MJ/kg. The result is reminiscent to 19 - 27 MJ/kg obtained for woody biomass by Lasode et al. [15]. The effort to compare the result of different models was made to confirm the report of Nhuchhen and Afzal [49]. They stated that while existing models can be effective in predicting HHV of biomass, it is limited as it fails to be potent for the HHV prediction of biochar. For parent biomass, HHV prediction deviates by 4 %, 4.2 % and 2 % for Yin [25], Sheng and Azevedo [26] and Boie [27] models respectively. It suggests that Boie model is well suited to predict HHV of raw woody biomass. However, the deviation becomes extremely large when same models were employed to predict the HHV of biochar. The deviations are 13.8%, 11.9 % and 4.77 % for Yin, Sheng and Azevedo and Boie models respectively. This implied that prediction of the HHV of biochar is still open to more studies, however, calorimetry is still the best method to obtain HHV of biochar. The improvement in HHV for biochar is traceable to the improvement in fixed carbon content which results from lower O/C and H/C atomic ratios. With 22 % improvement in HHV for mild conditions and 55 % for severe conditions, the biochar from Mw and Tw are suitable for pelletization and bio-coal briquettes as fuel.

Surface morphology of raw and torrefied biomass

The micrographs of raw and some torrefied conditions for *Gmelina arborea* and Tectona grandis are shown in Figs. 6 - 8. The fibrous nature of biomass is seen on the micrographs of raw *Gmelina arborea* and *Tectona grandis* with varied arrangement. This fibrous nature militates against grindability. Spongy-form structure can also be observed in the micrographs of both biomass. This structure forms the basis for its hydrophilic nature that makes it absorb moisture from the surroundings. The micrographs obtained for mild

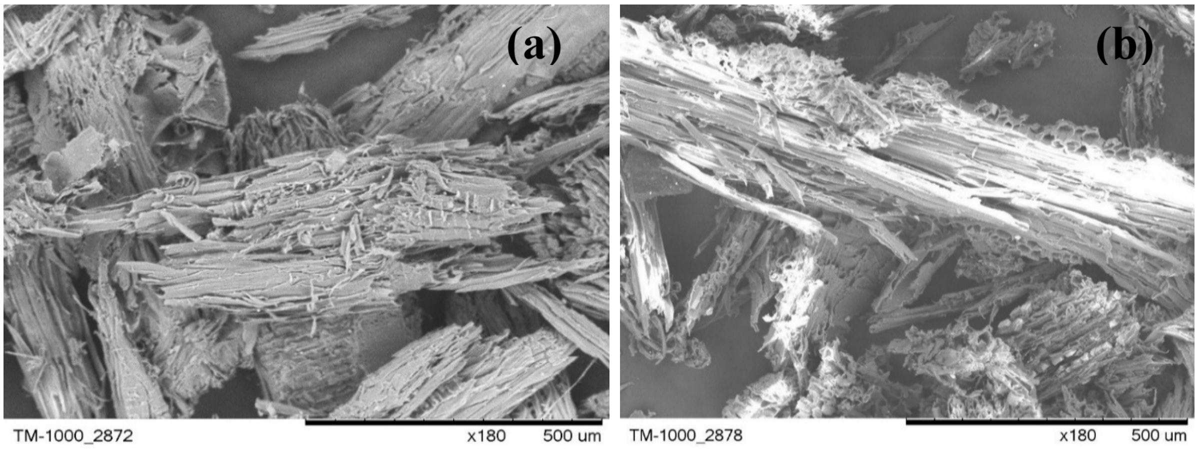

Fig. 6. Micrographs of raw biomass (a) RMw and (b) RTw.

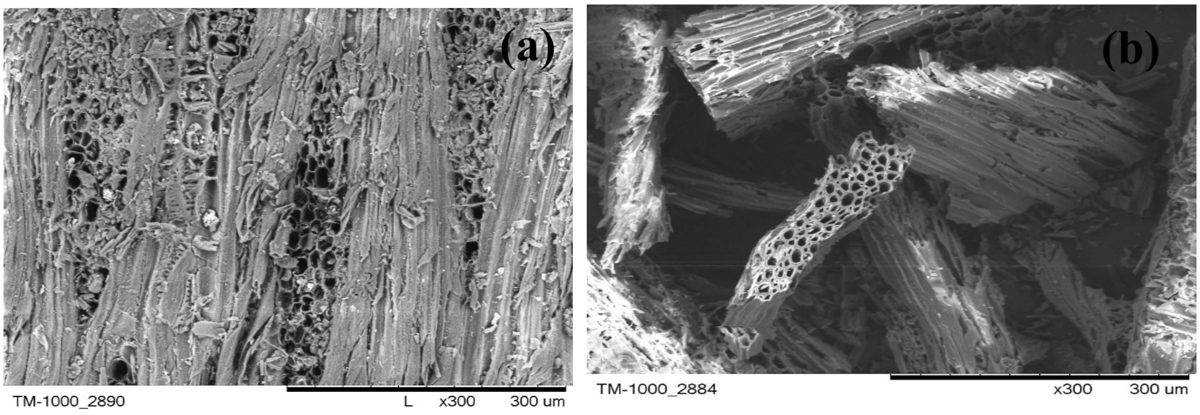

Fig. 7. Micrographs of treated biomass (a) T/240/60/6 and (b) T/300/30/6.

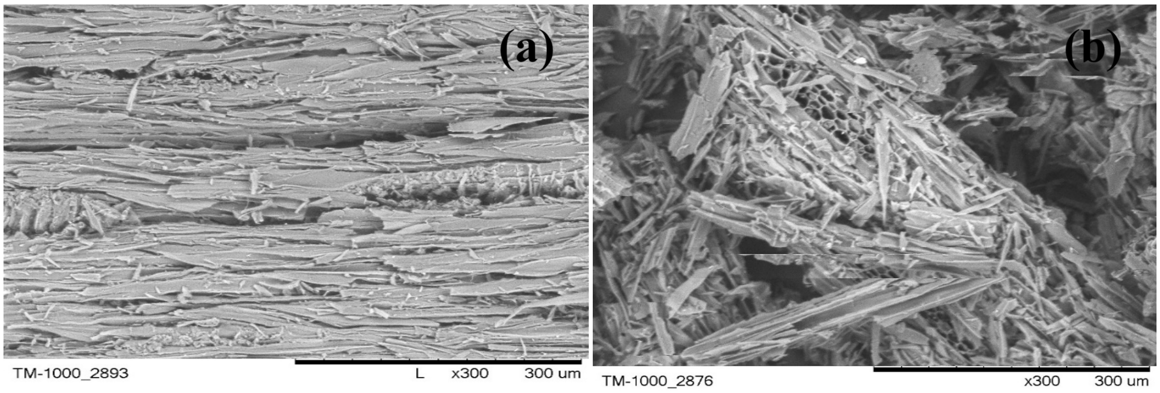

Fig. 8. Micrographs of treated biomass (a) M/240/60/6 and (b) M/300/30/6.

and severe conditions are reminiscence of each other for both biomass and therefore, a typical micrograph is reported to observe the influence of torrefaction parameters on pores formation and other characteristics visible. There were no clear features in term of pores on the micrographs of the raw samples above X180 and therefore the micrographs were taken at this magnification. However, micro, macro and mesopores are seen in the micrographs of biochar. *Gmelina arborea* and *Tectona grandis* torrefied at 240°C are filled with more tissue that were not devolatized leading to fewer pores observed on Figures 7a and 8a. This implied that the grindability enhancement will be low compared to samples torrefied at 300°C. As can be seen on Figures 7b and 8b, the morphology of torrefied *Gmelina arborea* and *Tectona grandis* were honey-comb-like with cylindrical holes connected by some large holes. The pattern of arrangement is similar to what was obtained for high pyrolysis of empty fruit bunch and rice husk biochars by Claoston et al. [50]. The arrangement of pores could enhances the grindability output at 300°C [39]. Higher level of crack formation and shrinkages were observed at the surface of the severely torrefied samples. This could be due to higher volatile loss in both *Gmelina arborea* and *Tectona grandis*.

CONCLUSIONS

The properties of lignocellulosic woody biomass of Nigerian origin was improved with torrefaction process under mild and severe conditions. Torrefaction under severe condition has the highest level of impact on the properties of biomass. The fixed carbon content increased from the range of 8 - 11 (wt. %) to 20 - 61 (wt. %) after torrefaction. The volatile matter content under mild condition was reduced by 7 - 10 % for both biomass as against 41 - 47 % under severe treatment condition. The fuel ratio increased from 0.11- 0.15 for Melina and Teak woods to a range of 0.22 - 0.25 for mild treatment conditions and 0.97 - 1.75 for severe treatment condition. An increment of 33 - 56 % in HHV was observed for severe treatment conditions as against 11-17 % of mild treatment condition. The increment in calorific value ultimately led to a 60 - 72 (wt. %) energy yield for severe treatment conditions and 73 - 94 (wt. %). The H/C and O/C atomic ratios of biochar were lowered towards that of sub-bituminous coal and peat. The surface morphology of *Gmelina arborea* and *Tectona grandis* showed honey-comb-like structure with cylindrical holes which are not visible on raw biomass. Biochar contained lower volatile matter, lower moisture, higher carbon and fixed carbon content as well as higher calorific value compared with raw biomass. Therefore, biomass of Nigerian origin is recommended to be subjected to torrefaction process prior to its application as fuel and reductant in metallurgical applications.

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