Exploration of Influence of Chemical Composition on Combustion and Fuel Characteristics of Wood-Charcoals Commonly Used in Bauchi State, Nigeria

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Received: 12.04.2018 Accepted:08.06.2018

Abstract- Wood-charcoal is commonly used as an energy source for household cooking and heating in Bauchi State. Although thought to be one of the major energy source contributor in the State, the chemical composition of wood-charcoal species and its influence on the combustion and fuel characteristics remain largely unidentified and such have contributed to unsustainable wood-charcoal exploitation. This study analysed the chemical composition of the commonly used wood-charcoals related to their combustion and fuel characteristics based on standard analytical procedure described by British Standard and European Norms (BS EN) methods. The results show that the charcoal of *Ficus platyphylla* (Ganji) had a very good fire-holding capacity and recorded the highest calorific value of 33.58 MJ/kg, followed by the charcoal of *Anogeissus leiocarpus* (Marke) with calorific value of 30.09 MJ/kg (which also displayed sluggish burning pattern). The charcoals of *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi), and *Pakia biglobosa* (Dorawa) burnt vigorously and their calorific values ranged between 23.16 and 26.71 MJ/kg. Therefore, the charcoals of *Ficus platyphylla* (Ganji) and *Anogeisus leiocarpus* (Marke) are the most appropriate wood species for charcoal production in the study area. This finding can help policy makers design and establish tree plantations with wood-charcoal species with the desirable attributes for sustainable development and environmental protection.

Keywords: Wood-charcoal, combustion, fuel, quality and characteristics.

1. Introduction

There are currently extensive interests in charcoal production and demand in developing countries owing to poverty and lack of access to modern energy services. In most developing countries including Nigeria, the problem of poverty and increased demand for energy has made the use of charcoal a popular phenomenon [1]. Charcoal is the solid residue that remains when wood is carbonised or pyrolysed under controlled conditions in a closed space. Charcoal can be obtained from other organic substances, but wood is the most commonly used in developing countries. The physico-chemical characteristics of charcoal depends partly on the carbonisation process, but largely on the wood specie [1,2]. Charcoal has a multiple value, but in Nigeria, it is primarily used as a source of domestic energy for cooking and many other heating applications. The majority of the urban poor relies on charcoal as the preferred source of domestic energy because of its convenience and affordability. Despite these features, combustion and fuel properties of wood-charcoal are the most valuable qualities that would make its use sustainable under competitive energy dynamics. However, of all the qualities which are essential in a good wood-charcoal no single one is quite so important as the burn. As a form of biomass, wood-charcoal can only be converted into high energy content fuel through either of the thermo-chemical and bio-chemical conversion processes. Burning or combustion is one of the thermo-chemical processes through which charcoal can be converted into fuel [3]. The chemical composition of wood-charcoal exerts a great influence on its combustion characteristics. The burning or combustion qualities of a wood-charcoal is a function of its evenness of burn, firmness and coherence of ash and fire-holding capacity. The fire-holding capacity refers to the length of time wood-charcoal continues to glow after ignition [4]. A good fire-holding capacity, is the main criterion in judging the combustion and fuel qualities of wood-charcoal. By far the majority of studies placed more emphasis on describing the desirable criteria for quality wood-charcoal as having high fixed carbon, low moisture and ash contents and volatile matter content [2, 5, 6]. These are commonly exploited to account for the calorific/heating value of wood-charcoal. However, often ignored is the influence of inorganic components, such as H, K, Ca and Si, S, Cl, on combustion and fuel properties of wood-charcoal. These are commonly present in raw wood and can be retained in its charcoal. For example, potassium (K) is an important nutrient for plant growth and is present in high quantities in most wood fuels [4]. It is a well-established fact that alkalis particularly potassium (K) aids combustion and increase fire-holding capacity of wood fuels [7, 8]. On the other hand, chlorine tends to foil combustion by salt products formed during thermo-chemical transformation thereby reducing the fuel property of biomass [9].

In Bauchi State, Southern Local Government Areas like Bauchi, Toro, Ganjuwa and Ningi are well known as the major wood-charcoal production base, where many local communities have perfected the technology of wood-charcoal production and made it as an enterprise. This enterprise is one of the major components of the wood fuel industry in the State and it is the main source of domestic fuel in the state capital and the provider in abundance to neighbouring urban areas such as Jos, Kano and Maiduguri. Accordingly, charcoal production plays an important role as a source of energy and cash income for the urban and rural populace, respectively. As such, increasing demand for wood-charcoal may create extra pressures on the environmental systems such as climate, challenging environmental policy goals for energy management and utilisation. Although, the production and/or use of wood-charcoal is not in itself a cause for concern, but when resources are harvested unsustainably and energy conversion processes are inefficient, serious adverse consequences are created on health, the environment and economic development [10-16]. It is therefore important to critically assess the quality of the wood-charcoals produced in the state, so as to acquire knowledge of the tree species with desirable charcoal qualities for sustainable production. In addition, this study also seeks to gain insights into the variability of the physico-chemical composition among the most commonly used wood-charcoals and to identify chemical constituents- that influence wood-charcoal quality characteristics, which might also be a desirable attribute in sustainable productions. The approach provides important informational facts such as fire holding capacity of the wood-charcoal species rather than working with users' impressionable perception. This improves and expands current understanding of this energy demand-user perception nexus, which could expunge hindrances and provide platform for energy policy and planning required for sustainable energy plantation for the protection of forest reserves and subsequent environmental degradation.

2. Materials and Methods

2.1. *Description of the study area*

This study was conducted in Bauchi State, Northeastern Nigeria, where wood-charcoal samples were collected from the major sites of charcoal production zones in the Southern part of the State that covered four Local Government Areas namely Bauchi, Ganjuwa, Ningi and Toro. The State is strategically located between latitude 9.3° and 12.3° north of the Equator. Longitudinally, the State lies between longitudes 8.5°and 11° East of the Greenwich Meriden which gives it a mixed climatic zone. The State is one of the few states in Northern Nigeria that has two distinctive ecological zones; namely, the Sudan savannah and the Sahel savannah, as depicted in Fig. 1. The Sudan savannah covers the Southern part of the State where the vegetation gets richer and richer towards the South, whereas the Sahel also known as the semi-desert vegetation covers the Western and Northern parts of the State, which is characterized by isolated strands of horny shrubs and sandy soils. On the other hand, the south-western part of the State is mountainous as a result of continuation of the Jos-Plateau while the Northern part is generally sandy as a result of the influence of the desert. The vegetation types shown above are conditioned by the climatic factors, which in turn determine the amount of rainfall received in the area. For instance, Bauchi State has a rainfall regime ranging from 1,300mm per annum in the South (savannah zone), and only 700mm in the extreme North [17]. This pattern is due to the fact that in the West African sub-region, rains generally come from the south as they are carried by the south-westerlies, and due to the effect of the North-east wind from the Sahara, the North experiences dry weather conditions. The rainy season starts earlier in the southern part of the state where it is heaviest and last longer. In contrast, the Northern tip of the State receives rain late around the month of June/July with a maximum of 700mm per annum.

In the same vein, the weather experienced between the Northern and Southern parts of the State varies considerably. While it is humid and hot in the early part of the rainy season in the south, the hot, dry and dusty weather lingers on for a while in the North as a result of its closeness to the desert region.

Fig. 1. Map of Bauchi State showing vegetation belts and sampling sites.

2.2. Wood-charcoal samples collection and preparation

The samples of the most common wood-charcoal species produced in Bauchi state were collected from the major sites of charcoal production zones in the southern part of the state. The wood-charcoal species collected were: *Anogeissus leiocarpus* (Marke), *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi), *Ficus platyphylla* (Ganji) and *Pakia biglobosa* (Dorawa). All the lump samples were collected in polyethylene bags and subsequently taken to laboratory where the samples were thoroughly prepared, milled or not milled and stored in air-tight plastic bags before taking for analysis of combustion and fuel related parameters.

2.3. Ultimate and proximate analysis, heating value measurement

The densities of the charcoal samples were determined using water displacement method. Density was calculated from the ratio of the mass to the volume of the charcoal in accordance with the method used by [18]. The densities were calculated as mass by volume of bio-solids. Carbon, hydrogen, and nitrogen content in the samples were analysed in accordance with BS EN ISO 16948:2015, which is specifically designated for solid biofuels [4]. Oxygen and sulphur contents in the samples were analysed on two separately configured CE instruments EA 1110 Elemental Analyser (Thermo Scientific) with aid of Thermo EAger Xperience software. The analysis of chlorine was conducted according to BS EN standard method BS EN ISO 14582:2016, in which a weighed sample was combusted in pure oxygen in an enclosed vessel (oxygen flask). The gases were absorbed in a suitable absorbent solution within the flask. The solution was washed from the vessel and made up to a known volume and the chloride was quantitatively determined by ion chromatography. The instrument software compared the chloride peak to a series of known standard materials (after calibration) and generated a report for the chlorine content on a weight basis. Proximate analyses were also conducted according to BS EN standard methods with the following adaptations. The BS EN ISO 18134-2:2017 method was implemented for moisture content, where a sample was placed into a suitably prepared and weighed tray and reweighed, which was then dried at 105 °C to constant weight and the total moisture/dry solids content was calculated from the reduction in weight. The ash content of a dried sample was determined gravimetrically as prescribed by BS EN ISO 18122:2015, by which a sample was weighed into a prepared ash crucible and placed in a furnace. The furnace was heated to 550 ºC ±10 °C where the temperature was maintained. Following combustion, the crucible and sample are removed, cooled in a desiccator and reweighed. BS EN ISO 18123:2015 standard method was used for volatile matter, where a dried sample was placed in a suitable crucible fitted with a close-fitting lid. The crucible and sample was weighed and heated in a furnace with a limited air throughput at a temperature of 900 ºC ±10 °C for 7 minutes. The sample and crucible were re-weighed and the volatile matter content determined by difference. Both ultimate and proximate analyses were performed at least in duplicate. Calorific value of the samples was determined in an Isoperbol calorimeter by burning in pure oxygen in a combustion bomb. Based on BS EN 14918/BS EN 15400 standard method, a weighed sample was placed in a combustion bomb which was then pressurised to 30bar with oxygen. A calorimeter bucket was filled with a known amount of deionised water which is placed in the calorimeter and the bomb placed in the bucket. The system was allowed to equilibrate and the bomb fired by electrical connection. The difference in temperature of the water in the calorimeter bucket caused by the ignition of the material in the bomb was measured and the calorific value calculated as heating value for each sample. The fixed carbon contents (FCC) of the samples were determined by deducting the sum of % volatile matter, % ash content and % moisture content from 100 as presented in equation (1).

$$Fcc\ (\%) = [100 - (\%\ V_c + \%\ A_c + \%\ M_c)] \tag{1}$$

where, A_c is ash content, M_c is the moisture contents and V_c is the volatile content of bio-solid.

The elemental analysis of Ca, K, and Si in the wood-charcoal samples was determined using instrument EDX 3600B Energy Dispersive *X*-ray Fluorescence Spectrometer. The wood-charcoal samples were pulverised to fine homogenous sizes, which were then pelletised for analysis. The average of values was determined on weight basis [19, 20].

2.4. SEM imaging

The morphological and surface characteristics of the investigated wood-charcoals were also viewed using a scanning electron microscopy (SEM). Here, small amounts of all the samples were first sputtered with a thin layer of carbon on a double-sided tape to improve their conductivity by minimising sample charging using a sputter coater. Images were captured with the aid of instrumentation of scanning electron microscope (Hitachi S-3000N) operated in high 2–10 kV accelerating voltage coupled with a secondary electron detector. Image magnifications used were in the range between 50x and 5000x.

2.5 Combustion characteristics

In an attempt to understand how each of the wood-charcoal samples burns, a test platform comprised of Bunsen burner, tripod stand and wire gauze on top of on an electronic digital balance (with least count of 0.1g) was made and the whole set-up weight was recorded after fully balanced. An oven dried and desiccator-cold sample of each of the wood-charcoal species of known weight was placed on a wire gauze, which was ignited by burner just underneath the wire gauze. This was allowed to burn until the temperature of the burning wood-charcoal declined to less than 100 °C, which was considered not adequate for cooking purpose [21]. Loss of mass was recorded in every 20 minutes interval (enough for the charcoals to attain high heat and start producing white-grey ash) and then normalised by initial mass of the wood-charcoal. The temperature change was monitored with a digital temperature indicator (accuracy of 1 °C) joined with a K-type thermocouple implanted inside the burning wood-charcoal.

2.6 Fuel value index and thermal fuel efficiency measurements

Fuel value index (FVI) was determined based on the method described by Jain [22]. The values of FVI were calculated using equation (2). Water boiling test was used to determine the thermal fuel efficiency of the wood-charcoal samples in accordance to the method described in the literature [23, 24], where each of wood-charcoal samples was combusted to boil one litre of water under similar conditions. Time spent to boil equal volume of water was recorded for each of the bio-energy source and the thermal fuel efficiency was calculated using equation (3).

$$FVI = \frac{Cv \text{ x } \rho}{Ac \text{ x } Mc} \qquad (2)$$

where C_v is the calorific value (KJ·g^{-1}), A_c is ash content (%), M_c is moisture content (%) and ρ is the density (g·cm^{-3}) of wood-charcoal.

$$T = \frac{Mw.Cp\ (Tb-T0)+Mc.L}{Mf \text{ x } Ef}$$

(3)

where T = Thermal fuel efficiency of the bio-energy; M_w = mass of water in the pot (kg); C_p = specific heat of water (KJ/kgK); T_o = initial temperature of water (K); T_b = boiling temperature of the water (K); M_c = mass of water evaporated (kg); L = latent heat of evaporation (kg); M_f = mass of fuel burnt (kg); E_f = calorific value of the fuel (KJ/kg).

3. Results and Discussion

Table 1 represents the proximate, ultimate and EDXRF-elemental analyses of all the attracted wood-charcoals, which represent the physico-chemical composition of the biofuels that describe their combustion and fuel characteristics.

3.1. Proximate analysis

The density, ash, moisture, volatile matter and fixed carbon contents constitute the proximate parameters of solid fuels. Among the tested wood-charcoals, density values ranged from 0.12 to 0.36, of which *Ficus platyphylla* had the highest value of 0.36 gcm^{-3}, followed by *Anogeissus leiocarpus* with density of 0.28 gcm^{-3} and the least values recorded were for *Combretum lamprocarpum, Butyrosperum paradoxum* and *Pakia biglobosa* with 0.21, 0.17 and 0.12 gcm^{-3}, respectively. Density of a solid fuel describes the sponginess and penetrability that exists between inter and intra particles, which enable easy infiltration of oxygen and out flow of burning solid fuel [25]. It is also a physical property that accounts the geometry (bulkiness and packing orientation) of a solid fuel [26]. Therefore, the high porosity index of *Ficus platyphylla* and *Anogeissus leiocarpus* could be one of the responsible factors that made them exhibited sluggish burning rate than other bio-energy sources with low densities (Fig. 2). The moisture percentage contents of the wood-charcoal species originally varied from 4.17 to 6.63%, of which *Combretum lamprocarpum* (Zindi) had the highest value of 6.63% and *Ficus platyphylla* (Ganji) recorded the lowest value of 4.17%.

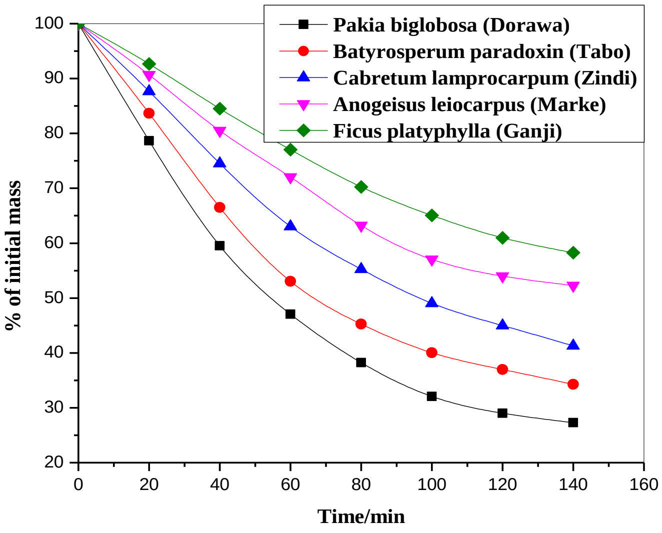

Fig.2. Combustion characteristics of the wood-charcoal samples.

The presence of moisture in solid bio-fuel influences its behaviour during combustion [27] and thus, affects physical properties and quality of solid bio-fuel produced. It has been reported that when moisture content of a charcoal material stands at 18% and below, the charcoal material does not contain free water but rather bound water that is chemically combined with the environment of the charcoal material [28]. This indicates that so long as a charcoal material contains moisture content of less than 18%, the bulk of its physico-chemical properties would not be influenced by moisture content. Consequently, as the moisture contents of all the wood-charcoal tested are quite below 18%, the materials contained no free water and therefore, the moisture content has no effect on the combustion and fuel properties of the wood-charcoals.

The wood-charcoals investigated in this study exhibited distinct ranges of ash content. The charcoal materials of *Anogeissus leiocarpus* (Marke) and *Ficus platyphylla* (Ganji) had ash content values of 6.51% and 5.35%, respectively. However, *Combretum lamprocarpum* (Zindi), *Butyrosperum paradoxum* (Tabo) and *Pakia biglobosa* (Dorawa) exhibited much higher ash content than the other two wood-charcoals, of which their values are 10.11%, 12.61% and 16. 91%, respectively. The high content of ash found in these charcoal materials may be attributed to the high accumulation of inorganic mineral such as calcium in their parent biomass [29]. Thus, wood-charcoal that is calcite-rich is bound to contain high ash content, as calcium is essential in the production of a good volume of ash and that large amounts of it injure combustion process [30]. The wide range of ash contents displayed by these wood-charcoals materials provides options for selecting appropriately a wood-charcoal with desirable combustion and fuel properties for sustainable production and utilisation. For example, wood-charcoal with high ash content tends to consume more of solid bio-fuel for cooking than wood-charcoal with low ash content (Fig. 2). As such, percentage of ash content is one of the factors that affect specific solid bio-fuel consumption negatively. In addition, ash is a noncombustible component of wood-charcoal and thus, influences negatively on the heat transfer to the surface of a wood-charcoal as well as diffusion of oxygen to the solid fuel surface during charcoal combustion [31]. This indicates that ash is an impurity that does not burn which in turn affects combustion volume and efficiency and as a result, wood-charcoals with low ash content are better well-matched for high fuel value and efficient thermal utilisation than wood-charcoals with high ash content (Table 2). This means that the higher the wood-charcoal's ash content, the lower its calorific value, which is consistent with the other studies reported in the literature [29, 32].

The charcoal materials of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) were found to have low volatile matter content of 13.59% and 17.79%, respectively. The charcoals of *Combretum lamprocarpum* (Zindi), *Butyrosperum paradoxum* (Tabo) and *Pakia biglobosa* (Dorawa) were observed to have higher volatile matter of 26.59%, 31.35% and 34.59%, respectively, which suggest that these charcoal materials contained large amounts of substrates that support quick ignition and easy combustion, as well as provide high fuel value. This makes the wood-charcoals highly reactive fuels gave faster burning rate during combustion than the other two wood-charcoals influenced by low volatile matter (Fig. 2). It has been reported in the literature that this feature determines stability of flame and combustion velocity, as volatile matters promote an increase permeability of flame in solid bio-fuels and reactivity of charcoal [33]. However, high concentration volatile matter reduces productivity of wood-charcoal during cooking, as it quickens loss of wood-charcoal mass induced by thermal degradation (Fig. 1). Therefore, wood-charcoal with low volatile matter content is better suited for domestic use, as it burns less vigorously than charcoal with high volatile matter. In addition, wood-charcoal with low volatile matter though difficult to ignite, but burns very sluggishly and cleanly [34], which is an advantage over others with high concentration of volatile matter that ignite easily and burn vigorously with smoke flame that is environmentally undesirable. The observed burning profile of the wood-charcoals depicted in Fig. 2 showed that the charcoal materials of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) took the longest time of burning with less stress of loss of mass compared to other three bio-energy sources. This could also be adduced to their low percentage of volatile matter content. On the other hand, high concentration of volatile matter content indicates that during combustion, bulk of the mass of the charcoal materials of *Combretum lamprocarpum* (Zindi), *Butyrosperum paradoxum* (Tabo) and *Pakia biglobosa* (Dorawa) suddenly reduced due to quick volatility and burning of the bio-fuels.

The State's most commonly used wood-charcoals exhibited different range of fixed carbon composition, which considered to be the dominant component of the proximate analysis of the wood-charcoal materials. The wood-charcoal of *Ficus platyphylla* (Ganji) revealed the highest fixed carbon content value of 76.89%, followed by *Anogeissus leiocarpus* (Marke) with the percentage of fixed carbon of 71.10%. However, the charcoal materials of *Combretum lamprocarpum* (Zindi), *Butyrosperum paradoxum* (Tabo) and *Pakia biglobosa* (Dorawa) had the lowest percentage of fixed carbon contents, which were determined to be 26.59%, 31.35%, and 34.59%, respectively, possibly due to high volatile matter and ash contents. This observation is strongly supported by negative correlation between fixed carbon and volatile matter contents, as well as fixed carbon and ash contents ($R^2 = 0.9973$ and 0.9542, respectively; Fig. 3). Fixed carbon content of solid bio-fuel is considered to be the percentage of carbon available for the fuel combustion after volatile matter distilled off and therefore, roughly estimates the heating value of a solid bio-fuel [35], as carbon acts as the main generator of heat during combustion. Therefore, with higher fixed carbon content and relatively low ash content, *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) are best suited for thermochemical energy conversion processes. This can further be supported by the fact that wood-charcoal material with very low fixed carbon content tends to prolong cooking time by its low heat release, which is contrary to wood-charcoal material with high fixed carbon content that releases heat intensively [26]. This fact alone suggests that fixed carbon content is the prime factor that dictates its caloric energy content of a solid bio-fuel, as high calorific energy usually corresponds with high fixed carbon content [36], Even though this is contrary to the observed results of *Butyrosperum paradoxum* and *Pakia biglobosa* (Table 1). This anomaly may be related to proportion of fixed carbon in the woods, which might be controlled *via* temperature and its resident time during carbonisation process. This could be supported by the plots depicted in Fig. 3, as it also infers that fixed carbon content increases with decrease in charcoal yield.

3.2. *Ultimate analysis*

The percentage of C, H, O, N, S, and Cl by weight and molar H/C and O/C ratios for the examined wood-charcoals samples are presented in Table 1 and 3, respectively. Carbon remained the dominant element in all the wood-charcoal samples. For all the five wood-charcoals were found to have almost similar carbon concentrations in the range between 70.26% and 76.59% except for *Pakia biglobosa* (Dorawa) that its carbon concentration was found to be the least in all the samples (64.38%). These wood-charcoal materials also had oxygen concentrations as the second highest elements that made up between 10.25% and 18.90%, followed by hydrogen concentrations that varied between 2.63% and 4.08% amongst the major compositional constituents of the wood-charcoals. This further suggests that the wood-charcoals have similar compositional structures and the concentrations of these major compositional constituents are in agreement with the earlier findings [29, 37, 38]. The H/C ratios for the wood-charcoals varied from 0.45 to 0.64, which fall within the range defined as black carbon [39]. Similarly, O/C ratios ranged from 0.11 to 0.19, of which *Anogeissus leiocarpus* (Marke) had the highest O/C value suggesting a greater degree of oxygenated structure in this wood-charcoal. Therefore, the most commonly used wood-charcoals probably had condensed aromatic structures with certain degree of stability relative to their corresponding parent feedstocks.

Table 1. Wood-charcoals chemical composition and heating value data.

Content	**Units**	***Anogeissus leiocarpus* (Marke)**	***Butyrosperum paradoxum* (Tabo)**	***Combretum lamprocarpum* (Zindi)**	***Ficus platyphylla* (Ganji)**	***Pakia biglobosa* (Dorawa)**
Proximate						
Density	gcm^{-3}	0.28	0.17	0.21	0.36	0.12
Moisture	wt%	4.60	5.66	6.63	4.17	5.10
Ash	wt%	6.51	12.61	10.11	5.35	16.91
Volatile matter	wt%	17.79	31.35	26.59	13.59	34.59
Fixed carbon	wt%	71.10	50.38	56.67	76.89	43.40
Ultimate						
C	wt%	76.13	73.55	70.26	76.59	64.38
H	wt%	3.55	3.13	2.63	4.08	2.83
O	wt%	18.90	15.66	10.25	16.29	12.38
N	wt%	0.43	0.26	0.22	0.52	0.32
S	wt%	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Cl	wt%	0.04	0.03	0.02	0.05	0.01
Calorific value	MJ/kg	30.09	23.14	25.36	33.58	26.71
EDXRF-Elemental						
Al	wt%	1.05	0.56	0.54	1.04	0.49
Ca	wt%	8.21	28.05	17.09	15.92	30.96
K	wt%	8.12	2.28	2.69	8.36	4.64
Si	wt%	1.16	0.53	0.55	1.36	0.46

Table 2. Fuel properties of the wood-charcoals.

Name of wood-charcoal species	**Fuel value index FVI**	**Thermal fuel efficiency T (%)**
***Anogeissus leiocarpus* (Marke)**	281	52.4
***Butyrosperum paradoxum* (Tabo)**	55	29.1
***Combretum lamprocarpum* (Zindi)**	80	32.7
***Ficus platyphylla* (Ganji)**	542	63.6
***Pakia biglobosa* (Dorawa)**	37	24.8

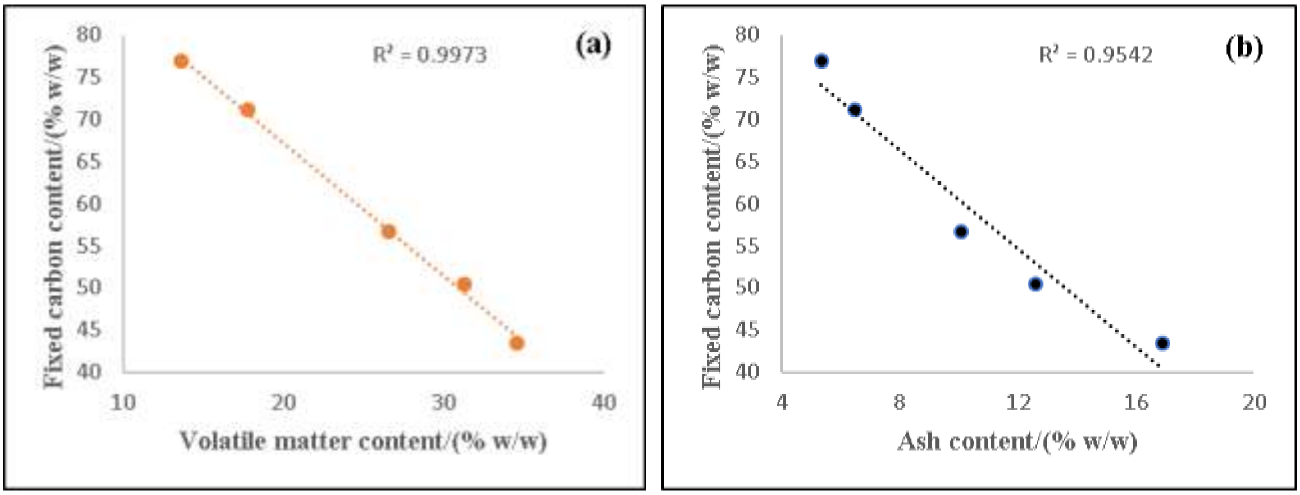

Figure 3. (a) Correlation between fixed carbon and volatile matter contents, (b) between fixed carbon and ash contents of wood-charcoals

Table 3. Mole values of C, H, and O in the wood-charcoal samples and their corresponding molar ratios of H/C and O/C.

Wood-charcoal samples	moles of carbon	moles of oxygen	moles of hydrogen	H/C molar ratio	O/C molar ratio
Anogeissus leiocarpus **(Marke)**	6.34	1.18	3.55	0.56	0.19
Butyrosperum paradoxum **(Tabo)**	6.13	0.98	3.13	0.51	0.16
Combretum lamprocarpum **(Zindi)**	5.86	0.64	2.63	0.45	0.11
Ficus platyphylla **(Ganji)**	6.38	1.02	4.08	0.64	0.16
Pakia biglobosa **(Dorawa)**	5.37	0.77	2.83	0.53	0.14

The amount of carbon, hydrogen and oxygen concentrations in the samples examined is an indication that these constituents can contribute immensely in the combustibility of the charcoal materials, which can better be explained in terms of H/C and O/C ratios. As the wood-charcoals of *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi), and *Pakia biglobosa* (Dorawa) exhibit the lowest H/C and O/C ratios are much likely to undergo greater thermal corrosion during combustion process due to low degree of structural stability that resulted in from greater loss of H and O relative to C. This could further explain the lower efficient thermal utilisation observed in these wood-charcoals than in the charcoal samples of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke).

Chlorine, nitrogen and sulphur, though have effect on reactions forming ash [40], are mainly significant in the formation of harmful emissions. It is well established that sulphur and chlorine contents in solid bio-fuel tend to prevent complete combustion as a result of reaction products formed that are injurious to burning quality of solid bio-fuel [27]. The injury is attributed to harmful effect of chlorides, SO_x and NO_x to the fact that these reaction products fuse and coat over wood-charcoal materials, thereby preventing complete combustion and in turn lowers the heating value of the solid bio-fuel. However, as the chlorine, nitrogen and sulphur contents reported here are below 1% is a welcome development since there will be little or no such effect of combustion prevention by the reaction products of Cl, S and N upon the surface of the wood-charcoals examined.

The calorific values of *Anogeissus leiocarpus* (Marke), *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi), *Ficus platyphylla* (Ganji), and *Pakia biglobosa* (Dorawa) were found to be 30.09, 23.14, 25.36, 33.58, and 26.71 MJ/kg, respectively (Table 1). The wood-charcoals of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) recorded the highest calorific values of 33.58 MJ/kg and 30.09 MJ/kg, respectively. This may be due to their high fixed carbon and low ash contents. The high fixed carbon content of these wood-charcoals could be associated to high lignin contents as supported by the SEM micrograms demonstrating the compaction and web network-like scenery of the charcoal materials (Fig. 5). Calorific value of a solid bio-fuel indexes the energy content of a solid bio-fuel, which has been established as the most important fuel property of a solid bio-fuel and is associated with ligneous features of the parent wood species [41]. Thus, the wood-charcoals sourced from the wood of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) better matched for household utilisation, as they would provide higher heat outputs and more advantageously burnt slowly than the other wood-charcoals owing to their condensed and fibrous assembly.

3.3. EDXRF elemental analysis

As shown in Table 1, out of a total of about 28 elements detected in the wood-charcoal samples using EDXRF analysis, the relevant elements with high weight percentages are Al, Ca, K, and Si. The partitioning of such inorganic components in biomass can vary substantially depending on the biomass type. For example, the types of wood used in this study- *Anogeissus leiocarpus* (Marke), *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi), *Ficus platyphylla* (Ganji), and *Pakia biglobosa* (Dorawa) are typically composed of Ca weight percentages of 8.21%, 28.05%, 17.09%, 15.92%, and 30.96%, respectively. On the other hand, *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) are both high in Al, K and Si weight percentages relative to other wood-charcoals. During combustion, K can typically react with other inorganic elements present in the ash formation to form reaction products such as K_2CaSiO_4 and/or $KAlSi_3O_8$ [42]. Indeed, silicates have been indicated to facilitate fixation of potassium in wood-charcoal as potassium silicates [42]. This formation of potassium species through either of chemical adsorption or physical adsorption in the charcoal matrix increases ash melting temperatures or prevents ash sintering during combustion process [43]. Thus, potassium species exert favourable influence on burning qualities of biomass-based charcoals, as it greatly enhances the fire-holding capacity of a solid bio-fuel by lessening ash deposit. This could be reasoned that presence of abundant availability of aluminosilicate-based product ($Al_xSi_yO_z$) in the matrix of biomass-based charcoal makes it to acquire glassy property, which could be responsible for making the charcoal to have good fire-holding capacity. Stimulatingly, *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) showed such glassy features in accordance to both contained high Al, K and Si weight percentages (Fig. 4a and b showing only the spectra of the charcoals of *Ficus platyphylla* and *Anogeissus leiocarpus,* respectively) relative to other wood-charcoals. This evidently account for and further support the circumstance that revealed their sluggish burning characteristics (Fig. 2) compared to other examined wood-charcoals, since aluminosilicate-based materials hold capacity to withstand high temperature conditions because of their temperature resilient characteristics.

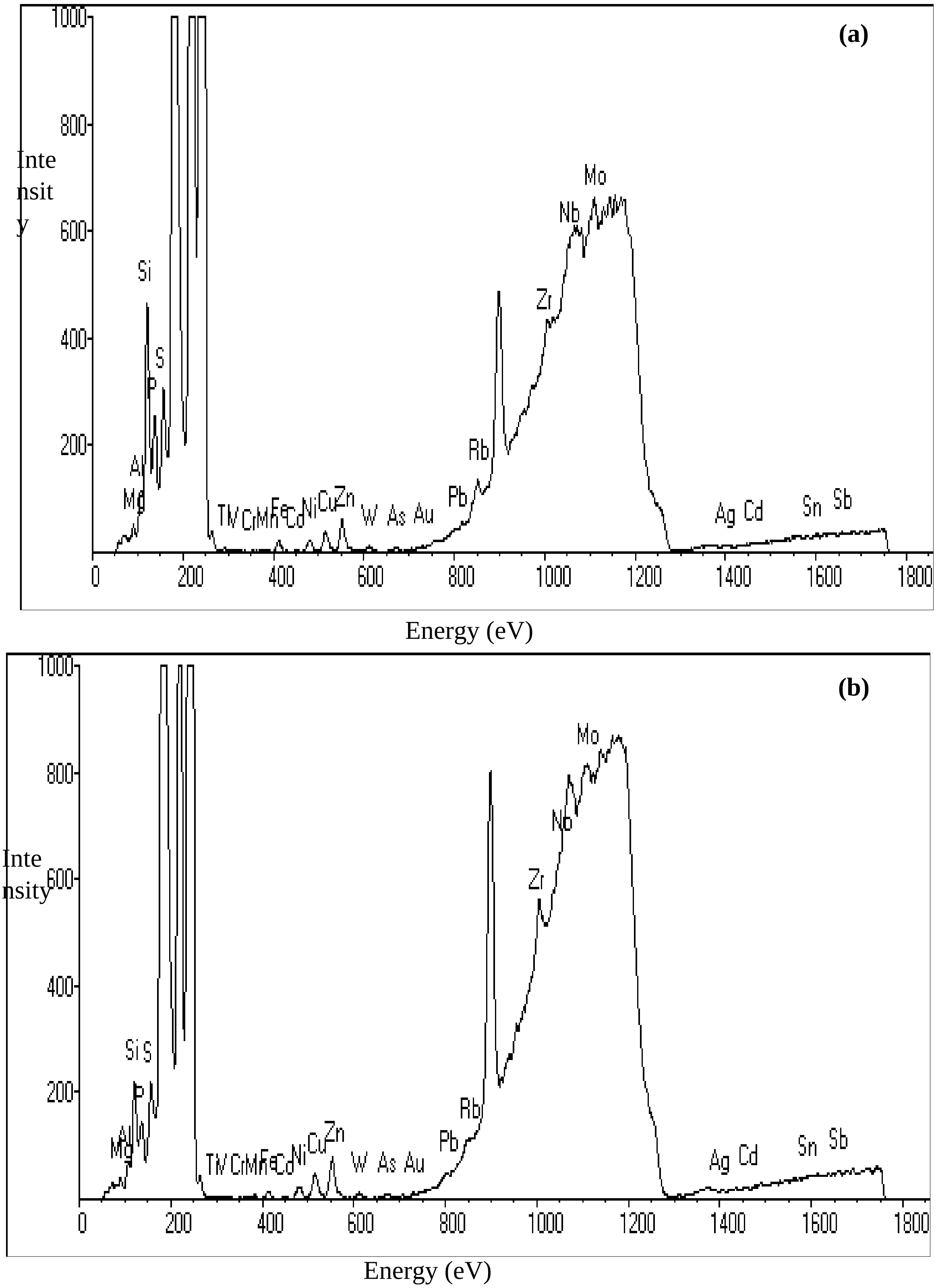

Fig. 4. EDXRF spectra (a) of *Ficus platyphylla,* (b) of *Anogeissus leiocarpus.*

3.4. SEM image analysis

Fig. 5 shows representative images of each of the examined wood-charcoals. The bared visual inspection of the images of the wood-charcoals demonstrates differences in the micrograms that depict clear distinct microstructures amongst the charcoal materials. The wood-charcoals are symbolised with observable micropores, which are more especially so obvious in the charcoals of *Pakia biglobosa* (Dorawa), *Butyrosperum paradoxum* (Tabo) and less in *Combretum lamprocarpum* (Zindi) (Fig. 5a, b, and c, respectively). In contrast, the microstructures of the charcoals of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) are condensed finer-grained materials that are largely highly compressed and in effect lack observable voids in their structural composition. This evidently further explain the slower burning profile of the charcoals of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) and faster in the case of other wood-charcoals (Fig. 2). The reason is that combustion reaction rate could be proportional to porous structure- if there is more space, there is more locations for the fuel to vaporise, heat transfer is easier and so the flame is more vigorous. By inference, wood-charcoals comprised of condensed fine-grain that are highly compressed are bound to have longer fire-holding capacity than the other types of wood-charcoal characterise by loose assemblies of char grains. This fact could be related to the higher resistance to thermal degradation of condensed fine-grained charcoal materials when compared to charcoals with loosened structures, mainly due to increased number of C-C and C=C present in their structures that generally explain by high density and fixed carbon content [44].

3.5. Combustion characteristics of the wood-charcoals

The burning profiles of the wood-charcoals are shown in Fig. 2. The steps of the thermal decomposition of all the charcoal samples were observed under the same oxidative atmosphere. The extent of initial weight loss was found to be 21.3%, 16.6%, 12.2%, 9.5% and 7.4% for *Pakia biglobosa* (Dorawa), *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi), *Anogeissus leiocarpus* (Marke), and *Ficus platyphylla* (Ganji), respectively. However, most of the loss of weight occurred in the thermal degradation zone where 72.7%, 65.5%, 58.2%, 47.7%, and 41.4% of the total weight loss for *Pakia biglobosa* (Dorawa), *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi), *Anogeissus leiocarpus* (Marke), and *Ficus platyphylla* (Ganji), respectively. This sudden weight loss was observed mainly due to release of volatiles and their combustion, as well as the combustion of char because of exposure of the samples to risen temperatures around 180−390 °C. This clearly indicates that the extent of weight loss in these wood-charcoal materials in the combustion steps differed by the parent wood species from which the charcoals were sourced. The difference in the burning profiles can be attributed to variances in the physical and chemical properties of the wood species that produced the examined charcoals. Hence, wood-charcoals of *Pakia biglobosa* (Dorawa), *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi) tend to consume more fuel for cooking than the charcoals of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke).

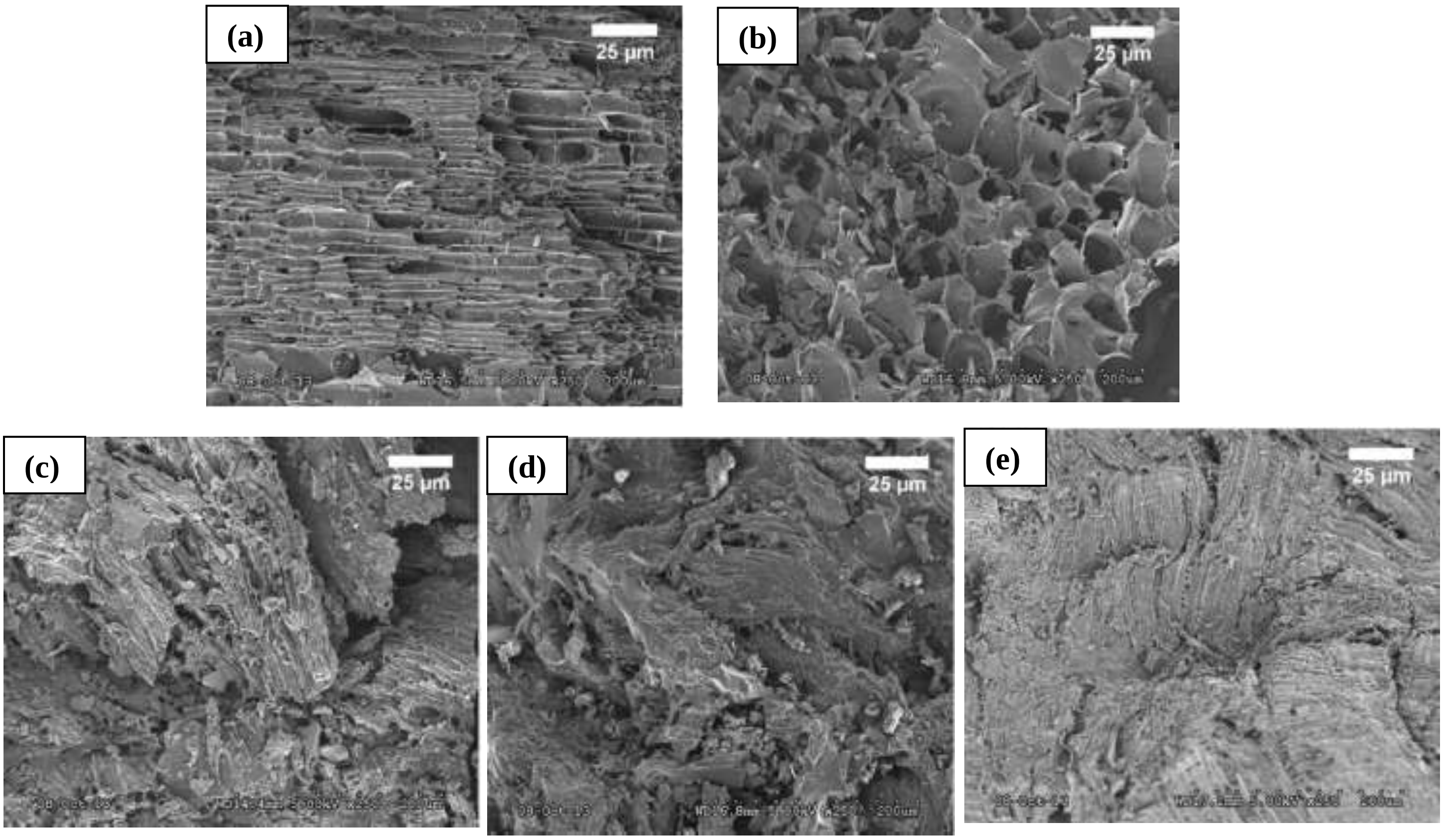

Fig. 5. SEM images of wood-charcoals examined: (a) *Pakia biglobosa* (Dorawa), (b) *Butyrosperum paradoxum* (Tabo), (c) *Combretum lamprocarpum* (Zindi), (d) *Anogeissus leiocarpus* (Marke), (e) *Ficus platyphylla* (Ganji).

3.6. Fuel value index and thermal fuel efficiency

Table 2 presents the fuel value index and thermal fuel efficiency of the wood-charcoal species. The indexes varied widely in the solid bio-fuels. The charcoal of *Ficus platyphylla* recorded the highest (542), followed by *Anogeissus leiocarpus* (281), *Combretum lamprocarpum* (80), *Butyrosperum paradoxum* (55), *Pakia biglobosa* (37). The high calorific value determined by high fixed carbon and low ash contents in the charcoal samples of *Ficus platyphylla* and *Anogeissus leiocarpus* explain the high fuel value index of these wood-charcoal species. The charcoal specie of *Pakia biglobosa* (Dorawa) had the lowest fuel value index (37), probably due to its lowest fixed carbon and highest ash contents, and comparatively lowest density. Fuel value index is an important parameter used for screening desirable solid bio-fuel species [45]. Consequently, the charcoals of *Ficus platyphylla* and *Anogeissus leiocarpus* own superior energy potential comparable to other charcoal species.

The thermal fuel efficiencies of the studied fuel sources quantified are *Anogeissus leiocarpus* (52.4%), *Butyrosperum paradoxum* (29.1%), *Combretum lamprocarpum* (32.7%), *Ficus platyphylla* (63.6%), and *Pakia biglobosa* (24.8%). The thermal fuel efficiency of the charcoal of *Ficus platyphylla* (63.6%) is the highest, followed closely by the solid bio-fuel of *Anogeissus leiocarpus* (52.4%). This is a demonstration that more heat during combustion was generated from the charcoals of *Ficus platyphylla* and *Anogeissus leiocarpus* than other charcoal samples. Although high thermal efficiency is one of the desirable fuel properties of solid bio-fuels, but in some cases, does not guarantee short cooking time- mean that itself is not a comprehensive indicator of fuel performance [27, 45, 46]. This could be associated with variation in ignition time typically influence by factors such as volatile matter content, inter and intra oxygen infiltration during combustion process and oxygen-scavenging effect caused by combustion reaction products with superior affinity for oxygen than the burning environment (for example, if only CO_2 could be the reaction product- means ‘waste’ no oxygen for oxidising H to H_2O or analogous and thus, could end up with more heat generation).

4. Conclusion

This study was conducted to evaluate the influence of chemical composition on combustion and fuel characteristics of wood-charcoals commonly used in Bauchi State, Nigeria. The combustion and fuel characteristics of the wood-charcoals examined in this study was found to be influenced by chemical composition of the parent woods used for their productions. The quality, in terms of combustion and fuel characteristics, of the charcoal produced from *Ficus platyphylla* (Ganji) was the highest, followed closely by the charcoal of *Anogeissus leiocarpus* (Marke). There is a wide variation in the qualities of these charcoals from other charcoal species of *Pakia biglobosa* (Dorawa), *Butyrosperum paradoxum* (Tabo), *Combretum lamprocarpum* (Zindi) examined in this research work. The evaluation revealed that charcoals of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) wood species are with the greatest energy potential, mainly due to their high calorific values, thermal fuel efficiency, fuel value indexes, density. In the same vein, the combustion characteristics of the investigated wood-charcoals indicate differences in their burning profiles, which resulted in from considerable dissimilarity in ash, volatile matter, fixed carbon contents and microstructural grain assemblies amongst the wood-charcoal species. With respect to this, charcoals of *Ficus platyphylla* (*Ganji*) and *Anogeissus leiocarpus* (Marke) burnt sluggishly while the other charcoal types underwent thermal degradation vigorously. The EDXRF analysis of the wood-charcoals resulted in the identification of numerous elements, of which Al, Ca, K, and Si could possibly have significance on the fire-holding capacity of the charcoal species. High presence of Al, K and Si in the charcoal samples of *Ficus platyphylla* (Ganji) and *Anogeissus leiocarpus* (Marke) that even appeared by developed glassy features could hypothetically support their good fire-holding capacity relative to other charcoal species. Therefore, description of desirable criteria for quality wood-charcoal is not primarily limited to calorific value relative to fixed carbon content, but it is also influenced by agglomerations of physico-chemical variables. Therefore, this research work has uncovered the importance of holistic consideration of combustion and fuel quality characteristics, apart from calorific value alone, in the appropriate selection of wood species for the production of charcoals in the study area. This initiative may reduce the rate of forest destruction thereby maintaining and expanding ecosystem services, forest health and land productivity in the process.

Acknowledgement

We are sincerely grateful to Tertiary Education Trust Fund, Nigeria (TETFUND) for the financial provision made available for this research work under the auspices of Institutional-Based Research Grant (processed number-TETFUND/DESS/ATBU/BAUCHI/PR/VOL.IX). The authors also thank OEA Laboratory Limited, UK, as well as NASENI (Centre of Excellence in Nanotechnology and Advanced Materials), Akure-Nigeria for all the laudable experimentations and testing carried out in their laboratories.

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