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Combustion characteristics of Torrefied corncob and African birch wood residues at higher heating rate

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ABSTRACT

The torrefaction of biomass generated from by-products of post-harvest agricultural activities such as corncob or woody residues from saw milling, pruning, and furniture production such as African birch wood, are renewable energy sources whose pyrolytic and combustion properties are crucial during process heating in various applications. This study investigated the combustion characteristics of corncob and African birch wood residues at a higher heating rate and their comparative energy qualities. Samples of corncob and African birch wood residues were collected, sorted, pulverised into particles, and torrefied independently. The raw and torrefied corncob and African birch wood particles were screened into 0.3, 0.5, and 1.0 mm sizes, and their thermogravimetric, proximate, ultimate, heating values, and energy quality analyses were carried out. The torrefied biomass showed better pyrolytic and combustion characteristics relative to the raw samples. However, African birch wood residues appear to be better than corncob residues. The higher heating values (HHVs) ranged from 21.46 to 21.63 MJ/kg and 23.1 to 25.6 MJ/kg for the torrefied samples of corncob and African birch wood residues, respectively. The torrefied sample of African birch wood residues exhibited the highest HHV (25.6 MJ/kg), which compared favourably with the value from a low-rank coal, such as lignite or brown coal. Torrefied African birch wood residues, with their high HHV, can be densified to replace low-rank coal and firewood in a variety of applications.

Introduction

The need to develop clean, alternative and renewable energy sources has become imperative due to the world's rapid economic and technological development, demand for energy that is particularly high in the industrial sectors, and the environmental challenges caused by the burning of fossil fuels, in particular, global warming and the subsequent climate change [1–3]. Coal and other non-renewable, finite fossil fuels could be replaced with biomass, a renewable alternative energy source [4–7]. This is due to their abundance, minimal pollutant emissions and carbon dioxide neutrality [8–10].

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Historically, agricultural and woody residues have been one of the most predominant energy sources, and they are becoming one of the most promising options for energy mix because of their sustainability potential and ecological friendliness [8,9,11]. Agricultural residues, also called 'agro- or crop residues,' such as corncobs are generated commercially from post-harvest agricultural activities and are widespread throughout the world's temperate regions. Woody residues on the other hand are generated during saw milling, pruning and furniture production. Due to their comparative economic advantage, they have become popular as an alternative fuel in a number of applications, including convectional boilers [1,2]. The low energy density, poor combustion and pyrolytic features of these agricultural and woody residues, suggest that their applications as energy sources would require a significantly huge volume than using fossil fuels such as coal [12].

A thermochemical pre-treatment like torrefaction is one of the essential steps to overcome these associated fuel property limitations and the logistic economics of sustainable energy solutions [2,13,14]. Torrefaction, often called '*mild pyrolysis*,' is a thermochemical reaction that take place between 200 °C and 300 °C in an inert environment. Torrefaction is frequently used to transform raw biomass into solid fuels with better combustion and pyrolytic capabilities. The end product may have characteristics similar to low-rank coal, making it a promising alternative in coal-fired power plants [12]. Following the torrefaction process, an increase in energy density is realised, along with a sizable mass loss of the resulting solid fuel [11]. This enormous loss of mass might be due to the removal of moisture content, release of substances with low melting points (i.e., volatiles) and the depolymerisation of lignocellulosic components [15].

The adoption of these biomass sources for energy applications relies on many factors such as kinetic decompositions, thermodynamics and combustion characteristics. Precise characterisation of the biomass sources and accurate investigation of their kinetic decomposition, thermodynamics and combustion characteristics would improve agricultural and woody residues potential as energy sources. Also, these would serve as useful information for the design and operation of biomass thermochemical conversion units that may be willing to use torrefied biomass as feedstock. The individual study of biomass energy values and thermal properties have become necessary because different biomass behave differently under the same set of conditions [1,2]. Although the thermal decomposition of lignocellulose biomass engenders the same number of phases during degradation. Thermogravimetric analysis (TGA) has proven to be a useful tool for investigating material thermal decomposition. It is used to analyse the trend of mass loss with respect to temperature at a specific heating rate, providing valuable data on biomass composition, kinetic decomposition, thermodynamic parameters, and pyrolytic and combustion characteristics [12,16].

Numerous investigations have revealed that torrefaction enhances the calorific value, mass and energy yield of biomass fuels and also, information on thermodynamic properties and decomposition kinetics of lignocellulose biomass had been reported. To enhance combustion qualities and improve the energy values and understand the kinetic decomposition of agricultural residues for solid fuel applications, Yiga et al., [17] studied the decomposition of carbonised selected agricultural residues. The research focused on the synergy between combustion and thermodynamic characteristics. The TGA was used to investigate the combustion characteristics along with other test such as higher heating value and proximate analysis. The study revealed that the thermochemical pre-treatment had an obvious impact on combustion and thermodynamic properties that were examined. Barontini et al., [12] examined torrefaction's impact on the devolatilisation characteristics of lignocellulosic biomass. Using TGA, their investigation examined the devolatilisation process of three lignocellulosic biomass with varying degrees of torrefaction. A kinetic model based on three parallel reactions that correspond to the chemical components of biomass was used to evaluate reaction kinetics using the TGA data. The authors reported that the torrefaction process significantly reduced the hemicellulose content of the biofuels under investigation. They reported that the findings of TGA depicted that, in comparison to carbon monoxide and carbon dioxide, the reduction in volatile production brought on by torrefaction pre-treatment was significantly greater for water and organic compounds.

Similarly, Akhtar et al., [18] investigated the torrefaction and thermochemical properties of corncobs, cotton stalks and sunflower flowers. The biomass was initially pyrolysed under benign conditions, followed by TGA, to understand the mass-temperature connection. The authors reported that an ideal temperature range was discovered to be between 260 °C and 300 °C, with a residence time of 20 to 30 min. The composition study revealed that for all the various kinds of agro-residues taken into account, torrefied biochar had a higher amount of lignin and cellulose and a lower content of hemicellulose than the raw samples. Cahyanti et al., [11] conducted a comparative analysis of selected fuel characteristics of wood and agro-residues through torrefaction. In their investigation, torrefaction of agro-residues (i.e., of barley straw and cumin stalks) and woody residues (i.e., of birch, spruce, and pine) was used at residence times of 30 and 60 min at temperature range of 225 °C to 300 °C. The heating value for all biomass increased as the torrefaction temperature rose, according to the authors' observations.

However, a review of the relevant published studies highlighted a significant gap in existing research. There is a lack of comprehensive studies on the kinetic decomposition, combustion characteristics, and comparative energy quality of raw and torrefied corncob and African birch wood. Additionally, the influence of torrefaction on the pyrolytic thermodynamic properties of these biomass materials has been under-explored. Without a deep understanding of the kinetic decomposition and combustion characteristics, it is challenging to optimise thermochemical conversion processes such as pyrolysis and gasification, which could lead to inefficient energy conversion and suboptimal product yields. Thus, this study examines the combustion characteristics of torrefied corncob and African birch wood residues and their comparative energy qualities at a higher heating rate.

Methodology

Sampling and sample preparation

The raw corncob (*Zea mays* L.) samples were sourced from the University of Ilorin farm in Ilorin, Kwara State, Nigeria (latitude

8.4799 N and longitude 4.5418 E) and the African birch wood (*Anogeissus leiocarpa*) were sourced from Odo-Okun, off Sawmill Garage Road, Ilorin, Kwara state, Nigeria (Longitude; 4.52620 and Latitude: 8.4707). The raw corncob and African birch wood samples were sorted, air dried, pulverised, sieved, and some of the raw corncob and African birch wood particles were torrefied. All of the samples were then stored individually. Thermogravimetric, proximate, ultimate, heating value and energy quality analyses were performed on the raw and torrefied particles.

Equipment and materials preparation

The equipment utilised in this investigation included a hammer mill, set of sieves, muffle furnace, weighing scale, crucible, thermogravimetric analyser and oxygen bomb calorimeter. The raw corncob and African birch wood residues were sorted to remove any dirt or debris, like sand, stones and other plant residues, afterward air-dried for 48 h to remove surface water interference. To lower the particle size for greater workability, the samples were hammer milled and then sieved and screened to 0.3, 0.5 and 1.0 mm particle sizes based on standard method BS EN 15,149–2 [19]. Then, the processed corncob and African birch wood particles were stored individually in zip-lock bags to enable subsequent procedures and prevent the prepared samples from acquiring ambient moisture.

Torrefaction process

An electric muffle furnace was used to torrefied the samples. Samples of dried, pulverised and sieved corncob and African birch wood particles weighing a total of 30 g each were put in the sample container and mounted in the furnace. Nitrogen gas was purged into the torrefying chamber at 100 mL/min to create and maintain an inert atmosphere throughout the operations. The samples were torrefied at 280 °C for a residence period of 30 min, at which point each procedure was stopped and the samples were removed for analysis [20].

Characterisations of the samples

Thermogravimetric, proximate and ultimate analyses, higher heating values and solid and energy yields were used to characterise the corncob and African birch wood particles.

Thermogravimetric analysis

Thermogravimetric analysis (TGA) was conducted to establish the pyrolytic characteristics that define the raw and torrefied corncob and African birch wood samples' mass loss during the torrefaction process, in accordance with standard method ASTM E1131 [21]. The thermogravimetric analyser (PerkinElmer TGA7) that comprised a combustion chamber and a balance connected to a computer system, was employed for the analyse. Twelve milligramm of each sample was placed in the analyser in an inert atmosphere. The initial weight reading was set at 100 % prior to beginning the heating process. Temperatures from 30 °C to 950 °C were considered while heating at 20 °C/min for all samples that were considered. At the end of the entire process, a plot of weight loss percentage against temperature was generated and obtained.

Combustion characteristic parameters

The parameters that depict combustion characteristics are flammability index, (F), which is often used to determine how reactive a fuel is at its early stages of combustion and combustion characteristic index, (S) – a parameter showing the swiftness of the combustion process, can be expressed as follows, respectively [17]:

$$F = \frac{\left(\frac{dx}{dt}\right)_{max}}{T_i^2} \tag{1}$$

$$S = \frac{\left(\frac{dx}{dt}\right)_{max}\left(\frac{dx}{dt}\right)_{mean}}{T_i^2\ T_f} \tag{2}$$

where T_i denotes the ignition temperature, T_f is the burnout temperature, $\left(\frac{dx}{dt}\right)_{mean}$ is the average combustion rate and $\left(\frac{dx}{dt}\right)_{max}$ is the maximum combustion rate.

Proximate and ultimate analysis

The raw and torrefied corncob and African birch wood samples were subjected to proximate analyses to ascertain their moisture content, volatile matter, ash content and fixed carbon (i.e., combustible solid) percentages' that are present in the samples. There volatile matters were computed after determining the moisture content of the raw samples by keeping the dried samples obtained at 925±20 °C for seven minutes in a closed crucible of the muffle furnace with model number OMEGALUX LMF-3550 in accordance with standard procedure ASTM D3175–18 [22]. According to ASTM D3174–12 [23], the resulting residual samples after the determination

of the volatile matter were gradually heated to 700±50 °C for 30 min in the muffle furnace. The fixed carbon content, F_C is the amount that remains after the deduction of moisture content, volatile matter and ash content from 100, i.e., [8]:

$$F_C = 100 - M_c - V_m - A_c \tag{3}$$

Where M_C, V_m and A_c denote the amounts of moisture content, volatile matter and ash content, respectively. The chemical composition of the significant elements, i.e., carbon (C), hydrogen (H) and oxygen (O) contents in the sample fuels were determined based on the established correlation for C, H and O as follows [8,24]:

$$C = 0.637F_C + 0.455V_m \tag{4}$$

$$H = 0.052F_C + 0.062V_m \tag{5}$$

$$O = 0.304F_C + 0.476V_m \tag{6}$$

All values determined in all analyses were reported on a dry basis.

Higher heating values

The higher heating value (HHV) test was conducted employing oxygen bomb calorimeter with model number Parr 6400 oxygen bomb calorimeter based on ASTM D5865–13 [25] standard to determine the raw and torrefied samples' energy content. The bomb calorimeter's sample holder was filled with one gram of the samples, which was then transferred to the steel capsule to determine the HHV for all samples. The procedure was repeated in triplicate for all samples that were considered.

Solid yield

The solid product yield for the samples was calculated using the standard process established by Parikh et al., (2007), in which an initial mass of raw corncob particles was supplied into the torrefaction chamber. After torrefaction, the total mass of the remaining

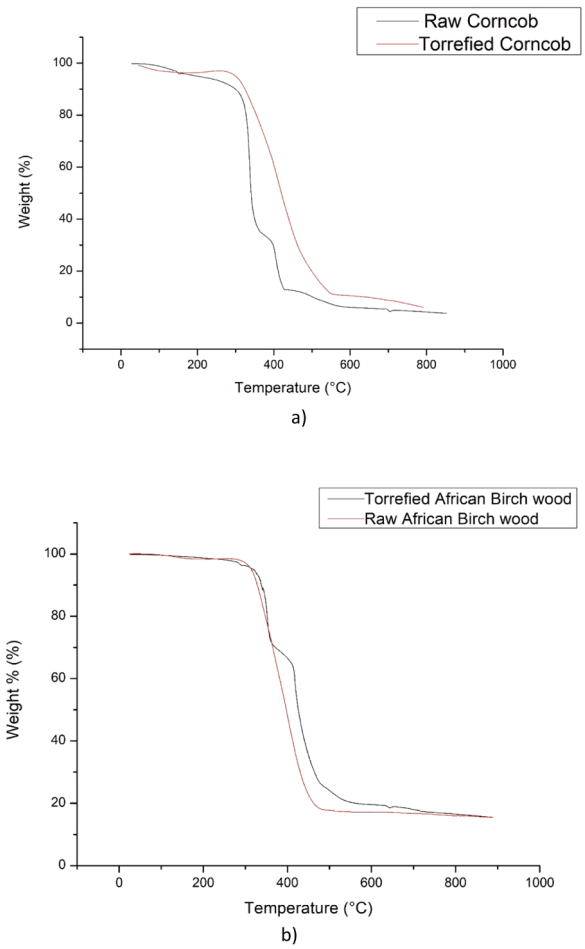

Fig. 1. TGA of a.) Corncob sample and b.) African birch wood sample.

product was measured and weighed. The solid yield, S_{yield} also known as the '*mass yield*' of the torrefied sample can be expressed as the ratio of the torrefied product's mass to the mass of the feed (i.e., the raw sample) [26]:

$$S_{yield} = \frac{mass\ of\ product}{mass\ of\ feed} \text{ x } 100 \tag{7}$$

Energy yield

The energy yield, E_{yield} was determined from the product of the solid yield and the energy density, i.e., [26]:

$$E_{yield} = S_{yield} \times E_d \tag{8}$$

Where E_{yield} is the energy yield, S_{yield} is the solid yield and E_d is the energy density.

Results and discussion

Thermogravimetric analysis

Figs. 1 and 2 show the thermogravimetric analysis (TGA) and differential thermal analysis (DTA), respectively of the raw and torrefied samples of corncob and African birch wood residues. The initial step of the various evolutional temperature regimes experienced the elimination of moisture – occurs when the temperature is below 160 °C for all samples at heating rate of 20 °C/min. At this temperature, mass loss by the raw samples of the biomass exhibited just 7 % to 7.2 % and <1 % for the torrefied samples and these mass losses are consistent with the values obtained in proximate analysis [27]. The low contents of moisture in torrefied biomass make them feasible as alternative solid fuels. The second stage of decomposition, which is the active pyrolysis stage took place within 150 °C to 550 °C and 124 °C to 600 °C temperature ranges for the raw sample and torrefied samples, respectively. Comparatively, thermal

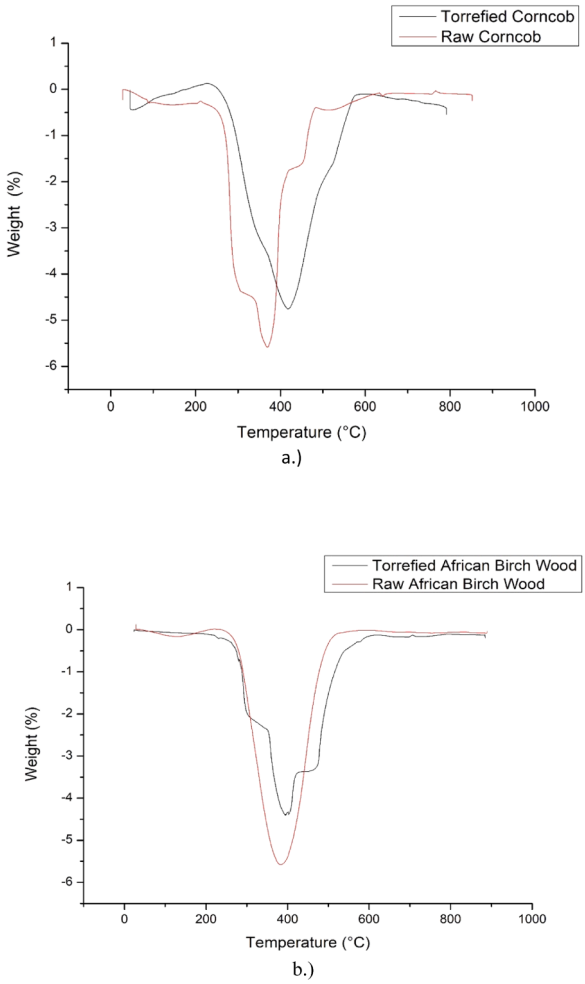

Fig. 2. DTA of a.) Corncob and b.) African birch wood residue sample.

decomposition commenced early at this stage, which is characterised by the loss of surface water, or water molecules held together by weak forces, and the elimination of light volatiles that had already occurred during torrefaction processes [27–29]. Lignin, cellulose and hemicellulose decomposition was also noticed at this stage, which may be classified to take place at two different stages: between 250 °C and 460 °C, and above 500 °C. The raw and torrefied samples' cellulose and hemicellulose contents disintegrated at 250 °C to 360 °C, and the lignin contents were thermally degraded at 500 °C and above. In the third stage, all the samples' final products were ash contents, which is why they displayed an almost constant trend until the very end, at high temperatures above 750 °C. Three distinct peaks were observed for the raw corncob samples on the DTA curves, with the first peak corresponding to the removal of moisture and the other two peaks occurring at the reactive stage, which corresponds to the decomposition of the hemicellulose and cellulose contents of the biomass. It could be observed from Fig. 2 that both corncob and African birch wood samples exhibited a maximum peak within the same temperature range, which corresponds to the region of reactivity for the biomass samples. Considering Fig. 2(b), each torrefied sample peak shifted to the right relative to the peak of their respective raw samples, which could be attributed to the effect of torrefaction on the biomass samples. Also, the changes in their pattern of peaks compare to the raw biomass signals that the torrefied biomass constituent had been modified [6].

Combustion characteristic parameters

Raw and torrefied samples of corncob and African birch wood samples had different combustion characteristics in a variety of ways. Therefore, parameters like flammability index and characteristic index were analysed. The onset temperature of raw corncob and African birch wood residues were found to be lower than the values obtained for torrefied samples (Table 1). This implies that the samples of torrefied product may be partially stable from self-ignition at a slightly higher temperature [30]. It can also be seen from Table 1 that the peak temperatures of the torrefied African birch wood samples are higher than those of the corncob samples, which could be alluded to the differences in cellulose contents of the African birch wood and the corncob residues. Also, previous studies postulated that the noticeable rise in peak temperatures of the torrefied samples above the raw samples was caused by the influence of temperature on the samples during torrefaction [30]. Noticeably, the offset temperatures of the samples of torrefied Africa birch wood residues are a little lower than those of the samples of torrefied corncobs. This disparity in the values of the offset temperature can be attributable to the composition of biomass components that varied based on the sources of the biomass [31]. The raw corncob samples have the highest flammability index (1.58×10^{-6}). It has been established that biomass with higher combustion rate and low on-set temperature exhibits higher flammability and this consequently leads to its easiness to combust [11]. The high value of combustion characteristic index that was obtained for corncob signals that corncob has better combustion characteristics than African birch wood. Therefore, it can be concluded that the corncobs' higher flammability and combustion characteristics index suggest that they have better combustion properties than the African birch woods, which compared favourably with findings reported by Cahyanti et al., [11].

Proximate and ultimate analyses

Table 2 presents the raw and torrefied samples of corncob and African birch wood residues proximate analysis for all samples that were investigated. It can be observed that the raw samples generally have higher volatile matter content than the torrefied ones. Because some volatile matter had been decomposed during torrefaction through a process known as devolatilisation, making the available volatile content in the torrefied samples to be lower compare to its raw samples. The value of the moisture content as presented in Table 2 falls within the range of 13.22 % to 1.00 % for all samples across all particle sizes. The low moisture content associated with torrefied biomass reinforces an established guiding norm that torrefaction had the impact of lowering the moisture content of the torrefied samples, which is characterised by the removal of surface and binding water from the biomass. The assessments of fixed carbon in this study's findings showed that torrefied African birch wood residues have higher fixed carbon content than the torrefied corncob samples. This complied with the stated guiding norms [28]. Compared to torrefied African birch wood residues, torrrefied corncob particles contained more ash. Studies have shown that agricultural residues contain high mineral content that was build up during growth, which makes it less desirable for energy application. Also, whether woody or agricultural residues, torrefied product generally has higher ash content than their respective raw biomass. This can be alluded to the fact that torrefaction of lignocelluloses produces more ash due to the large proportion of inorganic solid residues in the torrefied biomass [32].

Table 3 presents the ultimate analysis of the raw and torrefied samples of corncob and African birch wood residue. The carbon content of torrefied corncob particles clearly increased for both sample across all particle sizes. It is clearly shown from the table that torrefaction had obvious effect on carbon content of the two spices of biomass that were considered. Torrefied corncob and African birch wood residue samples with 1.0 mm particle sizes had a maximum carbon content of 54 % and 52 % respectively, which is nearly

Table 1
Combustion characteristics of raw and torrefied samples of corncob and African birch wood residues.

Sample ID	On-set	Temperature (°C) Peak	Off-set	Combustion Rate (%/min) (Max., Mean)	Flammability Index (10^{-6})	Combustion Characteristics Index (10^{-11})
Raw Corncob	210	380	440	0.07, 0.03	1.58	10.08
Raw African Birch Wood	220	376	460	0.07, 0.02	1.44	6.288
Torrefied Corncob	240	400	530	0.06, 0.02	1.04	3.93
Torrefied African Birch Wood	245	405	490	0.06, 0.02	1.00	4.07

Table 2
Proximate analysis of raw and torrefied corncob residues.

Properties	Raw						Torrefied					
	African Birch Wood			Corncob			African Birch Wood			Corncob		
Particle Size (mm)	0.3	0.5	1.0	0.3	0.5	1.0	0.3	0.5	1.0	0.3	0.5	1.0
Moisture Content	7.20	8.00	9.40	10.30	12.10	13.22	1.00	1.30	1.35	1.00	1.20	1.22
Volatile Matter %d.b	78.00	77.00	71.00	75.70	72.50	69.85	47.00	45.00	42.00	44.02	42.01	40.11
Ash Content %d.b	1.80	1.40	1.00	3.41	4.50	4.63	4.00	3.70	3.05	5.08	6.11	7.27
Fixed Carbon %d.b	13.00	13.60	18.60	10.50	10.86	12.3	48.00	50.00	53.60	49.00	50.64	51.35

similar to the carbon percentage in low-ranked coal [29]. It was found that the oxygen concentration of the torrefied samples was much lower than the value observed for the raw samples that were considered in this study within the same series for all particle sizes. The difference between the percentage carbon and oxygen content of raw and torrefied samples, as well as the production and release of carbon dioxide and water vapour, can be related to a number of reactions that occurred during torrefaction [29]. Both raw and torrefied corncob and African birch wood residue samples showed a small drop in hydrogen content for all particle size series. As particle size rose from 0.3 mm to 1.0 mm, it was discovered that the hydrogen concentration decreased. This decrease may have been brought on by various hydrocarbons emitted during the torrefaction processes, such as butane and methane [33]. Similar studies have found that torrefaction results in the emission of certain hydrocarbons, which reduces the net hydrogen level [5,11,29].

Higher heating values

Fig. 3 depicts the raw and torrefied corncob and African birch wood residue samples' higher heating value (HHV) profiles. The HHVs ranged from 16.66 to 16.81 MJ/kg, 16 to 18.2 MJ/kg for the raw samples of corncob and African birch wood residues respectively, and 21.46 to 21.63 MJ/kg, 23.1 to 25.6 MJ/kg for the torrefied samples of corncob and African birch wood residues, respectively. The heating value of corncobs, whether in the raw or torrefied category, is low compare to African birch wood residues. This could be attributed to the higher fixed carbon content of African birch wood residues. Also, higher proportion of lignin content in African birch wood residues could also be alluded to the higher value of HHV that was recorded for African birch wood residue. According to Kanwal et al., [15], torrefied agro-residues had an energy content of 22.79 MJ/kg, which is slightly higher than the experimental value obtained for torrefied corncob samples. This may be as a result of differences in the species nutrient build up during growth. Meanwhile, the energy value that was obtained for torrefied African birch wood residues compared favourably with the 24.6 MJ/kg HHV found in low-rank coal [32]. This signals that African birch wood residue has more potential to replace fossil fuels and firewood in terms of energy values perspective. Generally, torrefaction's pre-treatment procedure has the capacity to decreased moisture content, which may contribute to the relative rise in heating value between raw and torrefied corncob samples [15,34]. The torrefaction pre-treatment yielded an average improvement of about 30 %, demonstrating that torrefaction clearly affects the rise in HHVs of the torrefied lignocellulose samples. The increase in energy density seen in the torrefied samples, however, might be attributed to the larger fraction of lignin and the lower fraction of hemicelluloses and cellulose with low heating values. Also, according to Kanwal et al., [15] and Yang et al. [34], components with less energy than the biomass (as a whole) may have been lost during the torrefaction process. Among them were methoxy groups from lignin, carbonyl and carboxyl groups from cellulose, and carboxyl groups from hemicelluloses. Consequently, their loss increases the biomass's energy density after torrefaction.

Solid yield

A solid or mass yield of 58.4 % and 62.1 % was produced after torrefying 96 g of corncob and African birch wood residue particles each respectively. The reduction in mass yield can be attributed to a number of factors, including moisture loss, volatile organic matter, hemicellulose breakdown, and the amount of cellulose in the torrefied residues of the two biomass samples that were considered in this

Table 3
Elemental composition of raw and torrefied corncob residues.

	Particle size (mm)	C	H	O
Raw corncob	0.3	47.87	5.93	43.82
	0.5	48.23	5.91	43.67
	1.0	49.11	5.90	43.20
Torrefied corncob	0.3	52.33	5.46	37.35
	0.5	53.03	5.42	37.29
	1.0	54.00	5.40	36.85
Raw African birch wood residues	0.3	49.00	5.88	40.13
	0.5	49.26	5.76	40.06
	1.0	50.00	5.62	40.00
Torrefied African birch wood residues	0.3	52.88	5.31	35.18
	0.5	54.16	5.28	34.26
	1.0	55.12	5.18	34.11

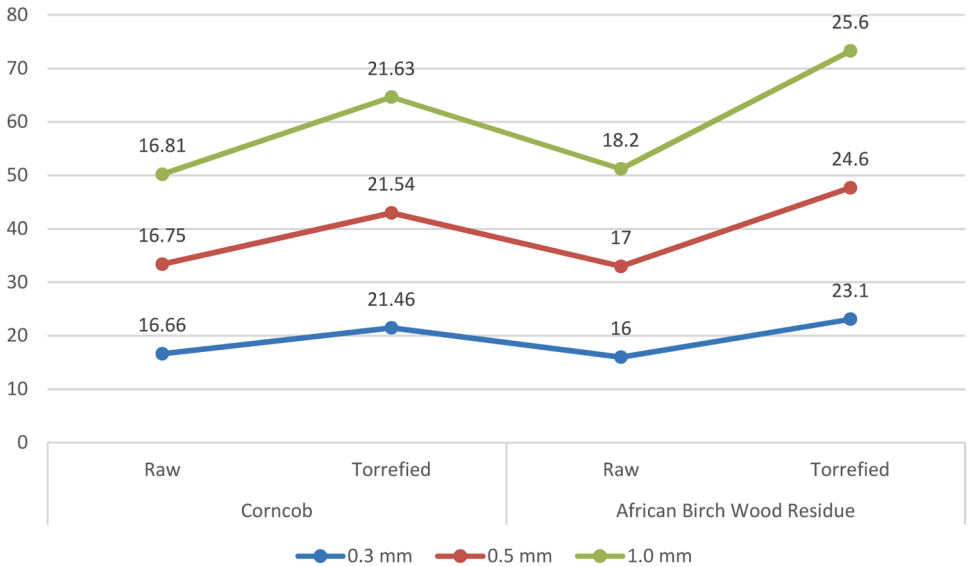

Fig. 3. Higher heating values of raw and torrefied corncob and African birch wood residue samples of different particle sizes.

study [35,36]. The discrepancy between the results published by Chiou et al. [37]; Yue et al., [38] and Manouchehrinejad and Mani [39], and the value found in this investigation is likely due to the different torrefaction temperatures and residence times that the samples underwent. Consequently, poorer solid yields are obtained with greater torrefaction temperatures and residence periods [40].

Energy yield

The energy yield of samples of torrefied samples for various particle sizes is presented in Table 4. The energy yield was found to very slightly depending on particle size. The highest energy yield of 89 % was obtained from torrefied African birch wood residue samples with 0.3 mm and 0.5 mm particle sizes, followed by samples with 1.0 mm, which produced 88 % of the total energy yield, respectively. It is clear that the energy yield is only slightly influenced by particle size, with smaller particle sizes having a higher energy yield [41]. Their reliable heat transmission characteristics provide an explanation for this. But if the torrefaction processes are hampered, the intended qualities could change. The fact that biomass with a higher lignin content is probably going to produce an end product with a better energy yield suggests that the African birch wood energy yield observed in this study is dependent on the components that make up the solid product, thus, making it to be superior compare to corncob residue. Changes in the energy yield of torrefied biomass samples were observed as a result of the almost complete removal of the cellulose and hemicellulose contents of the biomass [42]. A further claim made by Adeleke et al. [42] was that biomass with a higher lignin content generate more energy than biomass with a lower lignin content.

Conclusions

Combustion characteristics of raw and torrefied particles of corncob and African birch wood residues and their comparative energy qualities were carried out at higher heating rate to assess the potential of woody and agricultural residues for energy applications. The combustion characteristics and energy values were established for both raw and torrefied lignocellulose biomass residues to investigate the influence of torrefaction pre-treatment on selected fuel qualities. Torrefaction had a considerable effect on the general properties of the samples weather corncob or African birch wood residues. Thermogravimetric analysis and differential thermal

Table 4
Energy values of raw and torrefied corncob for all particle sizes.

Samples	Sieve size (mm)	HHV_{Raw} (MJ/kg)	$HHV_{Torrefied}$ (MJ/kg)	M_y (%)	E_y (%)	E_d
Corncob	0.3	16.66	21.46	58.4	74.75	1.28
	0.5	16.75	21.54	58.4	74.75	1.28
	1.0	16.81	21.63	58.4	74.75	1.28
African birch wood	0.3	16.00	23.10	62.1	89.00	1.44
	0.5	17.00	24.60	62.1	89.00	1.44
	1.0	18.00	25.60	62.1	88.00	1.42

*M_{yield} – Mass yield, E_{yield} – Energy yield, E_d – Energy density.

analysis revealed that torrefied samples exhibited greater onset temperatures, peaks and offset temperatures than raw samples. This suggests that torrefied samples have better combustion qualities than the raw corncob samples. The raw and torrefied African birch wood residues samples varied in a number of ways from the corncob samples. All of the samples of African birch wood residues that were examined showed a rise in volatile matter and an increase in the percentage of fixed carbon. Due to the higher fixed carbon contents of the African birch wood samples, their biochar burn out produce better heat of combustion. The percentage ash contents of corncob residues were higher than the values obtained for African birch wood residues under the same conditions, which imply that African birch wood residues is a favourable option for energy applications.

CRediT authorship contribution statement

H.A. Ajimotokan: Visualization, Conceptualization, Writing – review & editing. **N.S. Saidu:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **M.A. Aladodo:** Conceptualization, Data curation, Writing – review & editing. **K.O. Oladosu:** Writing – review & editing. **O.D. Samuel:** Writing – review & editing. **K.O. Abdulrahman:** Writing – review & editing. **A. El-Suleiman:** Writing – review & editing. **Y.S. Salihu:** Writing – review & editing. **K.R. Ajao:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

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