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Potentials of Torrefied Pine Sawdust as a Renewable Source of Fuel for Pyro-Gasification: Nigerian and South African Perspective

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ABSTRACT: The impacts of fossil energy on the climate and environment emphasize the need for alternative energy resources. The use of waste wood is one such method to potentially reduce fossil-based energy dependence. However, raw biomass fuel properties are generally poor and unpredictable, thus requiring pretreatment to maximize their energy potentials for an efficient conversion to syngas *via* pyro-gasification. Two species of pine sawdust (PSD) wastes generated in abundance from large-scale timber industries in Nigeria and South Africa were investigated for improvements in their fuel properties after torrefaction. Samples were torrefied under optimum conditions of 300 °C and 45 min. Different analytical procedures show that the higher heating value (HHV), enhancement factor, energy density, and solid yield of the Nigerian PSD exceeded those of their South African counterpart by 2.38, 5.37, 3.49, and 11.15%, respectively. The HHV of the torrefied fuels increased by 57.29 and 37.9% for the Nigerian and South African PSDs, respectively, when compared to the raw fuels. Also investigated were improvements in their H/C and O/C ratios and thermal degradation at varied heating rates.
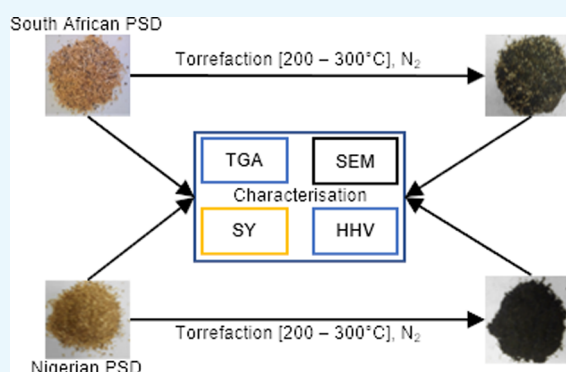
1. INTRODUCTION

Studies on the use of biomass for energy generation have received considerable attention around the globe. This is because biomass is a universally abundant renewable source of energy that can be found in different forms from different domestic and industrial activities. The amount and type available in a region may vary from another, but ultimately, it serves as an alternative source of fuel for energy production. Biomass availability in a region is also dependent on the level of agricultural activities going on in that particular region, available conversion technologies, and energy demand in that region.[1]

In South Africa and Nigeria, there is abundant agricultural waste such as wood pine sawdust (PSD), coffee husks and pulp, sugarcane bagasse, wheat straw, corn cob, and others.[2] According to Garba *et al.*,[3] Nigeria, for example, has an estimated annual biomass resource of around 144 million tonnes.[4] Pine trees are not originally an indigenous feature of South Africa or Nigeria. For South Africa, the seeds for different species were imported in the 17th century, at the behest of the First governor at the Cape, Jan van Riebeeck. The origin of the various species ranges from the Mediterranean to Northern Europe and had been in South Africa for over 370 years. The species *Pinus pinaster* dominates every other species because of its invasive nature and is found in most South African famous forests and national parks. Pinewood, for instance, is extensively

used by both countries for furniture and cabinet-making, construction, joinery, and decorative veneers. It accounts for about 96% of an estimated 4.1 million m^3 of lumber processed in South African sawmills annually.[5,6] Wood waste generated from the sawmill industry is unavoidably enormous and sustainable because of the increasing global demand and market for sawn wood and allied products.[7] In Nigeria, over 5.2 million tons of wood waste from sawmills is generated annually and is mostly incinerated or illicitly dumped in unauthorized locations.[8]

Currently, across the globe, biofuels with the potentials to serve as substitutes for coal and petroleum are extensively researched.[9,10] This is essential because of the environmental challenges and energy insecurity associated with fossil fuels for energy production. Importantly, fossil fuels deplete rapidly, and above all, the crash in the global oil price due to uncertainties such as the novel coronavirus (COVID-19) pandemic further limits the global interest in oil. Based on these, there is a need to
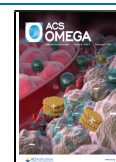
carry out studies on locally available biomass wastes, such as PSD, with the potential for large-scale energy generation.

Biomass is characterized by variable properties that limit their effective use as feedstock for thermochemical conversion or ultimately as fuel for energy production. In general, the fuel properties of raw biomass which include moisture content, energy density, hydrophobicity, HHV, O/C (oxygen to carbon ratio), H/C (hydrogen to carbon ratio), and their proximate and elemental compositions are poor when compared with those of conventional solid fuels such as coal. To ensure energy security, efficiency, and sustainability of localized bioenergy production, these properties should also be improved. Among these properties of the wood fuels, the one that must be improved to meet the energy goals is the HHV. The HHV and bulk density are critical to the energy density and overall fuel quality of wood. Other physicochemical properties such as moisture content (MC) affect grindability, bulk density, storage stability, and handling of the wood fuel.[11,12] Low MC in bulk wood ensures the production of uniformly sized sawdust particles during milling or grinding. Additionally, sawdust with low MC reduces the chances of particle agglomeration during feedstock loading and thus increases the efficiency of the reactor feeding system. Ultimately, a considerable reduction in the storage and transportation costs of fuels from the production site to the energy production plant, a reduction in operational difficulties, and an increase in the energy value can be achieved by enhancing these physicochemical properties of the wood feedstock.[13,14]

To improve the above-listed properties of the solid fuels (*e.g.*, PSD), several pretreatment methods can be employed. These are categorized into (1) biological methods, (2) chemical methods, and (3) thermal methods.[15] Biological pretreatments are slower processes when compared to the chemical and thermal pretreatment processes, but are the most environmentally friendly. Similarly, the chemical pretreatment is expensive, although the maintenance cost of reactors used for thermal pretreatment could equally make the process expensive.

To ensure system and energy efficiency, the quality of the biomass (PSD) was enhanced through torrefaction. Torrefaction can be described as the mild thermal upgradation of biomass by subjecting it to a low-temperature (200−300 °C) breakdown of its complex molecules and elimination of its volatiles in an inert atmosphere to increase its energy density.[16] Other improvements in biomass fuel properties through torrefaction are described in Figure 1.

Understanding the aforementioned parameters is key to assessing the potentials of the fuels for energy production. Several experimental studies on biomass torrefaction have been reported.[17−21] These studies, however, focused mostly on varying the torrefaction conditions on a variety of biomass types to achieve optimal reactor operation and for the production of high-quality biochar. An extensive study of the production of torrefied biomass for subsequent use as feedstock for syngas production *via* pyro-gasification is required to improve process efficiency. An ideal biomass feedstock for pyro-gasification would be the one characterized by a high carbon content, a moderate to high HHV, high energy density, low ash content, and low moisture and volatile matter content.

In this study, the properties of the PSD waste from South Africa and Nigeria were considered to ascertain their suitability as feedstocks for syngas (CO and H_2) production, *via* the hybrid pyrolysis and gasification process (pyro-gasification). By employing the thermal pretreatment process of torrefaction, improvements in the fuel quality and properties such as the
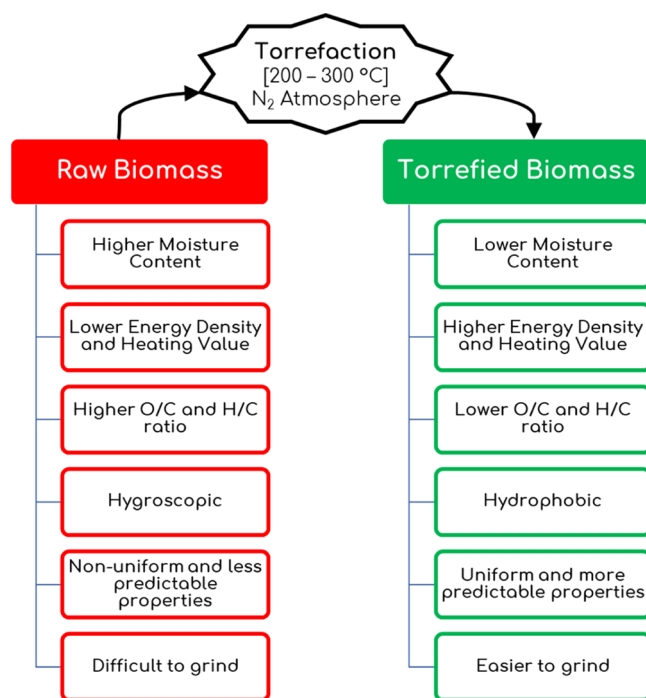

Figure 1. Schematic diagram of biomass undergoing torrefaction.

HHV, H/C and O/C ratio, solid yield, energy yield, and enhancement factor of both samples were also investigated for the beneficiation of PSD wastes for a pyro-gasification system. This study also investigated the effects of varying the heating rates when subjecting both species of PSD to a thermal decomposition process. These could be instrumental in complimenting waste management, energy security, and efficiency in biomass resource use for energy production.

2. RESULTS AND DISCUSSIONS

2.1. Characterization of Feedstock (South African and Nigerian PSD). The compositional analysis of South African and Nigerian PSD was carried out, and the result obtained is presented in Tables 2 and 3. There were some slight variations in the physicochemical compositions of the fuels. This was attributed to climatic and geographical differences under the growth conditions of both samples. Other factors which may also lead to significant differences in the properties of both samples include their handling and storage conditions during which the samples may be contaminated with impurities and absorb moisture from the atmosphere.

It can be observed that the volatile matter and fixed carbon contents of the raw PSD from both countries are high. After torrefaction, both samples exhibited lower volatile matter and moisture content, while the fixed carbon content increased. This is an indication of the expulsion of moisture and light volatile matter from the solid residue during the process. However, ash content remained unchanged, thereby attributing to the fact that ash is an inert solid and remains as part of the solid residue after torrefaction. A high carbon content in a fuel is an indication of its high calorific value, and it could be seen that the HHV of samples increased after torrefaction and were comparable to those reported in the literature.[23] For the torrefied fuels, the carbon contents and the HHV were comparable to those of coal such as Matla coal (South Africa) and coal from Ezimo, Amansiodo, and Inyi mines (Enugu) in the South-Eastern
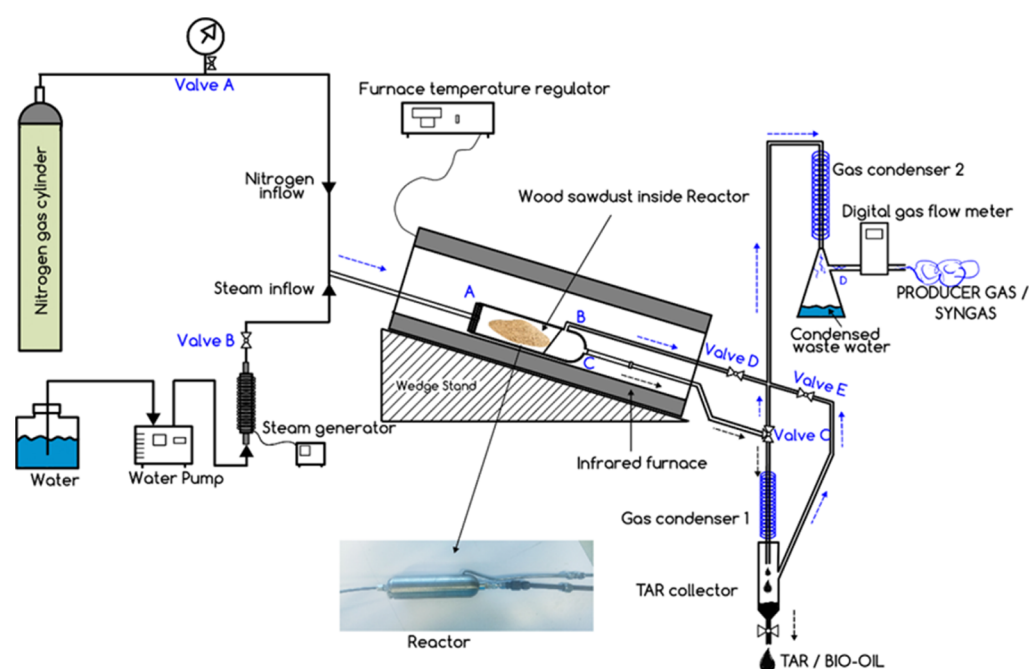
Figure 2. Schematic diagram of the experimental setup used for this study. Adapted with permission from Okoro; Harding; Daramola Pyro-Gasification of Invasive Plants to Syngas. In Valorization of Biomass to Value-Added Commodities.[22] Copyright [2020] [Springerlink].

Table 1. Structural Composition of the PSD Samples

country	cellulose (wt %)	hemicellulose (wt %)	lignin (wt %)	extractives (wt %)
Nigeria	23.92 ± 0.01	36.02 ± 0.10	33.33 ± 0.01	6.73 ± 0.01
South Africa	21.57 ± 0.02	38.02 ± 0.01	30.05 ± 0.01	10.26 ± 0.02

Table 2. Feedstock Characteristics of Raw and Torrefied PSD

	proximate analysis: air-dried basis			
	South African PSD		Nigerian PSD	
parameters (%)	raw	torrefied	raw	torrefied
ash content (wt %)	0.59	0.56	4.76	4.72
inherent moisture content (wt %)	8.55	3.08	6.69	3.89
volatile matter (wt %)	72.50	68.29	63.18	50.34
fixed carbon (wt %)	19.12	27.16	25.37	41.05
HHV (MJ/kg)	20.50	28.27	18.85	29.65
lower heating value (MJ/kg)[a]	19.86	27.08	17.97	28.49
	ultimate analysis: air-dried basis			
	South African PSD		Nigerian PSD	
parameters (wt %)	raw	torrefied	raw	torrefied
carbon	50.54	70.18	40.37	71.25
hydrogen	7.08	5.25	4.52	4.53
nitrogen	0.15	2.44	0.91	1.85
sulfur	0.57	0.43	0.00	0.31
oxygen[a]	41.66	21.70	54.20	22.06

[a]Calculated.

Table 3. Summary of the HHV, Energy Yield, Enhancement Factor, and Solid Yield of the Torrefied PSD Fuels

country	HHV [MJ/kg][a]	solid yield [%]	energy yield [%]	enhancement factor [−]
South Africa	28.27	52.44	73.94	1.41
Nigeria	29.65	65.60	79.80	1.57

[a]HHV at a torrefaction temperature of 300 °C.

region of Nigeria.[24,25] The qualities of torrefied PSD obtained from both countries are very high, hence indicating that they exhibit potentials as fuel for direct use in energy production and as feedstock for pyro-gasification.

Meanwhile, Figure 3 displays the biomass materials (PSD) used in the study before and after torrefaction. Biomass torrefaction has a considerable effect on the quality of the fuel (Figure 3) and corresponds to the properties as presented in Table 2.

The van Krevelen diagram (Figure 4a) compares a plot of H/C against O/C of raw and torrefied biomass. Because of its low fuel properties, the raw biomass is depicted on the upper right corner of the chart. However, by torrefying the raw biomass at 260, 280 and 300 °C, a shift toward the peat coal region can be observed. This is the most evident with the biomass torrefied at 300 °C which leaves a lignin-rich torrefied product. Therefore, 300 °C was reported to be an ideal final temperature for biomass torrefaction. This highlights the influence of temperature on the improved properties of the torrefied biomass. Such improvements are due to the breakdown and expulsion of the cellulose and hemicellulose in the form of volatiles, with a corresponding increase in the percentage weight of lignin. A similar trend in the reduction of the H/C and O/C of the South African and Nigerian PSDs from their raw to torrefied states can be observed in Figure 4b. However, the torrefied PSDs in comparison with the torrefied biomass in Figure 4a exhibited a lower H/C similar to that within the region of anthracite and O/C within the range of lignite. This could be as a result of their higher lignin composition and higher carbon composition—a characteristic of most tropical trees. Similar to Figure 4a, the torrefaction of the PSDs to 300 °C also enhanced the reduction of the H/C and O/
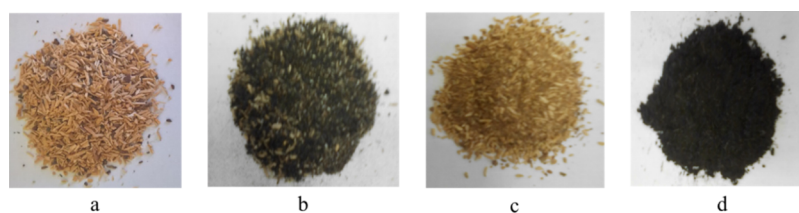
Figure 3. Photography image of fuel used: (a) South African raw PSD, (b) South African torrefied PSD, (c) Nigerian raw PSD, and (d) Nigerian torrefied PSD: Particle size: 0.2−1.0 mm.
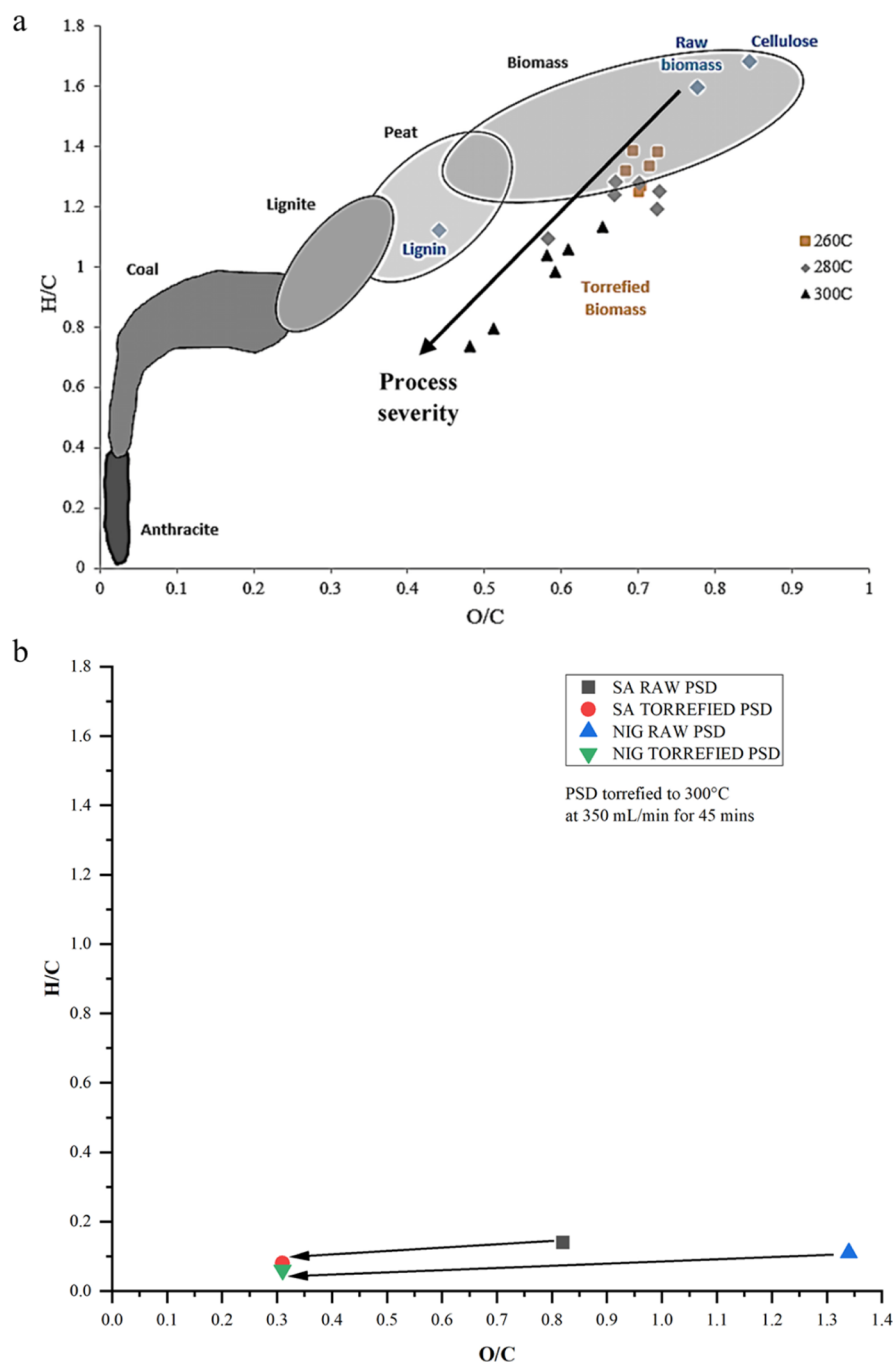

Figure 4. (a) Van Krevelen chart for H/C and O/C properties of raw and torrefied Biomass (sourced with permission from Granados; Basu; Chejne; Nhuchhen Detailed Iinvestigation into Torrefaction of Wood in a Two-Stage Inclined Rotary Torrefier. In *Energy&Fuels*.[20] Copyright [2017] [ACS]; (b) H/C and O/C charts of the South African and Nigerian raw and torrefied PSD (at 300 °C) in this study.

C ratios of the PSDs. Torrefaction is known to improve the fuel properties of a diverse range of biomass into products of similar properties.[20] In corroboration with this, the South African and Nigerian torrefied PSDs exhibited similar qualities, positioned at
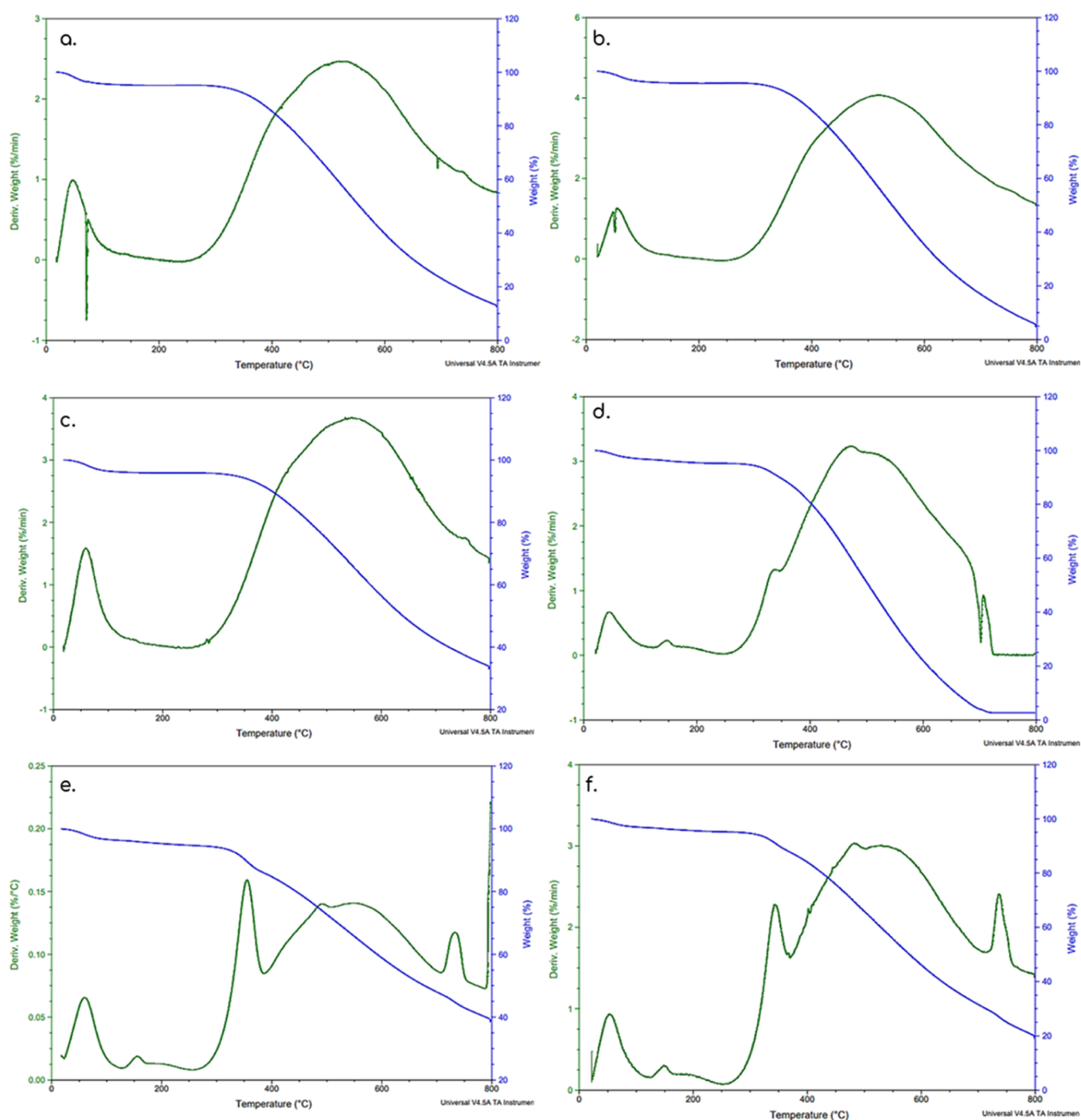
Figure 5. Thermal decomposition of Nigerian and South African PSD. (a) Nigerian PSD at 10 °C/min heating rate; (b) Nigerian PSD at 15 °C/min heating rate; (c) Nigerian PSD at 20 °C/min heating rate; (d) South African PSD at 10 °C/min heating rate; (e) South African PSD at 15 °C/min heating rate; and (f) South African PSD at 20 °C/min heating rate.

the same point despite the different positions of their raw counterparts on the graph (Figure 4b).

2.2. Structural Analysis. Typically, lignocellulosic biomass such as wood is composed majorly of three chemical components. They include cellulose, hemicellulose, and lignin. They also contain extractives and minerals in lower proportions.[26] According to the analysis carried out by Mansora,[27] the cellulose, hemicellulose, and lignin contents are in the range of 40−60, 20−40, and 10−25 wt %, respectively. Generally, cellulose is considered a major component of polysaccharides contained in woody biomass, followed by

hemicellulose and lignin.[28] These constituents play a critical role in the thermal degradation mechanism of biomass and should be well understood for the biomass material to be considered as a fuel for energy production.

The lignocellulose composition of the PSD from both countries is presented in Table 1. Understandably, there was no much variation in the lignocellulosic composition of both biomass materials and their values were similar to those found in the literature. Also, the results of the lignocellulosic properties of the fuels further explained the similarities of their chemical properties.

2.3. SEM Analysis. The results of the scanning electron microscopy (SEM) analysis performed for the South African and Nigerian fuels before and after torrefaction were presented and analyzed using a magnification of ×500. According to a study carried out by Pattanotai *et al.*[29] using Japanese cypress wood, the physiochemical properties, especially, surface morphology, were improved *via* the thermal treatment of the biomass material. The reactivity of the solid residue after thermal treatment was also observed to improve greatly during its gasification. In this study, the SEM images indicate a significant change in the surface morphology of the samples after torrefaction. For both samples, however, the untreated biomass particles appeared bulky with visibly loose fibers, indicating the presence of its holocellulose structural components. Conversely, the torrefied fuels can be observed to be more compact, exhibiting a more brittle appearance as indicated by the smooth surface texture of its particles. This was attributed to the rapid loss in moisture and volatilization of its holocellulose components during torrefaction which improves fuel hydrophobicity. Shrinkage of the particles resulting from the mass loss of the particles during the volatilization process can be observed with the torrefied samples. However, similar to the untreated biomass, there still appeared to be an agglomeration of the torrefied particles of the South African PSD, which was observed to be less prominent with that of the Nigerian PSD. The physical properties such as low particle agglomeration, brittleness, and compact appearance of the torrefied Nigerian PSD particles are desired attributes required for the easier handling and storage of solid fuels. These properties were less apparent than in the torrefied South African PSD. The torrefaction of the South African PSD at a higher torrefaction temperature, may, therefore, be required to improve its physical properties and surface morphology.

The results of the SEM images obtained from South African and Nigerian PSD demonstrated the importance of torrefaction as an effective method of enhancing the properties of the fuel. Therefore, torrefaction should be vigorously pursued to promote the development of commercial biomass torrefaction plants in both countries. The establishment of such plants will be instrumental to waste management, creation of employment, energy efficiency, and sustainability in the two countries.

2.4. Changes in Fuel Quality: HHV. The percentage increase in HHV from the raw to the torrefied PSD samples was calculated using the following expression

$$\frac{HHV_{torrefied} - HHV_{raw}}{HHV_{raw}} \times 100 \tag{1}$$

By comparing the properties of the fuel contained in Figure 3 (before and after torrefaction) in terms of the HHV, it can be found that the HHVs of the fuels were increased by 57.29 and 37.9% for the Nigerian and South African PSDs, respectively (Table 3).

It is noteworthy to state that the fuel quality of the PSD after torrefaction is rated based on the value of the enhancement factor (EF). It can be observed that the EF of the Nigerian PSD was higher than that of South African PSD (Table 3). This was attributed to the physicochemical properties of the fuel materials that are varied on the account of the differences in climatic and geographical growth conditions of both PSDs.

2.5. Changes in Fuel Quality: Compositional Analysis (Ultimate and Proximate). The percentage changes in fuel quality in terms of the elemental composition (ultimate and proximate analysis) were estimated after the torrefaction process. Table 2 shows that the changes in the carbon (C), sulfur (S), and oxygen (O) contents of the Nigerian fuel after torrefaction were higher when compared to those of South African fuel, whereas the reverse was the case for the hydrogen (H) and nitrogen (N) contents.

Similarly, the proximate analysis showed that the changes in the ash, volatile matter (VM), and fixed carbon (FC) contents of the Nigerian fuel were considerably higher than those of the South African fuel, but with a lower change in the moisture content (MC). Additionally, the variations in the physicochemical characteristics of the fuel are dependent on the geographical location[30] and can further be confirmed from the enhancement factor (EF) obtained for both fuels (Table 3).

2.6. Thermal Decomposition of South African and Nigerian PSD. The thermal degradation of South African and Nigerian PSD was carried out to understand the temperature-derivative weight/weight loss behaviors of the fuels. This analysis informs the development of their kinetic reaction rate equations and the determination of their activation energies which are vital for pyro-gasification efficiency. By doing so, enhancements in their energy conversion and production of their resultant secondary biofuels can be achieved to ensure efficiency. Figure 5a–f displays the thermal decomposition profiles of PSD from South Africa and Nigeria carried out at 10, 15, and 20 °C/min heating rates.

The graphs depict a clear distinction between the DTG thermogram patterns of Nigerian and South African PSD samples. A broader single peak stretching across a wide temperature range extending beyond 800 °C was observed with the Nigerian PSD when treated under the three heating rates. This highlights the high thermal stability of the Nigerian PSD despite the change in heating rate.

In contrast to the Nigerian PSD, separate peaks were observed at different temperatures with the South African PSD. Also observed was the thermogram degrading completely at 725 °C under the 10 °C/min heating rate (Figure 5d). However, thermal stability was improved with an increase to 15 and 20 °C/min, as the degradation stretched beyond 800 °C (Figure 5e,f). The individual peaks observed in the South African PSD were exhibited by the structural components—hemicellulose, cellulose, and lignin, indicating the peak rates of their decomposition occurring at different temperatures. In the case of the Nigerian PSD, the rates of decomposition of these components were, however, observed to peak at much closer temperatures than those of the South African PSD, resulting in the conjoined, broader peak.

Details of the thermodecomposition data of both samples are shown in Table 4. With regard to their rates of decomposition, the Nigerian PSD was observed to peak at generally higher rates

Table 4. Thermodecomposition Data of the Two PSD Samples with an Increase in Heating Rate

heating rate (°C/min)	peak rate of decomposition (%/min)		temperature at peak rate of decomposition (°C)		residue at 800 °C (wt %)	
	Nigeria	South Africa	Nigeria	South Africa	Nigeria	South Africa
10	2.5	3.25	520	470	14	3
15	4.2	0.163	510	350	6	39
20	3.75	3.125	550	490	34	20

and correspondingly higher temperatures than the South African PSD. Such peaks were attained at significantly higher temperatures because of increases in heating rate. The need for an increase in heating rates to attain higher rates of decomposition may be attributed to the high ash composition of the Nigeria PSD. Because of its inert nature, layers of ash deposited on the biomass surface may block its pores, thereby inhibiting the free transfer of heat to its inner particles.[22]

By increasing the heating rate from 10 to 15 °C/min, the peak rate of decomposition of the Nigerian PSD increased from 2.5 to 4.2%/min. This increase in heating rate was required to enhance the rate of its thermal decomposition, which in turn peaked at a lower temperature of 510 °C. However, the resultant effect of the increase in heating rate on the peak rate of decomposition of the South African PSD was different. The peak rate of its decomposition was observed to be the highest (3.25%/min) at 10 °C/min, resulting in a very low solid residue of 3 wt % at the 800 °C final pyrolysis temperature. However, this decreased significantly to 0.163%/min with the 15 °C/min heating rate, resulting in a higher residue of 39 wt % at 800 °C. Because of the significantly lower ash composition of the South African PSD, no further improvements were observed in its peak rate of decomposition with the increase in heating rate. The temperatures at the peak rate of decomposition of the South African PSD across the three heating rates set were also observed to be significantly lower than those of the Nigerian PSD. In general, the South African PSD was observed to be more reactive, requiring less thermal energy to decompose than the Nigerian PSD, mostly because of its low ash composition.

3. CONCLUSIONS

From the study, the following conclusions were made:

- The HHV, EF, energy, and solid yield from the Nigerian fuels were higher than those of South African fuels by 2.38, 5.37, 3.49, and 11.15%, respectively.
- The HHV of the raw fuels, when compared to that of the torrefied fuels, increased by 20.27 and 15.93% for the Nigerian and South African PSD, respectively, implying that the wood PSD has the potentials for use as a renewable fuel for pyro-gasification.
- The thermal degradation study of the fuel samples indicated that South African fuel is more reactive than Nigerian fuel and would need lower thermal energy for its decomposition. The low-temperature decomposition exhibited by the South African PSD indicates its low-temperature requirement for biofuel production via pyro-gasification. This also indicates its rapid ignition at lower temperatures if used as feedstock for combustion.

4. MATERIALS AND METHODS

4.1. Materials: Collection, Processing, and Characterization. The biomass material (PSD) used for the investigation was collected from one of the pine trees at the premises of the University of the Witwatersrand, Johannesburg (26.1929° S, 28.0305° E), while the PSD of Nigerian origin was collected from the Ogbete-Main market, Enugu (6.4348° N, 7.4848° E). Both fuel samples were pretreated by drying, milling and sieving, and torrefaction. The biomass materials were sun-dried and size reduced to 0.2−1.00 mm using Restec SM 200 biomass sawmill located at coal Lab in Richard Ward Building of the School of Chemical and Metallurgical Engineering, University of the

Witwatersrand, Johannesburg. The pretreated fuel samples were secured in air-tight plastic bags for further analysis.

4.2. Methods. *4.2.1. Torrefaction Process.* Prior to the final lab experiments, a preliminary torrefaction experiment was run using results obtained from design of experiments (DoE), by employing the Box Behnken Design (BBD) method. Three torrefaction temperature regimes including mild (200 °C), intermediate (250 °C), and severe (300 °C), at torrefaction residence times of 30, 45, and 60 min, respectively, were investigated. A temperature of 300 °C and a reaction time of 45 min were identified as the optimum operating conditions for the torrefaction process which is in corroboration with the van Krevelen chart.[20]

The same operating conditions of 300 °C and 45 min were employed for the final torrefaction experiments to maintain the accuracy of results. The weights of the biomass samples before and after torrefaction were measured, and the weight loss was calculated and recorded. Milled and sieved PSD (20 g, South Africa and Nigeria) was subjected to a torrefaction process in a tubular reactor using nitrogen at 300 °C and 350 mL/min for 45 min (Figure 2).

The reactor was flushed with a stream of nitrogen and compressed air to avoid contamination at the end of each experimental run. The reactor temperature was also increased to around 650 °C at the end of the pretreatment process to ensure that the volatiles and residual tars retained in the reactor were burnt and flushed off the reactor completely. The torrefied fuels were labeled and stored in air-tight plastic containers.

4.2.2. Characterization. The procedures for determining the structural (cellulose, hemicellulose, and lignin) composition of the wood samples were carried out as in the literature.[31,32] Meanwhile, the proximate analysis of the fuels was carried out following the standard procedure of the American Society for Testing and Materials (ASTM E870-82) for the proximate analysis. The elemental composition and the HHVs were determined experimentally using the CHNS-O organic elemental analyzers (FLASH 2000) and a Drycal modular oxygen bomb calorimeter (203M 1241), respectively. The energy content of a fuel is an important property that is usually considered before its selection for energy production. Therefore, in biomass torrefaction, the HHV should be accorded adequate attention. This is because if the HHV is improved, the energy quality of the fuel is automatically increased.

Besides being determined experimentally, the HHV of a solid fuel may also be estimated numerically by employing a empirical model as eq 2.[33] Other equations developed and reported in the literature for estimating HHV are listed in Table 1.

$$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O$$
$$- 0.0151N - 0.0211A \tag{2}$$

where C, H, S, O, and N represent the percentage carbon, hydrogen, sulfur, oxygen (obtained by difference), and nitrogen contents of the fuel (from the ultimate analysis) and A is the ash content (from the proximate analysis) (Table 5).

Meanwhile, in this study, the LHV of the PSDs was estimated using the following expression[33]

$$LHV = HHV - (0.212C \times 4.49) - (0.0024 \times 6.69) \tag{3}$$

where the LHV and HHV of the PSD fuel undergoing investigation are expressed in MJ/kg.

Table 5. Correlation for Estimating the HHV of Biomass[a]

different HHV (MJ/kg) correlations	reference
HHV[a] = 0.3536FC + 0.1559VM − 0.0078ash	Paikh *et al.*, 2005[34]
HHV[a] = 0.3491C + 1.1783H + 0.1005S − 0.1034O − 0.0151N − 0.0211ash	Channiwala and Parikh, 2002[35]
HHV[b] = 0.0893L[c] + 16.9742 (for wood biomass)	Demirbaş, 2001[36]
HHV[b] = 0.0877L[c] + 16.4951 (for nonwood biomass)	Demirbaş, 2001[36]
HHV[a] = 0.2949C + 0.8250H	Yin, 2011[37]
HHV[a] = 0.2521FC + 0.1905VM	Yin, 2011[37]

[a]HHV: higher heating value: FC: fixed carbon (wt %), VM: volatile matter (wt %); C: carbon (wt %); L: liquid = moisture content (wt %); H: hydrogen (wt %); O: oxygen (wt %); N: nitrogen (wt %). [a], [b], and [c] represent the dry basis (wt %), dry-ash-free extractive-free basis (wt %), and Lignin (wt %) respectively.

4.2.3. Thermogravimetric Analysis. The thermal degradation behaviors of the South African and Nigerian PSD samples under pyrolysis conditions were determined using a thermogravimetric analyzer (SDT Q600 V20.9 Build 20). Each PSD sample (10 mg) was subjected to a thermal treatment from room temperature to 800 °C under heating rates of 10, 15, and 20 °C/min and nitrogen gas flow of 10 mL/min in three separate experimental runs. Universal V4.5A TA Instruments Data Analysis software was used to extract, plot, and analyze the thermograms.

4.2.4. Scanning Electron Microscopy. SEM was used to determine the surface morphology of the wood PSD. The procedure employed involved mounting of a thin layer of the powdered sample on an adhesive carbon tape placed on aluminum studs and coated with an ultrathin gold−palladium alloy (AuPd) to ensure effective conductivity of the sample. An air duster was applied to blow away excess loose particles. The sample surface morphology was analyzed using a Carl Zeiss Sigma FESEM Oxford X-ACT EDX detector operating at an acceleration voltage of 5.000 kV.

4.2.5. Enhancement Factor (EF). When fuel is torrefied, its physiochemical quality is improved. The EF of a torrefied fuel is the energy density ratio used to evaluate the quality of fuel after torrefaction, and its value is always greater than one[33]

$$EF = \frac{[HHV_{tb}]}{[HHV_{rb}]} \quad (4)$$

where HHV_{tb} and HHV_{rb} (MJ/kg) are the HHV of torrefied and raw biomass, respectively.

4.2.6. Solid Yield. During thermal degradation of biomass *via* torrefaction, the biomass material is subjected to different degrees of temperature, for example, 200−300 °C, thus resulting in weight loss after the process. Dependent on the temperature and time used, a larger amount of the mass of the fuel may be consumed in the process. In this case, the mass ratio of the torrefied and the raw fuel is called the solid yield (SY) and can be expressed as[33]

$$SY = \frac{[M_{TB}]}{[M_{RB}]} \times 100 \quad (5)$$

where M_{TB} and M_{RB} (g) are the mass of torrefied biomass and raw biomass, respectively.

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Notes

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