Physicochemical and energetic properties of tropical hardwood biochars: Legal and environmental implications

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Abstract. Biochar from three tropical hardwoods — *Azadirachta indica* (Neem; AZD), *Leucaena leucocephala* (Lead tree; LCL), and *Albizia lebbeck* (Woman's tongue tree; BZK) — was carbonised at 600°C for 1 hour to see how strongly feedstock choice shapes biochar quality for energy, soil, and environmental use. The three species behaved quite differently. AZD produced the most biochar (37.01% mass yield) but the least energy-dense product (25.73 MJ/kg), making it best suited to carbon storage rather than fuel use. LCL released far more soluble minerals into water (EC 1273.33 µS/cm; TDS 776.73 mg/L) than the other two, a useful trait for nutrient-poor soils but a caution for salt-sensitive ones. BZK struck a different balance: lowest mass yield but highest calorific value (26.66 MJ/kg) and lowest salinity, pairing well with bioenergy and sodicity-sensitive soils. All three biochars were strongly alkaline (pH > 9), supporting acid-soil remediation regardless of feedstock. Overall, no single hardwood biochar suits every purpose: matching feedstock to intended application — carbon sequestration, bioenergy, or soil amendment — and pairing this with sound legal and environmental safeguards is key to deploying these biochars sustainably.

Keywords: Biomass pyrolysis, *Azadirachta indica* A. Juss., Carbonisation conditions, *Leucaena leucocephala* (Lam.) de Wit, *Albizia lebbeck* (L.) Benth., Calorific value, Soil amendment potential.

1. Introduction

The quest for the sustainable management of resources and mitigation of climate change has prompted scientific and technological interest in biochar (BC) (Gurwick et al., 2013). This is a black, solid and carbon-rich material synthesised from the carbonisation or pyrolysis of biomass feedstocks (Ngaba et al., 2025). BC is regarded as a promising material with multidimensional potentials (Basu, 2018). Over the years, BC has been proven to be an

important avenue for the sequestration of carbon (Luo et al., 2023; Li & Tasnady, 2023) soil health improvement (Das et al., 2021; Yadav et al., 2023), and polluted land remediation (Yang et al., 2019; Nguyen et al., 2023), along with valorisation waste streams (Stevens, 2020; Bhargava et al., 2024), and production of renewable energy (Sajjadi et al., 2019; Yrjälä & Zheng, 2020). The effectiveness of BC for various applications is fundamentally linked to its physicochemical and energy characteristics (Sajjadi et al., 2019). However, these properties are largely influenced by feedstock selection and carbonisation conditions (Basu, 2010).

Studies have long established that temperature has a fundamental impact on carbonisation, although the role of feedstock selection typically requires more emphasis (Basu, 2010; Basu, 2018). Although the characteristics of BC are typically derived from the composition of feedstock, high temperature conversion transforms organic compounds, accumulating ash, and reorganising carbon. The process yields BC with enhanced stability, higher pH, and concentrations of elemental ash and nutrients (Cárdenas-Aguiar et al., 2024; Tomczyk et al., 2020). Reported differences across carbonisation temperatures illustrate this clearly: at lower pyrolysis temperatures (below ~400°C), biochars tend to retain more oxygenated functional groups and volatile matter, giving lower pH, lower ash content, and correspondingly lower stability, whereas biochars produced at higher temperatures (above ~500–600°C), such as those examined in the present study, show progressively greater fixed-carbon content, alkalinity, and aromaticity, but reduced mass yield as more volatile matter is lost (Tomczyk et al., 2020; Ahmed et al., 2024). Feedstock type compounds these temperature effects: studies conducted internationally have reported divergent carbonisation behaviour across hardwood and softwood residues in temperate and boreal contexts (Jiang et al., 2017; Peng et al., 2013; Takada et al., 2020), agricultural and crop residues (Yuan et al., 2011; Tripathi et al., 2016), and, more recently, underutilised or invasive alien plants in South Asian and other tropical contexts (Fartyal et al., 2025; Bednik et al., 2022), yet comparable systematic evidence for regio-specific tropical African hardwoods, such as those investigated here, remains scarce. Notwithstanding the recognised significance of feedstocks, there are limited studies that systematically compare different BC derived from regio-specific, underutilised or invasive wood species in the literature. This is particularly evident under high-temperature carbonisation settings and feedstocks (Bednik et al., 2022; Fartyal et al., 2025).

One promising biomass is tropical hardwood species (THS), which constitute a massive and diverse resource characterised by high productivity and fast growth. THS such

as *Leucaena leucocephala* (Lead tree; LCL), *Albizia lebbeck* (Woman's tongue tree; BZK), and *Azadirachta indica* (Neem; AZD) are prevalent in sub- and tropical areas, where they serve as sources of fodder and timber (Ghosh, 1998; Gupta et al., 2021). Recently, it has become evident that such biomass are prospective feedstock for BC production. Nonetheless, a comprehensive understanding of their distinctive biochemical characteristics under high-temperature carbonisation settings is limited.

Regarding species selection, *Leucaena leucocephala* and *Albizia lebbeck* are both documented among tropical hardwood species that have naturalised, and in several regions behave as invasive alien plants outside their native ranges, where they can outcompete native flora and alter soil nutrient cycling; both species are well established and widely distributed across Nigeria, chiefly through historical introduction for fodder, shade, and fuelwood (Gupta et al., 2021). Their prevalence, combined with the limited value attached to their unmanaged spread, identifies them as underutilised invasive/naturalised biomass with strong potential for valorisation as biochar feedstock, consistent with recent work exploring invasive alien plants as biochar feedstock (Fartyal et al., 2025). *Azadirachta indica* (Neem), by contrast, is not generally regarded as invasive in Nigeria; it was included primarily as a widely available, fast-growing reference hardwood valued for its multipurpose uses, allowing its physicochemical and energetic behaviour to be benchmarked against the two candidate invasive species under identical carbonisation conditions. This distinction underpins the study's rationale: rather than examining carbonisation temperature and residence time in isolation, the work specifically targets underutilised and invasive tropical hardwoods, whose feedstock-specific pyrolytic response has received little systematic attention despite its relevance to both bioenergy recovery and invasive-species management. Currently, all three species are put to relatively low-value traditional uses in Nigeria, chiefly as fodder, live fencing, shade, and small-diameter fuelwood/timber; Lead tree and Woman's tongue tree, in particular, are frequently cleared as an agricultural nuisance with no further use for the resulting woody biomass. Converting this biomass into biochar could add considerable economic and environmental value beyond these traditional uses, by turning an otherwise low-value or discarded resource into a marketable soil amendment or solid fuel, while simultaneously supporting the managed control of two naturalised/invasive species.

Therefore, critical knowledge gaps exist concerning feedstock-based divergence in the major characteristics of BC. Studies have demonstrated that high carbonisation temperatures are associated with mineral concentration and alkalinity (Ahmed et al., 2024). However, the differences in the alkalinity, mineral leaching, and electrochemical potential of THS-based

BC remain poorly categorised (Joseph et al., 2015; Zhang et al., 2025). Furthermore, the compromise between BC mass yields and energy content under high temperature conditions requires evaluation amongst feedstocks such as THS. Hence, comprehension of such variations is critical for forecasting and modifying the functionality of BC for specific applications such as co-firing, heavy metal immobilisation, and amendment of soils.

Therefore, this study aims to examine the high-temperature carbonisation of *Leucaena leucocephala* (LCL), *Albizia lebbeck* (BZK), and *Azadirachta indica* (AZD). It examines the physico-chemical characteristics through mass yield (MY, %), mass loss (ML, %), and high heating value (HHV, MJ/kg). The study also highlights the variance in feedstocks and estimates inferences for energy recovery and environmental management. Lastly, the study uncovers the ideal applications of THS for BC production, which could improve the efficiency and sustainability of biomass utilisation approaches in severe thermal settings in tropical regions. Specifically, this study addresses the following research questions: (i) How do mass yield, mass loss, and higher heating value differ among Neem, Lead tree, and Woman's tongue tree biochars produced under identical high-temperature carbonisation conditions? (ii) How do the physicochemical and electrochemical properties (pH, EC, TDS, SAL, and ORP) of these biochars differ, and what do these differences imply for their environmental behaviour? (iii) Which practical applications — carbon sequestration, bioenergy, or soil amendment — are best suited to each feedstock, and what legal and environmental safeguards are needed to support their sustainable deployment?

2. Experimental methodology

2.1. Materials and Preparation

The hardwood species examined in this study were chosen based on their abundance and importance to the study's objectives. The selected species are *Leucaena leucocephala* (Lead tree; LCL), *Albizia lebbeck* (Woman's tongue tree; BZK), and *Azadirachta indica* (Neem; AZD). Lead tree is native to southern Mexico and Central America and was introduced across the tropics, including West Africa, chiefly for fodder, live fencing, and soil-erosion control; it is now naturalised and locally invasive across much of Nigeria, including Cross River State, where it persists along roadsides, farm boundaries, and fallow land. Woman's tongue tree is native to the Indian subcontinent and northern Australia and was introduced to West Africa, including Nigeria, mainly as a fast-growing shade, ornamental, and timber tree, and for fodder; it is likewise naturalised in southern Nigeria. Neem is native to the Indian

subcontinent and was introduced to Nigeria for shade, timber, and its valued medicinal and pesticidal properties; it is now one of the most widely planted multipurpose trees in Nigeria, including Cross River State, and is not generally regarded as invasive there. Stem cuttings measuring 2.5-4 cm in diameter were sourced from tree pruning in Calabar, Cross River State, Nigeria.

One individual tree of each selected tropical hardwood species was purposively sampled from Calabar South Local Government Area of Cross River State, Nigeria. Tree selection was based on the availability of the species within the sampling area, apparent maturity, good physical condition, and the absence of visible symptoms of disease, decay, termite infestation, or other serious defects. The selected trees were sufficiently mature and representative of the naturally occurring hardwood vegetation in the area.

For each hardwood species, sample was collected from one individual tree to minimise the influence of tree-to-tree variability on the physicochemical and energetic properties of the resulting biochars. Thus, the sample for each specie did not originate from the same tree. The sampling was conducted within the tropical forest/woodland environment of Calabar South Local Government Area, Cross River State, Nigeria. The collected wood samples were properly labelled according to species and individual tree, transported to the laboratory, and subsequently processed for biochar production and physicochemical and energetic characterisation.

The sample biomass was subsequently air dried for 12 weeks to lower/remove moisture to below 15 wt.%. The dried wood samples were subsequently cut into short lengths measuring 5 cm to obtain pellet-like materials for the carbonisation process, as depicted in Figure 1. The hardwood samples observed in Figure 1 appear as chunky and irregular fragments characterised by fibrous-grained and rough textures typical of dense and lignocellulosic biomaterials. Hence, their coarse morphology required cutting the samples into geometrically consistent cylindrical-shaped pieces. This was necessary to mitigate their intrinsic structural heterogeneity and ensure uniform access to heating during the process of carbonisation.

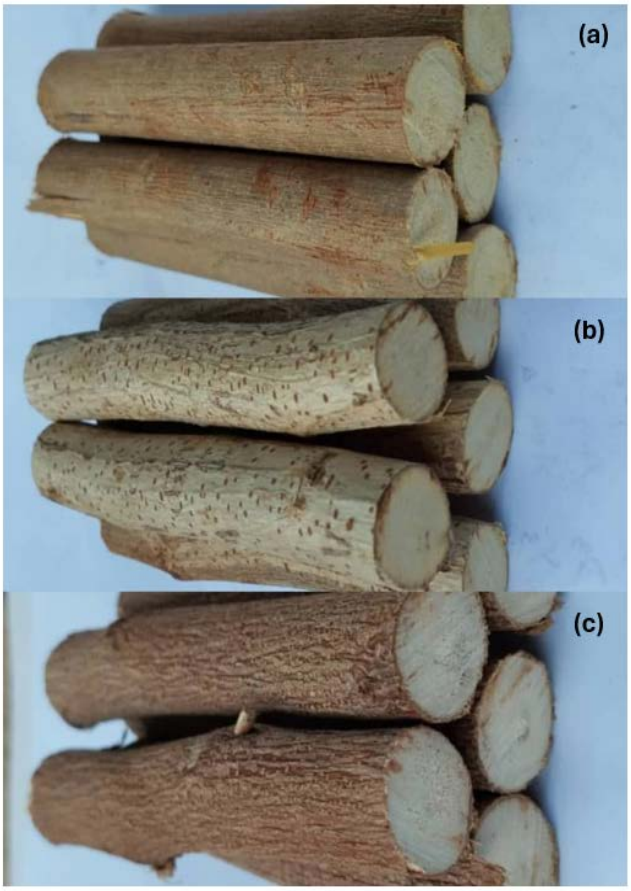


Figure 1. Raw hardwood tree samples before carbonisation (a) *Leucaena leucocephala* (LCL), (b) *Albizia lebbeck* (BZK), (c) *Azadirachta indica* (AZD)

2.2. Carbonisation process

The selected hardwood species, AZD, BZK, and LCL, were first converted into charcoal by the process of carbonisation using a muffle furnace under limited oxygen conditions. Each sample was carbonised at a temperature of 600°C for a residence time of 1 hour. A carbonisation temperature of 600°C was selected, rather than the ~550°C commonly reported in the literature, to ensure comprehensive devolatilisation and to maximise the fixed-carbon content, aromaticity, and thermal stability of the resulting biochar, consistent with reports that higher pyrolysis temperatures enhance biochar stability and alkalinity (Tomczyk et al., 2020; Ahmed et al., 2024. On completion, the samples were cooled to room temperature before computing their mass yield (MY, %), mass losses (ML, %) and higher heating values (HHV, MJ/kg) according to Eq 1-3 (Peng et al., 2013).

$$Mass\ yield\ (MY, \%) = \frac{Mass\ of\ charcoal}{Mass\ of\ Feedstock\ Biomass} \times 100 \quad (1)$$

$$Mass\ loss\ (ML, \%) = 1 - MY, \% \quad (2)$$

$$Higher\ heating\ value\ \left(HHV, \frac{MJ}{kg}\right) = 19.85 + 9.34(ML, \%) \quad (3)$$

The mass yield (MY, %) refers to the solid mass of charcoal product resulting from the thermal degradation process of carbonisation under the controlled conditions (Nyakuma et al., 2023). Conversely, the mass losses (ML, %) describe the total mass of materials, typically volatile matter and other lignocellulosic materials evolved, lost or removed by the thermal degradation process during the carbonisation (Nyakuma et al., 2022). Lastly, the higher heating values (HHV) expressed in MJ/kg describe the quantity of heat (MJ) released or evolved by the complete combustion of a unit mass (kg) of the charcoal product (Basu, 2010).

2.3. Physicochemical characterisation

Before the physicochemical characterisation, the solid mass of charcoal samples was converted into homogeneous biochar particles by mechanical fractionation using a dry milling machine. The pulverised charcoal samples, now termed biochar samples, were subsequently subjected to PC to determine their pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Salinity (SAL), and Oxidation-Reduction Potential (ORP). Next, the biochar was mixed with distilled water in the ratio of 1.20 w/v and stirred vigorously using a magnetic stirrer at a speed of 500 rpm for 10 minutes. The supernatant was then filtered using a filter paper before the resulting filtrate was subjected to tests for pH, EC, TDS, SAL, and ORP. The results are presented in sections 3.1-3.3. A stirring speed of 500 rpm for 10 minutes was adopted to ensure adequate mixing and equilibration of the biochar-water suspension while minimising particle attrition; this duration and speed are consistent with the extraction protocols typically applied to determine water-soluble ionic and electrochemical properties of biochar (Tomczyk et al., 2020; Nyakuma et al., 2022). Longer stirring times or higher speeds could plausibly increase the leaching of soluble minerals and thus elevate measured EC, TDS, and SAL values; this was not tested here and is identified as a limitation warranting further investigation.

3. Results

3.1. Morphological and textural properties

Figure 2 shows the hardwood tree charcoal samples for Lead tree (LCL), Woman's tongue tree (BZK), and Neem (AZD) produced via carbonisation at 600 °C and 1 hour residence time. All three biochars display a deep black colouration. LCL biochar consists of angular, sharp-edged fragments; BZK biochar consists of blocky, fissured pieces with a comparatively rigid, solidified appearance; and AZD biochar displays a granular, intermediate morphology.



Figure 2. Charcoal of hardwood tree samples after carbonisation (a) *Leucaena leucocephala* (LCL), (b) *Albizia lebbeck* (BZK), (c) *Azadirachta indica* (AZD)

3.2. Mass and Energy characteristics

Table 1 shows the mass and energy properties of the AZD, LCL, and BZK biochars. Mass yield (MY) ranged from 27.04% (BZK) to 37.01% (AZD); mass loss (ML) ranged from 62.99% (AZD) to 72.96% (BZK); and higher heating value (HHV) ranged from 25.73 MJ/kg (AZD) to 26.66 MJ/kg (BZK). AZD recorded the highest MY and the lowest HHV; BZK recorded the lowest MY and the highest HHV; LCL was intermediate on both measures (MY 30.27%; HHV 26.36 MJ/kg).

Table 1. Mass and energy properties of biochars

Sample	Mass yield (MY%)	Mass loss (ML%)	Higher Heating Value (HHV, MJ/kg)
AZD	37.01	62.99	25.73
LCL	30.27	69.73	26.36
BZK	27.04	72.96	26.66
Mean	31.44	68.56	26.25
SD	5.09	5.09	0.47
Minimum	27.04	62.99	25.73
Maximum	37.01	72.96	26.66

3.3. Physicochemical Properties

Table 2 shows the physicochemical properties of the hardwood biochars. pH ranged from 9.23 (AZD) to 9.43 (BZK); EC ranged from 700.33 µS/cm (BZK) to 1273.33 µS/cm (LCL); TDS ranged from 427.20 mg/L (BZK) to 776.73 mg/L (LCL); SAL ranged from 345.67 ppm (BZK) to 630.67 ppm (LCL); and ORP ranged from 60 mV (LCL) to 106 mV (AZD). LCL recorded the highest EC, TDS, and SAL of the three biochars, while BZK recorded the lowest values for these three parameters despite having the highest pH. AZD recorded the highest ORP, while LCL recorded the lowest.

Table 2. Physico-chemical properties of hardwood biochars

Code	pH	TDS (mg/L)	ORP (mV)	SAL (ppm)	EC (µS/cm)
AZD	9.23	551.44	106.00	449.67	904.00
LCL	9.40	776.73	60.00	630.67	1273.33
BZK	9.43	427.20	75.00	345.67	700.33

4. Discussion

4.1. Morphological and textural properties

The morphological features described above are broadly consistent with reported findings on the carbonisation of hardwoods of varying density. The deep black colouration observed across all three biochars indicates that carbonisation was accomplished, reflecting a high content of fixed carbon and comprehensive degradation of volatile matter typically observed during high-temperature carbonisation of biomass (Lehmann & Joseph, 2015). The noticeable friability and shrinkage of the physical structure across samples could be ascribed to the depolymerisation of holocellulose and lignin (Chettri et al., 2023), a process that releases

volatile matter and leaves behind a rigid aromatic-carbon structure (Ighalo et al., 2025) together with an internal porous network (Peng et al., 2013) that, although not visible to the naked eye, is critical to the biochar's function as either a soil enhancer or an adsorbent (Li & Tasnady, 2023; Lehmann & Joseph, 2015).

The textural differences among the three biochars likely reflect intrinsic differences in feedstock density, particle size, and biochemical composition (Jiang et al., 2017). The angular, fractured structure of LCL biochar is consistent with reports that fast-growing, lower-density hardwoods produce more open-pored, fractured char structures (Tripathi et al., 2016). By contrast, the comparatively rigid, solidified matrix of BZK biochar suggests a higher lignin content, which degrades over a wider temperature range and yields a denser char (Takada et al., 2020). The granular, intermediate morphology of AZD biochar may reflect its oily extracts and natural durability, which can promote the deposition of secondary tars during carbonisation (Basu, 2010). Overall, these morphological differences, although visually subtle, point to underlying variation in pore structure, surface area, and ash content among the three biochars, which the following subsections examine quantitatively.

4.2. Mass yield and energy content

The marked differences in MY among the three species likely reflect their differing responses to carbonisation, driven by the composition of their lignocellulosic material. AZD's high MY (37.01%) and correspondingly high resistance to thermal degradation may stem from recalcitrant polymeric structures that resist volatilisation, whereas LCL's greater mass loss suggests a more volatile-rich composition. BZK showed the most pronounced transformation, with the highest ML (72.96%), most plausibly linked to extensive holocellulose degradation, which decomposes readily during carbonisation. These patterns are consistent with the general principle that lignin-rich biomass favours solid biochar production, whereas holocellulose-rich material favours higher volatile yields (Lehmann & Joseph, 2015). Despite its lower MY, BZK's higher HHV illustrates the classic mass-yield/energy-content trade-off in biochar production. All three HHV values (25.73–26.66 MJ/kg) surpass typical values reported for solid biofuels (18–20 MJ/kg) (Basu, 2018; Vassilev et al., 2010; Nyakuma et al., 2023a), supporting their potential use as fuel in combustors or for cofiring with coal (Nyakuma et al., 2023b; Ighalo et al., 2025).

These findings sit within a wider, internationally documented pattern of feedstock-dependent divergence in biochar mass and energy yield. Comparable trends have been reported for hardwood and softwood residues carbonised in temperate contexts (Jiang et al.,

2017; Peng et al., 2013), for agricultural and crop residues (Yuan et al., 2011; Samal et al., 2021), and, more recently, for other underutilised or invasive alien plants carbonised under comparable high-temperature conditions (Fartyal et al., 2025; Bednik et al., 2022) — indicating that the divergence observed among AZD, LCL, and BZK reflects a broader, feedstock-driven pattern rather than one unique to this study or to Nigerian hardwoods specifically.

Beyond the immediate mass-energy trade-off, these results carry direct relevance to Nigeria's energy landscape and to global sustainability priorities. Nigeria continues to face substantial energy access and reliability challenges, with many households and small industries reliant on fuelwood, charcoal, and imported fossil fuels; densified, high-HHV biochars such as those from BZK and LCL offer a locally sourced, renewable solid-fuel alternative that could supplement household and small-scale industrial energy needs, thereby contributing to Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) through reduced reliance on raw biomass combustion and lower net carbon emissions. Beyond energy recovery, converting invasive LCL and BZK biomass into biochar also supports local livelihoods and invasive-species management, providing a low-cost, community-scalable use for biomass that would otherwise represent a management burden.

4.3. Physicochemical and electrochemical behaviour

All three biochars exhibited strong alkalinity (pH > 9), which may be attributed to the calcination of minerals and elementary cations at high temperature. High-temperature carbonisation is known to convert alkali and alkaline-earth metals into carbonates and oxides while degrading acidic phenolic and carboxyl functional groups, both of which raise alkalinity (Yuan et al., 2017). In particular, it was observed that all biochars displayed high alkaline (pH > 9) properties, with BZK showing the maximum value of pH (9.43) when compared to LCL (9.40) and AZD (9.23), suggesting that all three biochars, but BZK in particular, are well suited to remediating acidic soils.

The ionic behaviour of the biochars in contact with water reveals significant feedstock-driven differences (Tomczyk et al., 2020). LCL biochar has the highest TDS, EC, and SAL of the three, indicating an elevated concentration of soluble ions that potentially reflects a higher mineral-ash content in its intrinsic composition (Basu, 2010); soluble salts such as K^+ and Cl^- at this concentration can risk hampering seed germination or harming salt-sensitive plants, particularly in dry or poorly drained soils (Duan et al., 2024). AZD's intermediate ionic profile indicates a moderate mineral composition, while BZK's

comparatively low ion concentrations, despite its high alkalinity, suggest it is best suited to environments vulnerable to salinity problems (Mao et al., 2024). The consistency across EC, TDS, and SAL confirms that these three variables jointly track the salinity risk of each biochar; EC values above 1000 µS/cm, as observed for LCL, indicate a high risk of soil amendment without prior leaching (Zhang et al., 2025).

The highest ORP was observed in AZD (i.e., 106 mV), which indicates high capacity for oxidation compared to LCL (60 mV) and BZK (75 mV), pointing to a further axis of divergence in surface chemistry. AZD's comparatively high ORP indicates a surface that favours oxidative reactions through electron acceptance (Kumar, 2024), whereas LCL and BZK's lower ORP values indicate weaker oxidative tendencies; LCL's low value in particular may reflect a greater abundance of electron-donating functional groups such as phenolic –OH (Yuan et al., 2017). Biochar functionality in soil biogeochemical processes, such as microbial activity and pollutant breakdown, is therefore strongly impacted by these redox variations, which are likely to influence processes such as denitrification, nitrification, and metal mobility, and may also be tuneable through post-synthesis functionalisation strategies for specific redox applications (Zhao et al., 2025).

4.4. Legal and Environmental Implications for Practical Applications

The utilisation of hardwood biochars has both legal and environmental implications that bear on their practical applications, and provides a range of trade-offs that stress the importance of feedstock selection according to particular energy and environmental objectives. One such trade-off is carbon sequestration, for which AZD is the most promising biochar owing to its high MY; the high MY (37.01%) has the potential to enhance long-term storage of carbon in the soil. Conversely, BZK has the highest HHV (26.66 MJ/kg), indicating a promising avenue for bioenergy application. For the amelioration of acid soils, all three biochars showed promising potential, although BZK stands out for its lower EC (700 µS/cm), which could help lower the risk of soil sodicity (i.e., excess sodium). The lower ORP value of LCL indicates it is suited to redox-sensitive applications such as pollutant degradation and wetland restoration, potentially supporting the activities of anaerobic microbes, whereas AZD's comparatively high ORP value can enable oxidation of organic pollutants, enhancing its remediation role. These feedstock-specific profiles are broadly comparable to those reported for other biochar feedstocks internationally, including invasive alien plants (Fartyal et al., 2025) and mixed agricultural feedstocks (Bednik et al., 2022; Samal et al., 2021), reinforcing

that feedstock-tailored application, rather than a one-size-fits-all approach, is the more defensible strategy for biochar deployment generally.

Beyond biochar performance, biochar production from hardwood species carries broader environmental implications. The carbonisation of these hardwood species into stable, carbon-rich biochar creates a future carbon sink in the environment. It also presents a cleaner alternative to open burning, lowering air pollution and enhancing soil health via nutrient and water retention. Nonetheless, such benefits are contingent on the sustainable sourcing and processing of the biochar feedstocks. Unsustainable felling or poorly monitored carbonisation of these species could result in biodiversity loss, deforestation, and the emission of toxic contaminants such as Polycyclic aromatic hydrocarbons (PAH), other toxins, and particulate matter (Zhang et al., 2022). Regulatory and legal compliance is therefore critical to ensuring that feedstocks are obtained sustainably and ethically, that emissions are controlled through quality permits, and that final products are certified against safety and environmental standards, so that biochar can transform from a promising scientific innovation into a trusted, scalable, and sustainable solution.

5. Conclusion

In this study, we characterised and examined the physicochemical and energetic properties of tropical hardwood biochars from Neem, Lead tree, and Woman's tongue tree sourced locally in Calabar, Nigeria, and considered the legal and environmental implications of carbonising these species into biochar for various applications. High-temperature carbonisation of the three hardwood species produced biochars with distinctly different physicochemical and energy properties, confirming that feedstock identity, rather than carbonisation conditions alone, governs biochar functionality. This has direct practical implications: AZD is best suited to carbon sequestration given its high mass yield; BZK is best suited to bioenergy recovery and to sodicity-sensitive soils given its high calorific value and low salinity; and LCL is best suited to soil amendment in settings where salinity is not a limiting concern. All three biochars, being strongly alkaline, are additionally suited to the remediation of acidic soils. In addressing the knowledge gap identified at the outset — the limited systematic comparison of regio-specific, underutilised, and invasive hardwood species as biochar feedstocks — this study provides an evidence base for matching invasive and underutilised tropical hardwoods to appropriate bioenergy, soil amendment, or carbon sequestration applications in Nigeria and comparable tropical settings.

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