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ABSTRACT

Biomass in its natural form is characterized by poor ignition quality, excessive smoking and low combustion efficiency when used as energy source in boilers and blast furnaces. In this paper, the effect of torrefaction on the characteristics of tropical biomass feedstocks (rice husk, groundnut shell and corn cob) at different torrefaction temperatures (200, 250 and 300°C) were investigated. The result of biomass weight loss as a function of temperature variation revealed that at relatively low torrefaction temperatures of 200 and 250°C the weight loss were very pronounced when compared to the negligible weight loss at a torrefaction temperature of 300°C. Rice husk and corn cob exhibited a higher weight loss during torrefaction due to high degradation of the hemicelluloses inherent in the feedstocks. The oxygen:carbon of the torrefied biomass deduced from the ultimate analysis revealed a low and concentrated distribution in the Van Krevelin plot compared to the raw feedstocks. The thermogravimetric analysis of the feedstocks shows that the thermal stabilities were in the decreasing order (groundnut shell > corn cob > rice). The spectral analysis result for torrefied biomass samples showed that the intensity of the functional group peaks increased with increase in the torrefaction temperatures.

Introduction

Concerns about increasing CO_2 and other greenhouse gas emissions into the atmosphere from the combustion of fossil fuel derivatives has presently stimulated the urge to search for alternative energy sources [1]. Besides these environmental challenges, there is also a persistent increase in the price of petroleum-derived fuel, and uncertainty about its continuous supply in Nigeria. This situation has forced most Nigerians to shift from the use of kerosene as a source of domestic energy to the use of wood and wood charcoal as a cheap, abundant alternative energy source. This low-cost solid fuel accounts for about 51% of the nation's annual total energy consumption. The demand for this low-cost fuel was estimated to be about 43.3 million tonnes annually and is projected to increase to about 213.4×10^3 metric tons with a supply shortfall of approximately 28.4×10^3 metric tons within the next 15 years. The continuous use of wood is associated with deforestation and desertification. It is also associated with hardship as vulnerable persons including women and young children have to trek long distances to collect such materials [2]. According to Antwi-Boasiako and Acheampong [3], the use of wood charcoal as fuel is associated with emission of toxic atmospheric pollutants which are responsible for an appreciable number of health problems. The authors added that renewable solid biofuels produced from thermochemical conversion of biomass are a potential substitute for domestic energy supply in order to minimize the persistent use of wood fuel and ensure sustainability of the forest resources.

The biofuels produced from lignocellulosic biomass have a favorable life cycle and negligible greenhouse gas emissions, and offer greater socio-economic and environmental benefits [4]. These feedstocks are mainly made up of agricultural residues such as sugarcane bagasse, crop straws, and corn stover, switch grass, forestry wastes, wood, wastepaper, municipal waste, sawdust, rice husk, cotton stalk and groundnut husk [5–8]. These biomass residues are a promising energy source for domestic cooking due to their relative abundance as waste annually [5]. Biomass has been reported to account for about 10 wt% of the global primary energy demand [1]. Biomass can be effectively used to produce liquid, gaseous and solid fuel (char). Char can be utilized directly for combustion or co-fired with coal in furnaces or boilers for heat and electricity generation [7,8]. Nigeria as a nation has an estimated biomass resource of approximately 144 million tonnes annually [9]. It has been reported that Nigeria is significantly blessed with a vast landmass that could cater for the cultivation of both edible and non-edible oil seeds that have been established to have potential in producing adequate feedstock for the production of different kind of biofuels. The country has about 71.9 million ha of land considered to be very arable [5]. According to Jidere [10], the available

arable land for energy crop cultivation is approximately 28.2 million ha; however, only 2.39 million ha have been cultivated, which translates to about 8.5% of the total available arable land. Grasses of different types are among the country's agricultural produce. It is therefore very apparent that the potential of biomass as an energy resource in Nigeria is incredibly high owing to the fact that approximately 80% of the citizens live in rural and semi-urban areas and traditionally depend on biomass as their source of energy [5].

However, the use of biomass in its raw form as a solid fuel is characterized by low energy density, highly volatile matter and poor storage stability due to the presence of absorbed moisture. The presence of these undesirable constituents is largely responsible for its poor ignition quality, excessive smoke emission and low combustion efficiency in boilers and blast furnaces when used as a source of heat [11,12]. All of these characteristics make biomass difficult to handle, store and transport [5].

In order to enhance the combustion efficiency of biomass, several pretreatment methods have been employed. Drying, as one such pretreatment, has been reported to have impacted positively on the ignition and combustion efficiency of biomass. Torrefaction is another pretreatment method that can be effectively used to enhance the combustion efficiency of biomass feedstock [13,14]. Torrefaction (slow pyrolysis) is a thermo-chemical process where raw biomass is heated at a temperature range above 200°C up to 300°C in a non-oxidizing atmosphere to produce a large fraction of char [15]. In order to avoid oxidation and achieve high thermal degradation, nitrogen is usually used to provide an inert atmosphere. The process is characterized by a slow heating rate (5°C min^{-1}) at a desired residence time (typically 10–60 min). It may be able to retain about 70 wt% of the initial weight of biomass and about 80–90 wt% of the original energy content of biomass [8]. About 30 wt% of the weight is converted to volatile matters and about 10–20 wt% of the original energy content is evolved with the torrefied gases [16]. Lipinsky et al. [16] and Sadaka and Negi [15] reported that torrefied biomass contains lower amounts of oxygen and hydrogen. These have resulted in an increase in the calorific value of biomass and made the torrefied biomass similar in compositions to low-rank coal such as lignite.

Previous reviews on torrefaction of biomass have reported that torrefied biomass offers many advantages [15–17]. These advantages include the densification of biomass, reduction in the hygroscopic nature of raw biomass, and improved ignition and grinding ability of the resulting solid fuel. Consequently, the calorific value (CV) of torrefied biomass is always higher than that of raw biomass [14–16]. The substantial increment in CV reduces the torrefied biomass into an intermediate product for ease of long distance transportation.

Torrefaction also results in a change in the internal configuration of the biomass structure, which is largely responsible for the hydrophobic tendency [18]. The pretreatment process also helps in disrupting the fibrous structure of the biomass and increases uniformity in the torrefied product, making it an interesting, cost-effective and commercially competitive solid fuel. Pelletized torrefied biomass is a better replacement for liquefied petroleum gas, kerosene, firewood and charcoal as energy source for heating, cooking and other industrial applications in both urban and rural areas [19]. Torrefied biomass has advantageous properties (low moisture, lower emission of smoke and increased heating values) that improve fuel quality [19]. Although the benefits of torrefaction are known, there is still no known available commercial-scale reactor for this purpose in most part of sub-Saharan Africa.

Most previous literature on torrefaction of biomass focused on biomass samples from temperate regions, such as bamboo, banyan and willow [20], hemicellulose, cellulose and lignin [21], reed canary grass and short-rotation willow coppice [22], willow [23,24] and deciduous wood-beech and willow [25]. In contrast, relatively little work has been carried out on the torrefaction of tropical biomass feedstocks. The relatively few works documented on tropical biomass feedstock focused on single biomass [20–25]. Different torrefied biomass has different volatiles, compositions, heat contents and reactivity when utilized in power generation. Appreciable numbers of these properties have not been established for most tropical biomass feedstocks. This paper intends to investigate the variations in the properties of different tropical biomass materials during torrefaction.
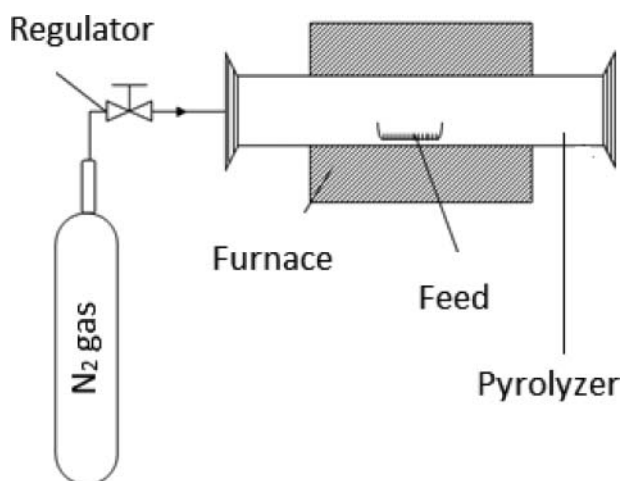
Material and method

Material

Rice husk (RH) was collected from Bida, Niger State, Nigeria, while corn cob (CC) and groundnut shell (GS) were collected from Beji, Niger State, Nigeria. After the seeds were removed, the agricultural wastes were oven dried for about 6 hours. Then the dried residues were pulverized to millimeter size in the feed grinder. After grinding, the samples were passed through a 150-μm sieve (laboratory test sieve model).

Method

Description of experimental setup

A schematic diagram of the experiment is shown in Figure 1. The system was made up of a reactor, nitrogen steel cylinder, rotameter and product gas collection unit. The steel cylinder (3 L at 180 bar) was used to create an inert environment. The flow rate was controlled by the rotameter. The reactor comprised a horizontal clamp

Figure 1. Schematic diagram of biomass torrefaction system.

Table 1. Proximate and fiber analysis of raw rice husk, corn cob and groundnut shell.

Sample	Rice husk	Corn cob	Groundnut shell
Proximate analysis (wt%)			
Moisture	3.81	5.44	8.44
Volatile matter (VM)	66	64	63.81
Fixed carbon (FC^a)	22.01	21.08	19.33
Ash	8.18	9.48	8.42
Fiber analysis (wt%)			
Hemicellulose	32	35	21
Cellulose	41.6	45	49
Lignin	12.5	15	19

furnace (Carbolite 21-301418) and glass tube pyrolyzer. The glass tube pyrolyzer was fabricated in the Science Equipment Development Institute (SEDI) Minna, Nigeria. The samples were placed in the pyrolyzer for torrefaction and the furnace provides heat at different reaction temperatures. The furnace pressure was monitored using a pressure gauge, and vacuum pump was used to reduce pressure build-up in the reactor. The experiment was carried out at the Centre for Genetic Engineering and Biotechnology (Step B) of Federal University of Technology, Minna, Nigeria.

Torrefaction process

About 3 g of sample with particle size of < 150 μm were placed inside the crucible and inserted into the pyrolyzer. The system was closed and degassed with nitrogen for 5 min before the reaction. The horizontal furnace was switched on and heated at a rate of 10°C min^{-1} and maintained at a set torrefaction temperature of 200°C for 1 hour. After reaction the system was allowed to cool down and the sample was removed through the outlet tube exit. The product gas was allowed to escape through the outlet tube. The experiment was repeated at 250 and 300°C for 1 hour.

Characterization

The raw biomass and torrefied biomass were analyzed for proximate, ultimate, fiber, energy and thermogravimetric properties. Accordingly, standard procedures of the American Society for Testing and Materials (ASTM) were used for proximate and ultimate analyses. The proximate and ultimate experiments were replicated 3 times and the results were reported as arithmetic means. The result obtained for each run exhibited good reproducibility under identical conditions, and the standard deviation was less than 1. The lignocellulose analysis, hemicellulose, cellulose and lignin contents were determined following the method adopted in a previous study [26]. A bomb calorimeter was used

to measure the calorific value of the samples in accordance to ASTMD-240. The thermogravimetric analysis (TGA) was carried out by use of TGA equipment (Perkin ElmerTGA-4000). The TGA equipment was purged with nitrogen gas at a heating rate of 10°C min^{-1} where the temperature ranged from 30 to 900°C. Fourier transform infrared spectroscopy analysis (FTIR) of biomass samples was performed using SHIMADZU Series FTIR Spectroscopy.

Results and discussion

The basic properties of the materials such as proximate, fiber and ultimate analyses are given in Tables 1 and 2. To explore the impact on torrefaction temperature on the biomass feedstocks, three torrefaction temperatures of 200, 250 and 300°C at a constant torrefaction time of 1 hour.

Variations in physio-chemical properties

A mass balance accounts for what goes in and out of system. In a mass balance, yields of solid residue (char), permanent gases and condensable vapour (tar) are important. The gas and tar yields are ignored during the torrefaction process [14–16]. The resultant mass yield of the solid fuel and the changes in mass yields with response to temperature are shown in Figure 2. The results revealed that at relatively low torrefaction temperatures of 200 and 250°C the weight loss was very pronounced, whereas at a torrefaction temperature of 300°C, the weight loss of the tested biomass becomes relatively negligible.

Table 1 indicates that the content of hemicelluloses in rice husk and corn cob were high (32 wt% and 35 wt%) as against the 12 wt% recorded for groundnut shell. It was reported [27] that the thermal degradation of hemicelluloses is relatively active when compared to cellulose and lignin at high torrefaction temperatures. This was, however, a plausible reason for the pronounced impact of torrefaction on the rice husk and corn cob. The lignin content of groundnut shell was determined to be 19 wt%. This value was higher than the 12.5 wt% and 15 wt% reported for rice husk and corn cob, respectively. The high lignin content for groundnut shell was responsible for the higher resistance to thermal degradation of

Table 2. Ultimate analysis, ash content and calorific value (CV) of raw and torrefied biomass.

Samples	Temperature (°C)	Ultimate analysis				Ash content	CV (MJ/kg)	CV upgrade
		C	H	O	N			
Rice husk								
Raw		43.83	6.76	46.07	0.93	8.18	15.81	1.0
	200	51.89	6.01	41.33	0.92	7.33	19.34	1.22
	250	52.44	5.90	40.53	0.92	6.12	20.33	1.28
	300	53.56	5.81	39.45	0.77	5.55	20.87	1.32
Corn cob								
	Raw	45.02	6.51	45.41	0.31	9.48	17.12	1.0
	200	52.11	5.90	40.24	0.29	7.92	20.66	1.21
	250	52.73	5.77	40.01	0.29	7.02	21.44	1.25
	300	53.91	5.63	39.01	0.29	6.41	21.92	1.28
Groundnut shell								
	Raw	45.32	6.03	43.54	0.51	8.42	18.42	1.0
	200	52.30	5.73	39.41	0.51	3.12	21.34	1.16
	250	53.45	5.41	38.11	0.51	2.44	22.11	1.20
	300	55.00	5.29	37.7	0.51	2.02	22.66	1.23
Coal [26]		74.12	4.22	6.93	1.91	11.58	26.73	
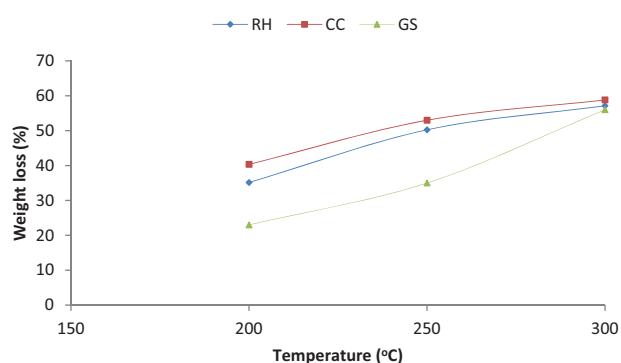
Figure 2. Weight loss distributions of various biomass feedstocks against torrefaction temperatures.

this feedstock when compared to rice husk and corn cob as the torrefaction temperatures increases. Juxtaposing the three tested biomass samples at a torrefaction temperature of 300°C, it was obvious that the weight loss was independent of the lignocelluloses nature of the biomass materials at this temperature. The result depicts that the rate of weight loss tends to become uniform at the higher torrefaction temperature of 300°C. However, only about 45 wt% of mass was retained at this severe torrefaction temperature.

The ultimate analyses as well as CV of the raw and torrefied biomass samples are shown in Table 2. The results of the ultimate analysis of the fuel shown in Table 2 reveal that the chemical compositions of the biomass samples were altered as a result of torrefaction at different temperatures. The hydrogen, oxygen and sulfur contents were observed to decrease with increasing temperature while the carbon content increased as the torrefaction temperature increased from 200 to 300°C. The nitrogen content exhibited a different trend as the value obtained for raw and torrefied biomass samples remained almost constant except for some slight decrease observed for rice husk whose initial content was 0.93 wt% and later became 0.77 wt% at the torrefaction temperature of 300°C. The variation in elemental composition could be attributed to differences in biomass structural composition [27].

The ash content is characterized by the presence of large amounts of alkaline and alkaline earth metals (AAEMs) such as sodium, potassium and calcium. During biomass combustion these metals may interact, leading to melting of the ash particles and thereby promoting the formation of deposits on the heat transfer surfaces. The ash content from this study compares favorably with 6.75–11.35 wt% for temperate biomass feedstocks reported by [28], but differs significantly from the ash content of 38.6 wt% reported by Aboyade et al. [29].

Table 2 shows that the ash content of raw rice husk (8.18 wt%) decreases to 7.33, 6.12 and 5.55 wt% upon torrefaction at 200, 250 and 300°C, respectively. The ash contents of corn cob and groundnut shell also exhibit a similar trend, and it can therefore be concluded that increasing torrefaction temperature progressively reduces the ash content of the tested biomass materials. The low ash content observed in this study indicates a very low ash deposit formation tendency and reduces the maintenance cost when the torrefied products are to be employed for energy generation.

It has been well established that when fuel is burned, carbon plays an exothermic role whereas oxygen plays an endothermic role. Table 2 shows that the higher the torrefaction temperature, the higher the carbon content and the lower the oxygen content. This leads to an increase in the CV of torrefied biomass. Bridgeman et al. [24] also reported that torrefied biomass loses more hydrogen and oxygen compared to carbon. Consequently, the CV of torrefied biomass is obviously upgraded upon torrefaction. The CV of rice husk, corn cob and groundnut shell in Table 2 were enhanced by factors of 1.32, 1.26 and 1.18 at the torrefaction temperature of 300°C, respectively. Chen et al. [20] observed that the increasing trend of CV enhancement in torrefied bamboo, banyan and willow. The CV obtained in this study compares favorably with 18–23 MJkg^{-1} and 26 MJ kg^{-1} for torrefied temperate biomass feedstock [21–24] and sub-bituminous coal [29], respectively.
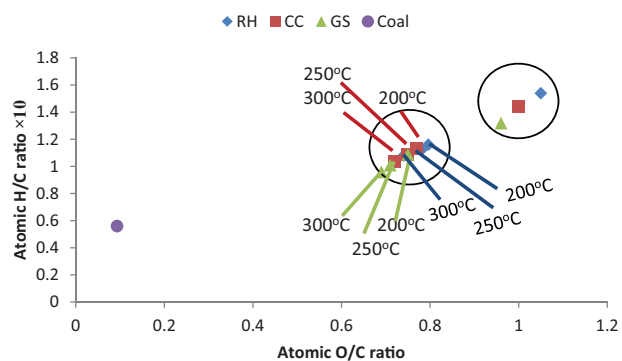
Figure 3. Van Krevelen diagram for raw and torrefied (at different of 200, 250 and 300°C) biomass samples of corn cob (CC), groundnut shell (GS) and rice husk (RH).

It was observed that raw samples exhibited a wide distribution range in the Van Krevelin points, as shown in Figure 3. The wide distribution range observed can be attributed to the heterogeneous nature of C-H and C-O bonds in raw biomass. The torrefed samples, however, displayed condensed H/C and O/C points in the Van Krevelin plot due to the propensity of the torrefed sample to devolatilize from the less porous nature of condensed torrefed samples.

Thermal stability

Figure 4 shows the results of the thermogravimetric analyses of the three biomass materials. Fundamentally, the curves are divided into three distinct regions, regardless of the kind of biomass tested. In the first stage, at a temperature less than 200°C, there was an observable slight weight loss attributed to moisture loss and the volatile release of AAEMs. The second stage ranges between temperatures of 180 and 500°C. The significant reductions in weight observed were mainly due to the thermal decomposition of lignocelluloses. In the third stage, at temperatures beyond 500°C, reduction in biomass weight was not significant when compared with the first stage. This stage was associated mainly with the decomposition of heavy components. Figure 4a shows the TG curves for the three tested samples. The results show a significant change in mass

between 180 and 450°C. The decomposition of groundnut shell occurred at a higher temperature than that of the other biomass materials. The higher thermal stability exhibited by groundnut shell was explicable by the fact that groundnut shell has higher lignin content (19 wt%) in its cell walls than corn cob (15.01wt%) and rice husk (12.5 wt%). According to Chen et al. [25], lignin is known to possess high-strength intricate macromolecules connected by straight links.

The second stage of weight loss exhibits two distinctive peaks (major and shoulder peaks), as depicted in Figure 4b. From the major peak and shoulder in the derivative thermogravimetric (DTG) curve, the lignocelluloses components can be identified. The first weight loss range from a temperature of 180–254°C was found to be similar to the curves of decomposition of hemicelluloses [24,29] whereas the second weight loss, which is the decomposition at higher temperature (254-500°C), is thought to be due to decomposition of the complex and/or aromatic structures such as cellulose and lignin [24,29]. The DTG curve does not show a conspicuous distinction between cellulose and lignin. Both corn cob and rice husk show a major peak (cellulose and lignin) with a shoulder (hemicellulose), while for the degradation rates of groundnut shell only one major peak was present. The absence of a shoulder in the groundnut shell was attributed to the low content of hemicellulose in its fiber.

To show the impact of torrefaction upon hemicellulose, cellulose and lignin, the thermogravimetric (TG) and DTG curves of the three tested samples in the N_2 environment were plotted in Figure 5. Often when biomass is torrefed, the chars are produced at higher temperature. It can be observed in Figure 5 that the devolatilization of volatile species during torrefed fuel production occurs at higher temperatures compared to the raw fuels. This was not unexpected as the torrefed fuels are less reactive due to decreased AAEMs and increased cross linking [27].

Figure 5a and b show that at a torrefaction temperature of 200°C the weight loss and DTG curves of rice husk significantly shifted toward higher temperature, but when the torrefaction temperature was raised to
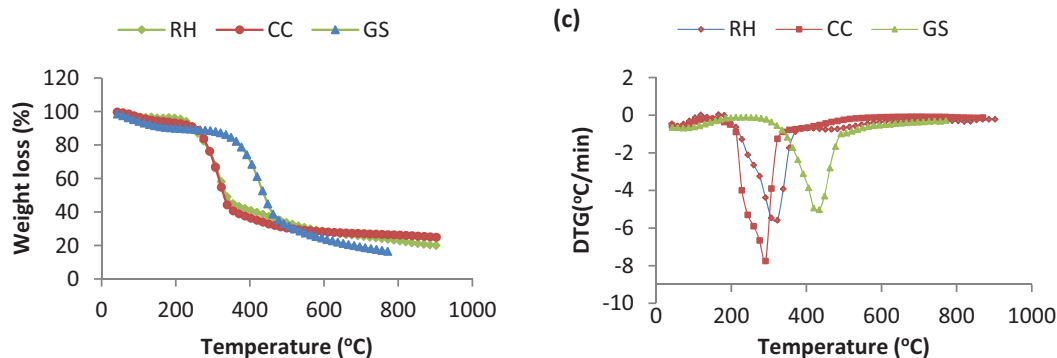
Figure 4. Distribution of: (a) Thermogravimetry (TG) and (b) derivative thermogravimetry (DTG) of raw corn cob (CC), groundnut shell (GS) and rice husk (RH).
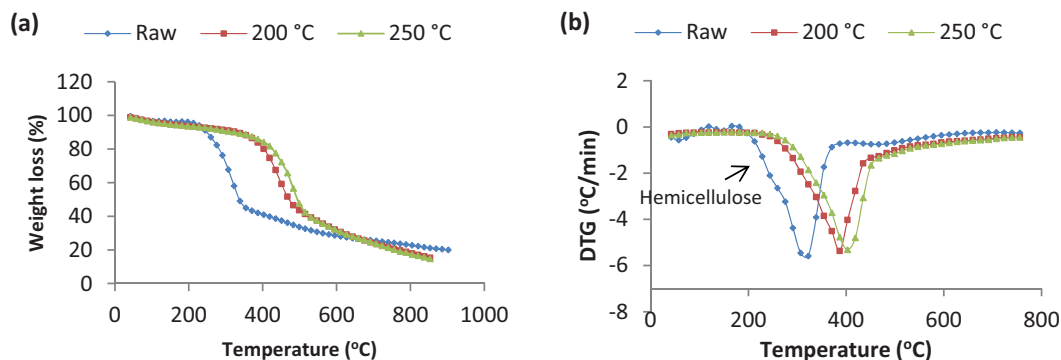
Figure 5. Distribution of: (a) Thermogravimetry (TG) and (b) derivative thermogravimetry (DTG) of raw rice husk and torrefied rice husk at 200 and 250°C.
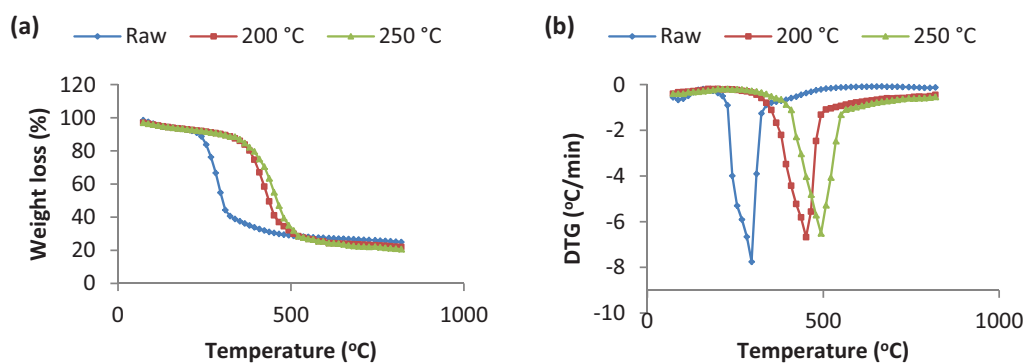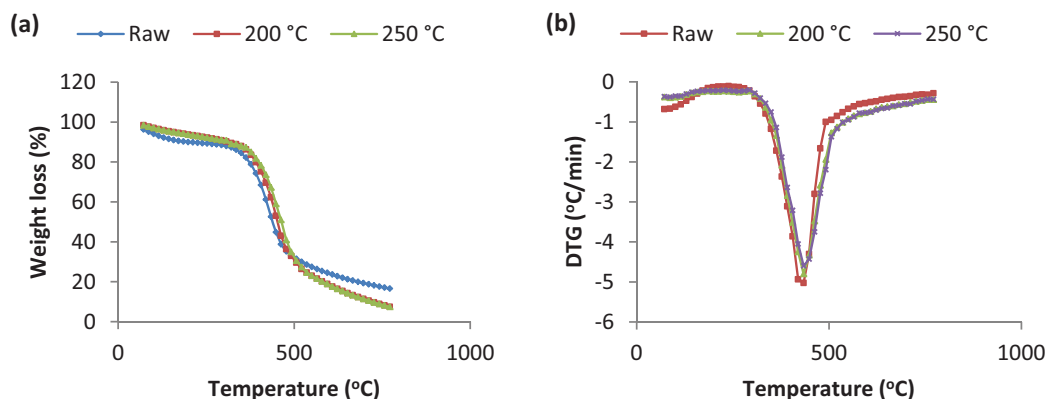

Figure 6. Distribution of: (a) Thermogravimetry (TG) and (b) derivative thermogravimetry (DTG) of raw corn cob and torrefied corn cob at 200 and 250°C.

300°C the shift observed was minute. Figure 5b shows that during torrefaction of rice husk at 200°C, the hemicellulose content of raw rice husk disappears, signifying that the rice husk was sensitive to torrefaction. Cellulose and lignin decompose above 200°C, thereby contributing to a minor mass loss. This loss was, however, not visible in the thermograph curve due to insensitivity of cellulose and lignin degradation at torrefaction temperatures of 250 and 300°C. Chen et al. [27] reported lignin possesses the highest resistance to thermal decomposition during torrefaction of bamboo, banyan and willow. The ash contents of torrefied fuels depicted in the TG curves in Figures 5a, 6a and 7a were lower than those of raw biomass samples due to the

partial release of AAEMs during the torrefaction process. The decrease in ash content observed in the TG curves was consistent with the proximate result for ash content of biomass samples. Mani et al. [30] and Kim et al. [31] reported similar decreasing trends for the ash content during the pyrolysis of wheat straw and yellow poplar, respectively.

The behavior of corn cob curves in Figure 6a and b follow the same trend as those for rice husk. Increases in torrefaction temperature progressively increase the shift toward higher temperature. The hemicelluloses present in raw corn cob disappear in the torrefied samples and the disappearance is closely related to temperature. However, the TGA of groundnut shell

Figure 7. Distribution of: (a) Thermogravimetry (TG) and (b) derivative thermogravimetry (DTG) of raw groundnut shell and torrefied groundnut shell at 200 and 250°C.
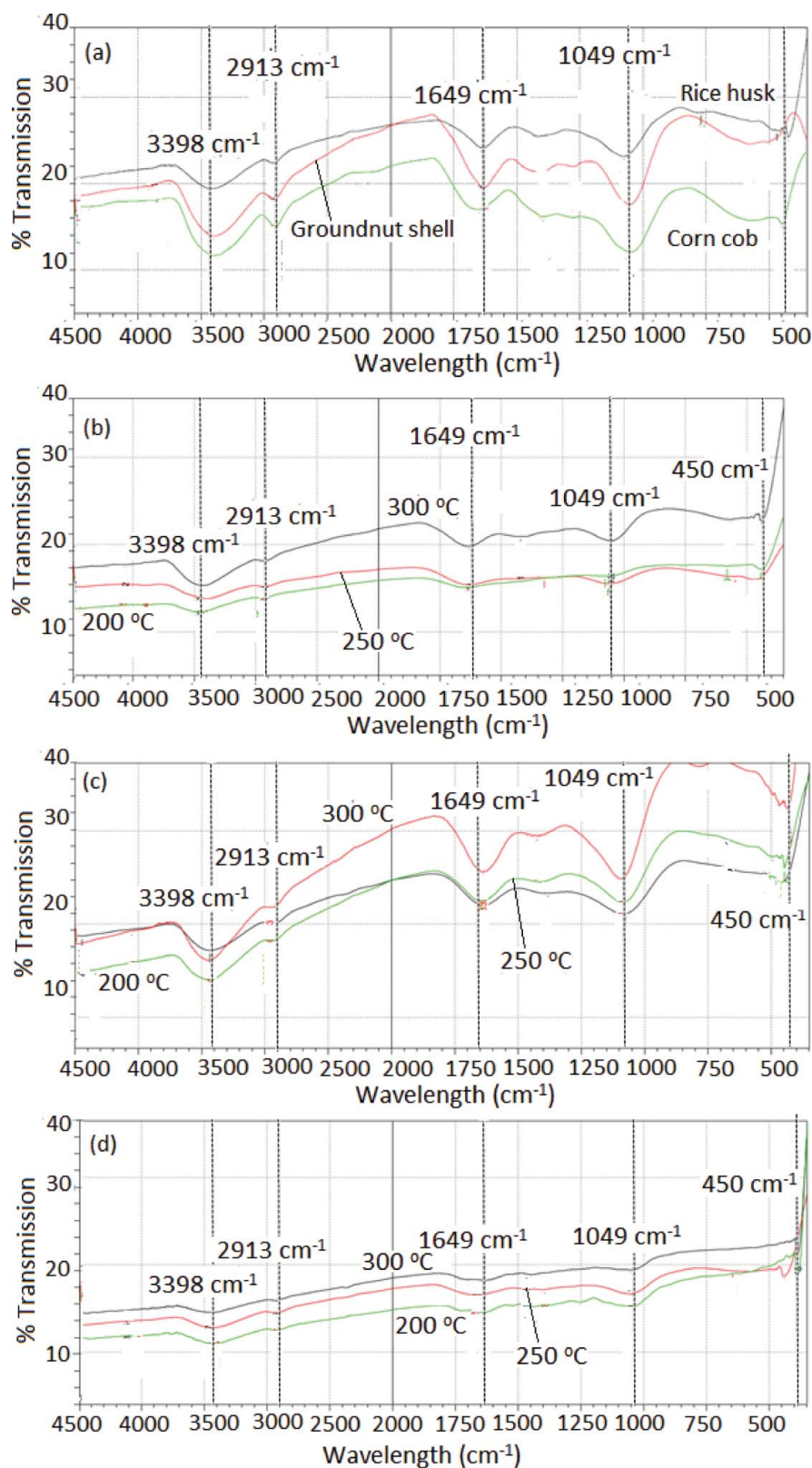
Figure 8. FTIR spectra of (a) raw corn cob (CC), groundnut shell (GS) and rice husk (RH); (b) torrefied GS at 200, 250 and 300°C; (c) torrefied RH at 200, 250 and 300°C; and (d) torrefied CC at 200, 250 and 300°C.

in Figure 7 differs significantly when compared to that of corn cob and rice husk. The weight loss in Figure 7a shifted to higher temperature marginally even at the torrefaction temperature of 250°C. The presence of hemicellulose in the raw groundnut shell was not visible in the weight loss curve depicted in Figure 7b.

Fourier transform infrared spectroscopy (FTIR) analysis

The functional groups which give the surface chemistry of the raw and torrefied products were deduced from FTIR analysis. The infrared (IR) spectra of raw and torrefied biomass materials are shown in Figure 8a–d. The

Table 3. The main functional groups of the raw and torrefied biomass samples.

Wave number (cm^{-1})	Functional groups	Compounds
3600–3000 (s)	OH stretching	Acid, methanol
2860–2970 (m)	C—H stretching	Alkyl, aliphatic
1722 (m)	C = O stretching ketone and carbonyl	Ketone
1632 (m)	C = C	Benzene stretching ring
1060 (w)	C–O stretching and C–O deformation	C–OH (ethanol)
700–400 (w)	C–C stretching	

functional groups and the FTIR signal with the possible compounds are listed in Table 3. It can be observed that the biomass samples are made up of alkene, esters, aromatics, ketone and alcohol with different oxygen-containing functional groups such as OH (3600–3000 cm^{-1}), C–H$_n$ stretching (2860–2970 cm^{-1}), C = O stretching ketone and carbonyl (1722 cm^{-1}), C = C (1632 cm^{-1}), and C–O (1050 cm^{-1}) [31–34]. Figure 8a illustrates the possible chemical functional groups of the raw biomass samples. The first IR peak that occurs at 3398 cm^{-1} was apparently due to hydroxyl (O-H) groups which were found in all raw biomass samples. The highest IR absorbance of OH, C–H$_n$, C = C and C–O were found in raw rice husk while raw groundnut shell contained higher C = O stretching ketone and carbonyl groups. The comparison of raw corn cob and rice husk revealed a very large difference in the fingerprint of about 1049cm^{-1} of the untorrefied IR spectra.

The impact of the torrefaction process on the three biomass samples is shown in Figure 8b–d. The FTIR spectra shown in Figure 8b–d correspond to the volatile matter released at different torrefaction temperatures of 200, 250 and 300°C, respectively. Overall, the IR absorbance for different functional groups became more sharp and visible when the temperature was increased from 200 to 300°C. At torrefaction temperatures of 200 and 250°C, C–H$_n$ stretching, C = C, C–O stretching and C–C stretching nearly overlap in the entire wavelength as shown in Figure 8b for torrefied groundnut shell. But at a higher torrefaction temperature of 300°C, IR absorbance increases in the entire wavelength. The absorbance of OH stretching decreased in the range of 3600–3000 cm^{-1} at torrefaction temperature of 300°C, while the absorptions of C–Hn stretching (2913 cm^{-1}), C = C (1649 cm^{-1}) and C–O stretching (1049 cm^{-1}) increased. For rice husk (Figure 8c), the intensities of the hydroxyl vibrations decreased with increase in torrefaction temperature while those of CH, aliphatic remain intense, showing that there was dehydration and rearrangement of molecules leading to alkyl-carbonyl structures mostly of the ketonic and aldehydic type. The result of the FTIR analysis shows appreciable consistency with the work of Oksman et al. [35] and Haiping et al. [36].

Conclusion

The impact of torrefaction on the physical and chemical properties of biomass samples (rice husk, corn cob and groundnut shell) has been investigated in this study. The result of mass loss variation revealed that at relatively low torrefaction temperatures of 200 and 250°C the weight loss was very pronounced, whereas at a torrefaction temperature of 300°C, the weight loss of the tested biomass became relatively negligible. The oxygen:carbon deduced from the ultimate analysis of the torrefied biomass displayed a low and concentrated distribution in the Van Krevelin plot when compared to the raw biomasses. The thermal stabilities of the biomass feedstocks were found to follow this trend of groundnut shell > corn cob > rice husk in the decreasing order of magnitude. Furthermore, following torrefaction of the three feedstocks studied, the intensity of the functional group peaks increased as the torrefaction temperature increases.

Disclosure statement

No potential conflict of interest was reported by the authors.

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