



Research article

Constituents, morphological and thermal stability characteristics of wood ash and wood charcoal microparticles for composites application

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ABSTRACT

This research investigates the physicochemical properties of wood ash and wood charcoal, two by-products derived from the pyrolysis of wood, focusing on their potential applications as sustainable reinforcement materials in composite manufacturing. Through a systematic characterisation process, we analysed both materials' chemical composition, thermal stability, crystallographic structure, and surface morphology. The findings reveal that wood ash is rich in calcium and magnesium oxides, which enhance its mechanical properties and reactivity, making it an effective additive in composite formulations. Moreover, wood charcoal exhibits a high carbon content and specific surface area, contributing to its thermal stability and adsorptive capabilities. The porous nature of wood ash and the unique structural characteristics of wood charcoal position them as promising candidates for various industrial applications, including construction, environmental remediation, and energy storage. This research underscores the importance of utilizing renewable biomass by-products, highlighting their role in advancing sustainable material practices and promoting environmental stewardship.

1. Introduction

The shift towards sustainable and environmentally conscious practices has necessitated the exploration of alternative materials derived from natural and renewable sources[1–4]. Among the numerous by-products generated from agricultural and industrial processes, wood ash and wood charcoal stand out due to their availability, sourceability, cost-effectiveness, and potential for value-added applications [5–7]. The characterisation of these materials has become an important area of research for utilising their unique properties for different industrial and structural purposes[8–10]. Wood ash is the residue left after wood combustion in industrial boilers, domestic stoves, and biomass energy plants. It consists of a complex mixture of inorganic compounds, including oxides of calcium, potassium, magnesium, and trace elements such as manganese and zinc, which contribute to its chemical reactivity and functional versatility[11,12]. The physicochemical properties of wood ash vary based on the type of biomass, combustion temperature, and ash collection methods, necessitating detailed investigations to

optimise its utilisation[13,14]. Previous studies have demonstrated its potential as a partial replacement for cement in concrete production, a source of nutrients for agricultural soils, and a raw material for composite material development[15,16].

Wood charcoal, on the other hand, is a solid carbonaceous material produced by the pyrolysis of wood under oxygen-limited conditions. The process involves thermal decomposition, which drives off volatile components and concentrates the carbon content, resulting in a material with unique properties such as a high specific surface area, thermal stability, and adsorptive capacity[17]. These properties make wood charcoal suitable for a wide range of applications, including water purification, soil remediation, energy storage, and as a reinforcement material in polymer composites [9,18]. Despite its promising applications, the performance of wood charcoal is highly dependent on the pyrolysis conditions, including temperature, heating rate, and wood type, highlighting the need for systematic characterisation [5,19].

While wood ash and charcoal utilisation has been explored in various contexts, significant challenges remain in fully understanding their

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behavior and properties. Factors such as particle size distribution, crystallinity, porosity, and surface chemistry critically influence their performance in specific applications [20,21]. For instance, the crystalline phases in wood ash, such as quartz and calcite, contribute to its mechanical reinforcement properties in composites. In contrast, the porous structure of wood charcoal enhances its adsorptive and catalytic capabilities [15,19,22]. This underscores the importance of detailed physicochemical and microstructural characterisation to tailor these materials for specific industrial uses [10,23]. Moreover, the environmental benefits of utilising wood ash and wood charcoal extend beyond their functional properties. Their incorporation into material development contributes to waste minimisation, reduced reliance on non-renewable resources, and the mitigation of environmental pollution caused by the improper disposal of wood-derived by-products [16,24]. By adopting a circular economy approach, these materials can be transformed into valuable resources, promoting sustainability and supporting global efforts to achieve a low-carbon economy [19,25].

The scope of this research is to provide a comprehensive characterisation of wood ash and wood charcoal. This includes an in-depth analysis of their chemical composition, crystallographic structure, thermal stability, and surface morphology [26–28]. Additionally, the study explores their mechanical properties and potential as reinforcement materials in advanced composites [29,30]. Such systematic characterisation aims to bridge existing knowledge gaps, enabling the optimisation of these materials for diverse applications in construction, environmental management, and material science [31–34]. The characterisation of wood ash and wood charcoal represents a critical step toward the development of sustainable materials. By harnessing their unique properties and addressing their variability, this research aims to unlock their full potential and contribute to the advancement of green technologies [35–37].

2. Materials and methods

2.1. Materials

The stem of dried cylindrical shape hardwood used in this study was sourced from farmlands in Akure, Ondo State, Nigeria. Selection criteria were based on observable physical properties, including density, durability, and mechanical resistance that ensure its suitability for further processing [38]. However, the species identification was not conducted, as it was beyond the scope of this study. The selection adhered to sustainable harvesting practices and was based on structural integrity and physical robustness [39].

2.2. Experimental procedure

2.2.1. Production of wood ash and wood charcoal

The dried hardwoods were subjected to pyrolysis in an oxygen-limited environment at temperatures between 500°C and 700°C for 4 h. This thermal decomposition process facilitated the removal of volatile components, resulting in the formation of wood charcoal. Following the initial pyrolysis, the charcoal lumps were milled and sieved to achieve a particle size below 180 µm. To obtain wood ash, a portion of the charcoal lumps underwent secondary pyrolysis in a coal-fired pot, where further combustion led to complete carbonization for 5 h, leaving behind ash residues. The resultant wood ash particles were similarly sieved to a size below 180 µm to ensure uniformity in subsequent analyses.

2.3. Characterisation of samples

2.3.1. X-ray diffractometry characterisation

The crystallinity of the samples was analysed via XRD and representative XRD patterns are shown below. The X-ray diffraction was performed to obtain further evidence about the structure of the samples.

X-ray powder diffractometry (p-XRD) measurements were performed on a Shimadzu XDS 2400 H diffractometer with Cu anode control, 40 KV, 30 M.A, optics: Automatic divergence slit), in Bragg-Brentano configuration, using Cu-K α radiation (1.54Å)

2.3.2. Scanning electron microscopy analysis (SEM/EDS)

Scanning electron microscopy (SEM, Hitachi SU 3500 scanning microscope, Tokyo, Japan) examination was carried out to determine the morphologies of the samples. The samples were coated with gold under a vacuum before the examination was carried out. Sample preparation includes cleaning the surface, stabilising, rinsing, dewatering, drying, mounting, and coating the sample. The samples are coated with a thin layer of approximately 20 nm gold.

2.3.3. X-ray fluorescence characterisation

The method employed in this analysis is the energy-dispersive analysis (ED-XRF) and the machine model used to determine the basic chemical composition of the sample is the Shimadzu EDXRF-702HS. The sample was grounded to a fine powder (to obtain a homogenous sample) using a vibration grinding mill with a steel milling

2.3.4. Fourier transform infrared spectrophotometry analysis

FTIR spectra were recorded within the frequency range of 4000 cm⁻¹ to 500 cm⁻¹ using an FT-IR spectrometer (Infrared spectrometer Varian 660 MidIR Dual MCT/DTGS Bundle with ATR)) with a detector at 4 cm⁻¹ resolution and 200 scans per sample. it usually requires sample preparation before analysis

2.3.5. Brunauer-Emmett-teller surface area analysis

The BET Surface Area Analyser was used for surface area determination by measuring the number of N₂ molecules adsorbed at monolayer coverage, which gives information needed for calculating the surface areas, it was calculated by the instrument. 0.3 g of the sample was weighed and loaded into the BET glass sample tube, and the weight of the tube before and after loading was recorded. The samples were degassed at 473 K for 3 h by connecting the tube to micromeritics flow prep 067 linked with Nitrogen gas to remove physically adsorbed water molecules

3. Result and discussion

3.1. Scanning electron microscopy and energy dispersive X-ray analysis

3.1.1. Morphology and surface structure analysis

The Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis results for wood ash and wood charcoal provide valuable insights into their morphological and compositional differences. For Wood Ash, Fig. 1 reveals an irregular and porous surface,

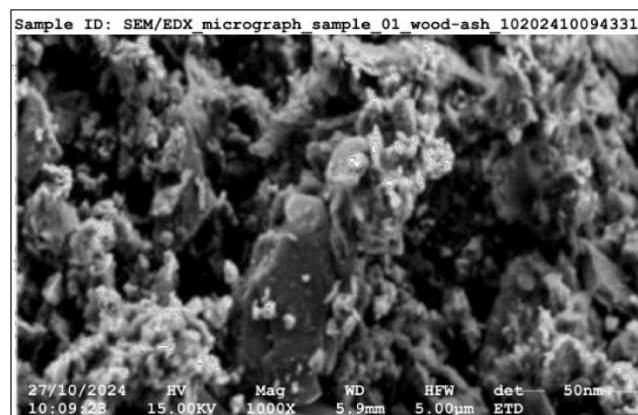


Fig. 1. Scanning Electron Microscopy (SEM) image of wood Ash.

typical for ashes formed from combustion. Porosity indicates spaces that could lead to a high surface area, especially for applications requiring adsorption, such as filtration or catalysis. However, irregular shapes could limit structural uniformity in composites which is a similar trend as stated by Sing k. [40]. Considering Particle Size and Distribution, wood ash average particle sizes ($\sim 20\ \mu\text{m}$), making it comparable to applications requiring micron-scale particles. However, slight variations in particle distribution due to morphology may affect how it packs and distributes within a matrix. Moreover, the Bulk Density of Wood Ash of $0.58\ \text{g/cm}^3$ indicates a relatively lightweight material, which could be beneficial for lightweight composite applications as stated by Serafimova et al., [13]. For the Wood charcoal, Fig. 2 reveals particle agglomerations with a rough morphology, likely due to partial carbonisation. This agglomerated structure tends to increase mechanical interlocking in composite applications, enhancing material toughness. However, rough morphology could reduce flowability and homogeneity if used as a fine powder in certain applications [13,41]. Considering Particle Size and Distribution, wood charcoal samples have average particle sizes ($\sim 20\ \mu\text{m}$), making it comparable for applications requiring micron-scale particles. However, slight variations in particle distribution due to morphology may affect how each material packs and distributes within a matrix. Moreover, the Wood Charcoal with Slightly higher bulk density ($0.64\ \text{g/cm}^3$) suggests a denser material, potentially due to higher carbon content from carbonisation.

3.1.2. Elemental composition of EDX analysis

Fig. 3 shows that Wood Ash is dominated by calcium (41.25 %), with significant amounts of carbon (33.08 %), oxygen (17.09 %), and smaller amounts of silicon, magnesium, and iron. Ban et al. [42] explained that high calcium content suggests potential applications in cementitious materials as a reactive filler or as a source of calcium ions as clearly stated in Table 1 from the composition extracted in Fig. 3. This confirms elemental composition results shown from the XRF. However, Fig. 4 reveals Wood Charcoal Predominantly contain carbon (65.70 %), with smaller amounts of oxygen (6.07 %), silicon (8.06 %), calcium (10.39 %), and potassium (8.25 %). The high carbon content makes wood charcoal better suited for applications needing carbon-rich materials, like activated carbon or conductive fillers. Lower oxygen content indicates fewer oxygenated functional groups, making wood charcoal more thermally stable and resistant to degradation as clearly stated in Table 2 from the composition extracted in Fig. 4 which is agreement with Bull et al. [43] These results were in conformity with the elemental composition results from the XRF analysis.

3.2. Brunauer-Emmett-teller surface area analysis

The BET surface area for wood ash was found to be $735.547\ \text{m}^2/\text{g}$, and this significantly higher surface area of wood ash suggests a more

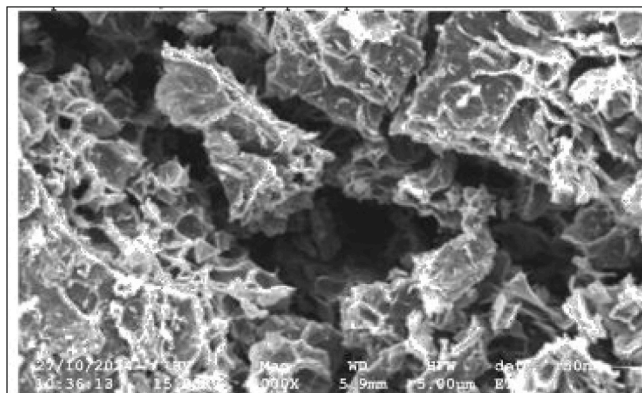


Fig. 2. Scanning Electron Microscopy (SEM) image of wood Charcoal.

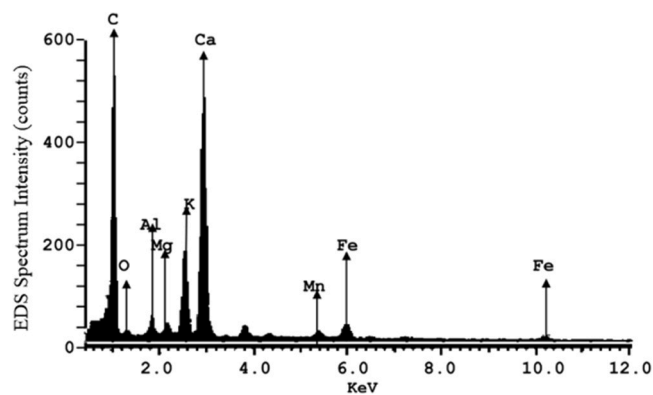


Fig. 3. Variation of elemental composition of wood ash from EDX analysis.

Table 1
Elemental composition of wood ash.

Element	Composition (%)
Carbon (C)	33.08
Oxygen (O)	17.09
Silicon (Si)	7.10
Calcium (Ca)	41.25
Magnesium (Mg)	0.75
Iron (Fe)	0.73

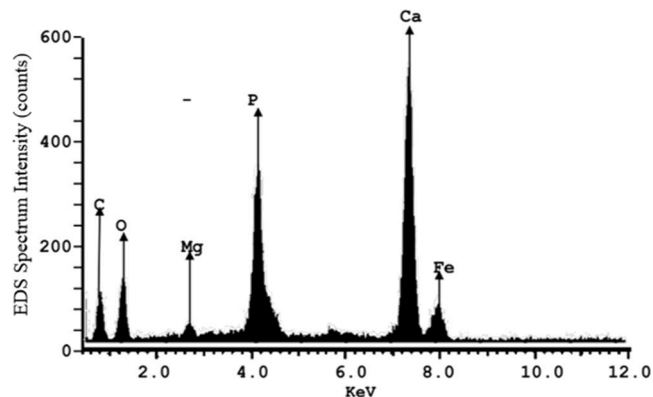


Fig. 4. Variation of elemental composition of wood charcoal from EDX analysis.

Table 2
Elemental composition of wood charcoal.

Element	Composition (%)
Carbon (C)	65.70
Oxygen (O)	6.07
Silicon (Si)	8.06
Calcium (Ca)	10.39
Aluminum (Al)	0.86
Potassium (K)	8.25
Magnesium (Mg)	0.35
Iron (Fe)	0.32
Manganese (Mn)	0.21

porous structure, which can enhance its reactivity and potential applications in fields such as catalysis, adsorption, and environmental remediation as previously reported [44–47]. Table 3 shows that the pore volume for wood ash was $0.103\ \text{cm}^3/\text{g}$ with a pore diameter of $3.950\ \text{nm}$, indicating a mesoporous structure. Moreover, BET surface area for wood charcoal was found to be $220.538\ \text{m}^2/\text{g}$ indicating that it

Table 3

Variation of surface area and pore volume relationship of wood ash and wood charcoal.

Sample	Surface area (m ² /g)	Pore volume (cm ³ /g)	Pore Diameter (nm)
Ash	735.547	0.103	3.950
Charcoal		0.040	1.675
	220.538		

has a highly porous structure which makes it highly effective for applications like filtration, or as a support material in catalysis. [44–47]. The wood charcoal exhibited a lower pore volume of 0.040 cm³/g and a smaller pore diameter of 1.675 nm, suggesting a more microporous structure as shown in Table 3. The differences in pore characteristics can influence the materials' performance in applications like filtration and adsorption [13].

3.3. Fourier transform infrared spectrophotometer analysis

The FTIR analysis was conducted to detect the changes in the functional groups as shown in Table 4.

The peak assignments in the FTIR spectrum corresponds to a functional group as shown in Table 5, such as: O–H stretching (hydroxyl groups) indicates possible hydrophilic sites, C=O stretching (carbonyl or carboxylic groups) implies oxidation and C=C stretching (aromatic groups) suggests higher stability and thermal resistance as can be seen in Fig. 5. For the hydroxyl Groups (O–H stretching) in wood ash, the prominent peak at 3092.85 cm^{−1} corresponds to the O–H stretching vibrations of phenolic hydroxyl groups. The presence of these groups indicates that wood ash retains organic functionalities that can enhance its reactivity [48]. Hydroxyl groups are known to participate in hydrogen bonding. Considering the methylene groups (CH₂ and CH₃ stretching) for wood ash, the peak observed at 2596.03 cm^{−1} signifies the stretching vibrations of methylene (–CH₂) and methyl (–CH₃) groups. These groups are indicative of the organic matter decomposition process and suggest that wood ash contains a significant amount of carbonaceous material. The presence of these aliphatic groups can contribute to the ash's physical properties, such as its texture, porosity, and surface area, which are crucial for applications in soil enhancement and carbon sequestration. The aliphatic nature of these groups may also contribute to the hydrophobic characteristics of the ashes, affecting its interaction with water and nutrients in the soil. Also, carboxylic groups (C=O and C–O stretching) for wood ash (2478.95 cm^{−1}) denotes oxidised carbon structures, which in material science can be associated with functionalised carbon surfaces. In composites, carboxylate surfaces can enhance bonding with matrices like polymers or metals. The Amide functional groups (C–N and N–H stretching and bending) in wood ash suggests nitrogen-containing functionalities, likely derived from protein residues in the original biomass. In engineering, nitrogen-functionalised carbons are significant for applications that require enhanced adsorption properties, such as gas capture and catalytic supports. The nitrogen content could also increase the surface reactivity, making the ash potentially

Table 4

Transmittance and functional group of wood ash.

Run #	Transmittance (%)	Functional group
1	45.21	Hydroxyl group
2	32.39	Methylene groups
3	44.06	Carboxylic
4	31.78	Amide II
5	44.10	Amide I
6	57.13	Pyrophosphate
7	57.09	Siloxane
8	36.54	Amine
9	60.82	Alkanes

Table 5

Transmittance and functional group of wood charcoal.

Run #	Transmittance (%)	Functional group
1	38.72	Hydroxyl group
2	61.94	Methylene groups
3	57.60	Carboxylic
4	68.32	Amide II
5	63.75	Amide I
6	51.26	Pyrophosphate
7	81.25	Siloxane
8	60.48	Amine
9	38.72	Alkanes

suitable for chemical adsorption processes or catalytic reactions. The presence of pyrophosphate indicates phosphorus compounds, which are commonly retained in biomass ash after combustion. From an engineering perspective, phosphorus content in materials can improve flame-retardant properties, making wood ash potentially useful as a fire-resistant additive. Additionally, phosphates are known for promoting cross-linking in polymers, and their presence might aid in creating thermally stable composites when used in materials engineering applications [49,50]. Siloxane bonds indicate the presence of silicon-based compounds, likely originating from soil or mineral contaminants in the wood. In material science, siloxane and silicate compounds contribute to Ash's thermal stability and mechanical reinforcement potential. Silicon-rich ash could serve as a filler in composites to enhance thermal resistance and dimensional stability, especially in polymers used in high-temperature environments. Alkane structures (CH₂ Out-of-Plane bending and C–C stretching) denote residual alkane content, suggesting incomplete breakdown of carbon chains during pyrolysis. For material applications, residual alkanes reduce thermal stability. For the wood charcoal, Fig. 6 provides a detailed view of its chemical composition, structural characteristics, and potential applications. The hydroxyl Groups (O–H stretching) in wood charcoal, the peak at 3216.80 cm^{−1} indicates the presence of hydroxyl groups. These groups enhance the reactivity of charcoal, making it suitable for applications in adsorption and catalysis. The hydroxyl groups can facilitate interactions with various pollutants, enhancing the material's effectiveness in environmental remediation processes, such as water purification and soil decontamination. Considering the methylene groups (CH₂ and CH₃ stretching), the peak at 2503.62 cm^{−1} reflects the presence of methylene groups, which are prevalent in carbonaceous materials. The high concentration of these groups suggests that wood charcoal has a substantial organic carbon content, contributing to its structural integrity and thermal stability. The presence of methylene groups also indicates that wood charcoal can serve as a precursor for activated carbon production, which is widely used in gas and liquid phase adsorption applications. Also, carboxylic Groups (C=O and C–O stretching) for wood charcoal (1364.28 cm^{−1} and 894.17 cm^{−1}) denote oxidised carbon structures, which in material science can be associated with functionalised carbon surfaces. In composites, carboxylate surfaces can enhance bonding with matrices like polymers or metals. However, the presence of C=O groups even after carbonisation implies partial oxidation, which may enhance dispersibility in polar solvents or affect electrical conductivity in applications like activated carbon electrodes. The C=C bonds are indicative of aromatic ring structures, which are essential in carbon-rich materials post-pyrolysis. Aromaticity reflects the material's transformation from a lignocellulosic structure resembling activated carbon, typically associated with high thermal stability and mechanical rigidity. Aromatic structures improve material integrity under high temperatures and are valuable for structural components in composites or as fillers in reinforced polymers for high-performance applications. The Amide Functional Groups (C–N and N–H Stretching and Bending) reveals nitrogen-containing functionalities. The nitrogen content could also increase the surface reactivity [51,52]. The presence of pyrophosphate indicates phosphorus compounds which could improve flame-retardant

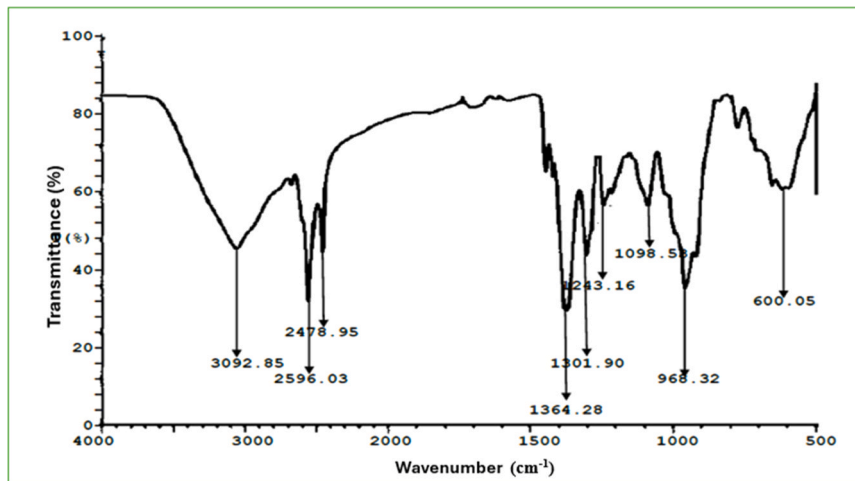


Fig. 5. Fourier Transform Infrared Spectrophotometer (FTIR) for wood Ash.

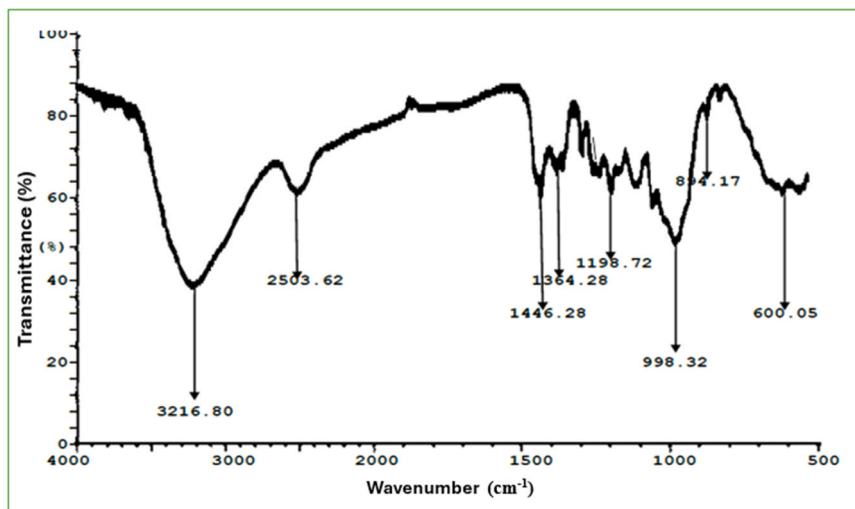


Fig. 6. Fourier Transform Infrared Spectrophotometer (FTIR) for wood Charcoal.

properties. Siloxane bonds indicate the presence of silicon-based compounds, Alkane structures (CH_2 Out-of-Plane bending and C-C stretching) denote residual alkane content, suggesting partial decomposition of carbon chains during pyrolysis. Their presence in charcoal could indicate flexibility in the carbon network.

3.4. X-ray fluorescence analysis

Table 6 reveals the XRF results of wood ash. The high calcium oxide

Table 6

Elemental composition of wood ash and wood charcoal.

Basic oxide	Formula	Wood ash Composition (%)	Wood charcoal composition (%)
Silicon Oxide	SiO_2	39.77	74.16
Aluminum Oxide	Al_2O_3	4.26	3.70
Magnesium oxide	MgO	9.43	3.80
Calcium Oxide	CaO	19.46	4.51
Iron Oxide	Fe_2O_3	2.26	0.20
Potassium Oxide	K_2O	10.31	2.02
Loss of Ignition	LOI	7.98	10.19

content in wood ash suggests its potential as a binder and strength enhancer in composite materials. CaO contributes to the formation of bonds within the composite matrix, improving mechanical strength. This makes wood Ash a candidate for applications where structural integrity is needed. Additionally, CaO is alkaline, which can enhance chemical resistance in acidic environments [53,54]. The high K_2O content in wood ash supports better processing flexibility and compatibility with various matrix. Magnesium oxide is known for enhancing toughness and thermal stability. In wood ash, MgO contributes to the composite's overall strength, particularly in improving fracture toughness, which helps the material resist cracking under stress [55,56]. This makes wood ash suitable for applications where shock absorption and durability are required, such as in load-bearing materials or composite panels. In addition, Fe_2O_3 can contribute to coloration, potentially giving the material a natural hue that could reduce the need for additional pigments. Mechanically, Fe_2O_3 can enhance wear resistance and hardness, making wood ash a suitable choice for coatings or finishes where abrasion resistance is important. Loss on Ignition (LOI) measures the amount of material lost upon heating, often related to organic or volatile content. The relatively lower LOI in wood ash indicates it has less organic residue, which can make it more thermally stable and predictable in high-temperature applications. This characteristic is advantageous for composites exposed to heat, as it minimises material loss and maintains structural integrity. SiO_2 contributes to hardness, chemical

resistance, and durability. These results show a similar trend with Kose et al. [10]. Interpreting the results from Table 6, the high silicon oxide content in wood charcoal makes it particularly suitable for applications requiring thermal stability and structural strength. SiO₂. It contributes to hardness, chemical resistance, and durability. In polymer composites, high SiO₂ content enhances thermal stability and mechanical properties, making wood charcoal an excellent choice for reinforcing polymers intended for high-temperature or high-stress environments. However, the low calcium oxide content in wood charcoal makes it less effective as a binder, though, it still contributes some strength and stability, making wood charcoal suitable for use as a filler in applications where binding strength is less critical. Its primary role would likely be as a supplementary strengthener rather than a primary structural component. Also, the low K₂O content in wood charcoal means it contributes less to fluxing and melting properties. This characteristic makes wood charcoal more suited to applications that prioritise thermal stability over easy processing, as it is less likely to alter the thermal behavior of the composite. Magnesium oxide is known for enhancing toughness and thermal stability. MgO contributes to the composite's overall strength, particularly in improving fracture toughness, which helps the material resist cracking under stress. With a lower MgO content, wood charcoal provides moderate improvements to toughness but primarily enhances other properties like thermal stability due to its SiO₂ dominance. Its MgO content may still contribute to modest improvements in impact resistance, useful in applications that demand durability with moderate flexibility. Iron oxide is commonly used to influence color and UV resistance in composites [16]. The low iron oxide content in wood charcoal means it contributes minimally to color and wear resistance, making it more of a neutral filler in composites. Its contribution is less about pigmentation or wear but may slightly impact the hardness of the composite. Loss on Ignition (LOI) measures the amount of material lost upon heating, often related to organic or volatile content. The higher LOI in wood charcoal reflects a greater presence of carbon and organic matter, which can influence the composite's behavior at high temperatures. Higher organic content can contribute to thermal degradation, but it also enhances the composite's carbon content, potentially making it suitable for applications where carbon-rich fillers are desired, such as conductive or antistatic materials.

3.5. XRD analysis

Table 7 reveals that wood ash predominantly contains crystalline phases. The major peaks correspond to minerals such as gypsum, quartz, albite, and calcite. The crystalline nature is supported by the sharp diffraction peaks observed at specific 2θ angles. Gypsum (CaSO₄·2H₂O) Detected at 8.27 % for in the wood ash, will contribute to hydration reactions if used in cement or other composite matrices. The Calcite (CaCO₃) in wood ash present in smaller quantities (~5.66 %), it may buffer acidity in composites or stabilise the structure and enhance

thermal stability [8]. Lastly, the Amorphous content in wood ash (~5.46 %) reflects unstructured material that might influence mechanical properties unpredictably while in wood charcoal, the Amorphous Carbon dominant (~50 %), providing flexibility and a degree of conductivity, potentially useful in energy applications or polymer composites as seen in Fig. 7. These results show a similar trend to Muhammed et al. [57]. Table 8 shows a higher proportion of amorphous material (~50 % across various peaks), with only minor crystalline phases like quartz and calcite. This is evident from broader and less intense peaks for the wood charcoal. The quartz Detected at ~16.08 % and minor peaks, contributing rigidity and thermal stability. Moreover, Amorphous Carbon provides flexibility and a degree of conductivity, potentially useful in energy applications or polymer composites as seen in Fig. 8.

4. Conclusion

The characterisation of wood ash and wood charcoal in this research have revealed their potential applications in sustainable materials development with wood ash possessing the optimum values and properties. Scanning electron microscopy analysis showed that wood ash possesses an irregular and porous surface which can lead to a high surface area. This porosity is beneficial for applications in adsorption. The presence of functional groups, such as hydroxyl (O–H) and carbonyl (C=O) groups, indicates that it retains organic functionalities that enhance its reactivity. This characteristic suggests that wood ash and wood charcoal can be effectively utilized in various chemical processes and as a reactive filler in composite materials. X-ray fluorescence analysis reveals a high content of calcium oxide (CaO) and magnesium oxide (MgO) in wood ash, which are known to enhance the mechanical strength and toughness of composite materials. This makes wood ash a suitable candidate for applications requiring structural integrity and resistance to cracking under stress. The lower loss on ignition (LOI) in wood ash indicates a reduced organic residue contributing to its thermal stability. This property is advantageous for high-temperature applications, as it minimizes material loss and maintains structural integrity in heat-exposed environments. By transforming these by-products into valuable materials, we can support a circular economy and contribute to global efforts aimed at achieving a low-carbon economy.

CRedit authorship contribution statement

Oladele I.O.: Formal analysis, Conceptualization, Investigation, Methodology, Funding acquisition, Project administration, Investigation, Methodology, Software, Visualization, and Writing the original draft. Writing – review & editing. **Ajayi M.A., Taiwo A.S., Orisawayi A.O., Ajileye J. O., Oyegunna S.A.** Conceptualization, Formal analysis, Methodology, Software, Supervision, Visualization, Writing – review & editing, Supervision, Resources.

Table 7
XRD analysis of wood ash.

Peak	2θ/degree	Plane	Intensity	d-Value (Å)	Minerals	Compositions (wt%)
1	12.98	0 1 0	42.76	6.8111	Gypsum	8.27
2	18.99	1 0 4	98.54	4.6681	Quartz	21.89
3	19.98	0 1 2	28.41	4.4380	Amorphous	5.46
4	22.98	1 1 0	72.54	3.8655	Quartz	13.10
5	24.00	1 1 1	64.26	3.7037	Quartz	11.47
6	25.98	1 1 3	28.81	3.4253	Albite	5.54
7	28.98	2 0 0	28.94	3.0775	Calcite	5.66
8	31.04	2 0 2	26.98	2.8780	Calcite	5.27
9	34.00	0 1 6	27.34	2.6338	Quartz	5.34
10	37.12	1 1 6	19.46	2.4191	Albite	3.80
11	38.16	1 0 2	21.58	2.3555	Calcite	4.22
12	45.00	1 2 1	17.13	2.0120	Quartz	3.34
13	58.25	2 2 2	17.10	1.5821	Quartz	3.35
14	62.00	3 0 0	16.86	1.4950	Quartz	3.29

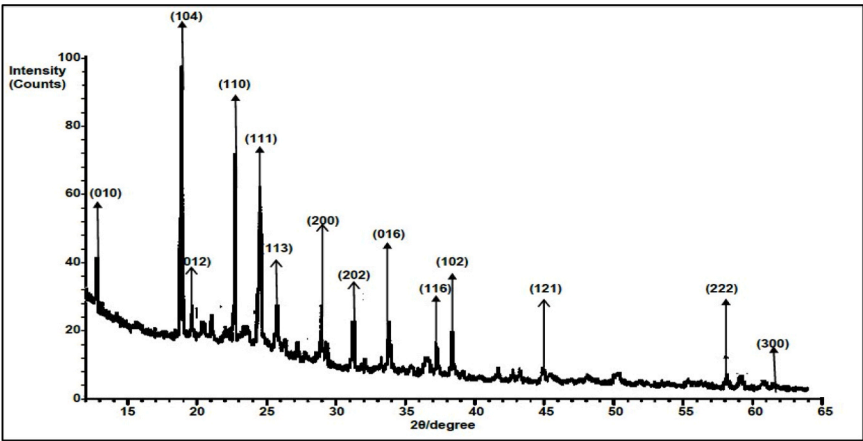


Fig. 7. XRD analysis image of wood ash.

Table 8
XRD analysis of wood charcoal.

Peak	2θ/degree	Plane	Intensity	d-Valve (Å)	Minerals	Compositions (wt%)
1	18.21	0 1 0	22.83	4.8657	Amorphous	10.12
2	22.23	0 1 2	26.17	3.9938	Amorphous	11.60
3	25.98	1 1 3	36.29	3.4253	Quartz	16.08
4	27.10	1 0 4	64.63	3.2864	Amorphous	28.64
5	30.20	1 1 0	12.58	2.9559	Calcite	5.58
6	34.98	0 1 6	16.02	2.5620	Calcite	7.10
7	36.00	1 1 6	15.47	2.4919	Quartz	6.86
8	38.98	2 0 0	15.41	2.3078	calcite	6.83
9	45.00	2 0 2	9.93	2.0120	Quartz	4.40
10	61.32	3 0 0	6.29	1.5100	calcite	2.79

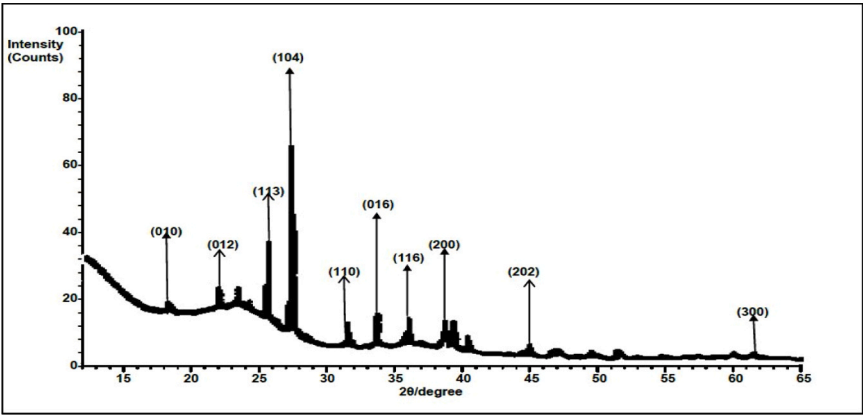


Fig. 8. XRD analysis image of wood charcoal.

Declaration of Competing Interest

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

Data availability

Data will be made available on request

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