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Review

Characterization and Environmental Impact of Biochar: Implications for Soil Quality, Climate Change Mitigation, and Agricultural Sustainability

Zebidi Oum El Hana[1*], Amamra Ayat[1], Gater Ichrak[1] , Sana Zekkour[1], Meriem Barkou[1], Ala Grira[1]

[1]Department of Process Engineering and Petrochemical, Faculty of Technology, University of El Oued, El Oued 39000, Algeria
***Correspondence**: zebidoumelhana@gmail.com

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Abstract

Biochar, a carbon-rich material produced from biomass pyrolysis, has emerged as a promising tool for enhancing soil quality and mitigating environmental challenges. This essay explores the physicochemical characterization of biochar through techniques such as BET analysis, SEM, FTIR, Raman spectroscopy, XPS, NMR, XRD, TGA, and stability assessments. It further examines biochar's influence on soil quality, including its effects on physicochemical properties, contaminant remediation, microbial activity, crop improvement, carbon sequestration, and greenhouse gas mitigation. By synthesizing these aspects, the essay highlights biochar's potential to improve agricultural productivity and contribute to climate change mitigation, offering insights into its role as a sustainable solution for soil management and environmental resilience.

1. Introduction

Biochar, a stable carbon-rich product derived from the thermal decomposition of organic matter under limited oxygen conditions, has garnered significant attention for its multifaceted applications in agriculture and environmental management[1]. Its unique properties, such as high surface area, porosity, and chemical stability, make it a versatile material for improving soil health and addressing global challenges like climate change. As global populations grow and arable land faces degradation, sustainable solutions to enhance soil fertility and reduce environmental impacts are increasingly critical [2, 3].

The characterization of biochar involves a suite of advanced analytical techniques that reveal its physical, chemical, and structural attributes [4, 5]. These properties underpin its ability to interact with soil systems, influencing nutrient retention, water-holding capacity, and pollutant immobilization. Furthermore, biochar's environmental applications, such as carbon sequestration and greenhouse gas reduction, position it as a key player in climate change mitigation strategies[6].

Recent research underscores the strong link between biochar's feedstock origin, production conditions (e.g., pyrolysis temperature and residence time), and its functional performance in soil environments[7]. For instance, biochars produced at higher temperatures (>500 °C) typically exhibit greater aromaticity, surface area, and stability enhancing their capacity for long-term carbon storage and contaminant adsorption whereas those derived from manure or crop residues often contribute more nutrients but may be less stable over time[8]. This variability necessitates a systematic approach to biochar characterization to ensure its effective and context-specific deployment in agricultural and ecological restoration projects. Understanding these structure–function relationships is essential for optimizing biochar design and maximizing its co-benefits across diverse agroecosystems[9].

The purpose of this review is to evaluate the characterization of biochar and its influence on soil quality, highlighting its role in sustainable agriculture and environmental management. Through a detailed analysis of biochar's properties and their effects on soil physicochemical characteristics, microbial activity, crop productivity, and climate-related benefits, the essay seeks to underscore the importance of biochar as a tool for addressing pressing global challenges. It aims to inform researchers, policymakers, and practitioners about the transformative potential of biochar in fostering resilient ecosystems.

2. Characterization of Biochar

Characterizing biochar is crucial for evaluating its capacity to remove pollutants and assessing its potential uses. Structural and elemental analyses play a vital role in predicting the environmental impact of biochar. Additionally, biochar interacts with metals, and this interaction is influenced by pH levels, with two main considerations: 1) biochar's behavior varies with pH, and 2) metal ion speciation changes in response to pH. These factors highlight biochar's effectiveness as a potent adsorbent for removing soil pollutants. Various methods for characterizing biochar include surface functional group analysis and elemental composition assessments [10]. Several modern techniques for biochar characterization include Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), Nuclear Magnetic Resonance Spectroscopy (NMR), Brunauer-Emmett-Teller (BET) analysis, proximate and ultimate analysis, and Raman Spectroscopy, as illustrated in Figure 1.

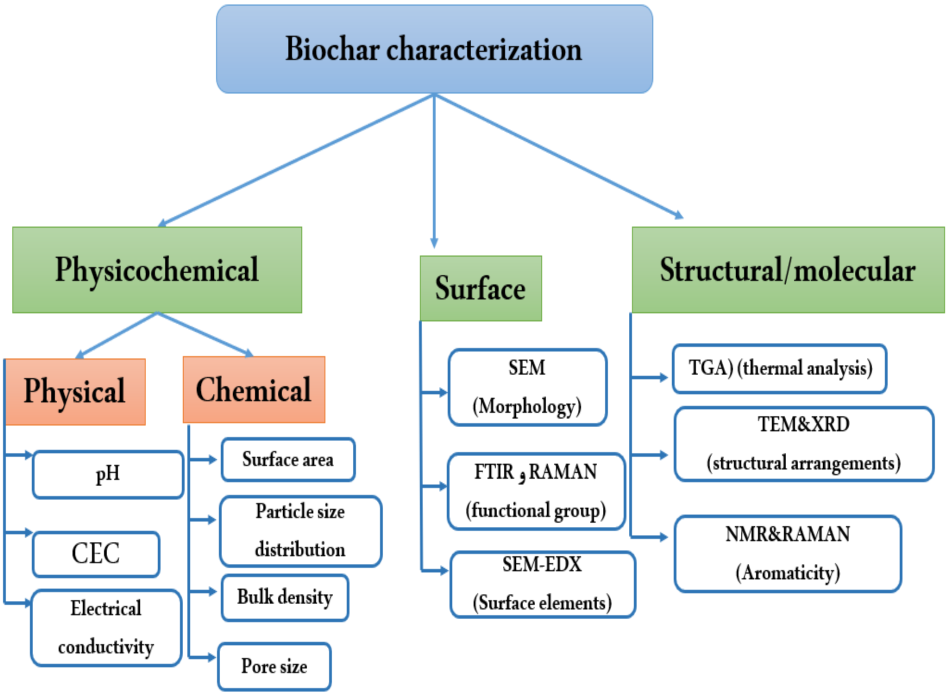

Fig. 1 Characterization of the physicochemical properties, surface, and structure of biochar.

2.1. Surface Area and Porosity

Biochar with a larger surface area and high porosity generally exhibits better sorption capabilities. The porous surface of biochar is created during pyrolysis, which involves the loss of water through dehydration. According to the International Union of Pure and Applied Chemistry (IUPAC), pores in biochar are classified as micro (<2 nm), meso (2−50 nm), and macro (>50 nm). Biochar with smaller pores cannot adsorb pesticide molecules, regardless of their polarity or charges. Scanning Electron Microscopy (SEM) is used to characterize the pore size. The surface area of biochar is a key factor for determining its sorption capacity, and temperature plays a significant role in its formation. Activated carbon generally has a much larger surface area compared to raw biochar. Biochar produced without activation has a low surface area and lower porosity [11]. Activation processes, both physical and chemical, are essential for increasing biochar's porosity and surface area.

2.2. Functional Groups

The key functional groups present on the surface of biochar that enhance its adsorption properties include hydroxyl (−OH), carboxylic (−COOH), amine, amide, and lactonic groups. The type of biomass feedstock and pyrolysis temperature are the primary factors determining the abundance and nature of these surface functional groups[12]. While surface area and porosity govern the accessibility of these groups to contaminants or nutrients, the solution pH influences their ionization state thereby modulating adsorption capacity without altering their actual concentration on the biochar surface. Fourier Transform Infrared Spectroscopy (FTIR) is typically used to characterize these surface groups. Biochar produced at different temperatures shows significant variations in its surface functional groups. In addition to FTIR, Nuclear Magnetic Resonance (NMR) can also identify functional groups in biochar.

2.3. Scanning Electron Microscopy (SEM)

SEM is used to examine the surface structures of biochar. SEM images reveal that different procedures and temperatures lead to significant changes in the surface morphology of biochar particles, although the overall shape remains largely unchanged. With increasing temperature, the formation of pores in biochar improves, enhancing its pore properties. SEM provides a detailed description of the microporous and mesoporous distributions, as well as the arrangement of pores in biochar. It can also predict surface morphology changes before and after the adsorption process. When combined with Energy Dispersive X-ray Spectroscopy (EDX), SEM allows for an analysis of the elemental composition of biochar. SEM-EDX is widely used to assess biochar surfaces after adsorption of contaminants, though it is less effective for organic contaminants[13].

2.4. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is a non-destructive vibrational technique used to analyze the functional groups on the surface of biochar. As pyrolysis temperature increases, significant chemical and structural changes occur in biochar, which can be monitored effectively using FTIR. Within the 650–800°C range, FTIR spectra reveal the gradual loss of aromatic groups. In Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS), samples are converted into pellets using potassium bromide, which are then placed in contact with an Attenuated Total Reflectance (ATR) crystal for functional group analysis [14].

2.5. Thermogravimetric Analysis (TGA)

TGA is used to study the thermal properties of biochar in relation to temperature. This technique is particularly useful for describing and comparing the thermal behavior of biochar and its mixtures with biomass. TGA can also be used to examine the ignition characteristics of biochar. The heating of biochar begins at room temperature and increases up to 1000°C. TGA helps analyze the thermal decomposition processes of biochar and its stability at higher temperatures [15].

2.6. X-ray Diffraction (XRD)

X-ray diffraction is a widely used technique for determining the crystallinity and structure of biochar. XRD patterns provide distinct features of amorphous material produced at temperatures above 350°C. This technique helps identify the crystalline nature of biochar, with sharp XRD peaks indicating the presence of nanocrystals. As pyrolysis time increases, particle size grows, and XRD patterns are valuable for producing high-quality biochar with enhanced sorption efficiency[16].

2.7. Brunauer-Emmett-Teller (BET) Analysis

BET analysis is employed to measure the surface area of biochar, a crucial factor in determining its sorption capacity, especially in removing pollutants from soil and water. After pyrolysis, biochar typically exhibits a significant increase in surface area compared to raw feedstocks. The creation of micropores during pyrolysis is evident, and surface area increases with the heating rate. The release of volatile matter during pyrolysis results in biochar with higher porosity, more diverse pore structures, and lower density [17].

2.8. Raman Spectroscopy

Raman Spectroscopy is an essential technique for studying molecular structures, relying on vibrational transitions within molecules when exposed to electromagnetic radiation. Raman scattering shifts the frequency of the incident radiation due to the absorption of vibrational energy. This method enables precise measurements of chemical and nanostructural changes during biomass carbonization. Raman spectroscopy is highly sensitive, requires minimal sample preparation, and is less prone to interference, making it suitable for biochar characterization. However, its cost may limit its widespread use [18].

2.9. Nuclear Magnetic Resonance Spectroscopy (NMR)

NMR is a technique used to analyze the structural composition of biochar by observing the resonance frequencies of specific nuclei in the molecules. Solid-state NMR methods can identify the general content of carbon functional groups, the extent of aromatic ring formation, and the overall structure of biochar. NMR is useful for investigating the aliphatic and aromatic hydrocarbon content of biochar. However, the presence of ferromagnetic minerals can interfere with NMR signals, and biochar produced at high temperatures may produce a low signal-to-noise ratio [19].

2.10. X-ray Photoelectron Spectroscopy (XPS)

XPS is employed to study the structure and composition of biochar produced at various thermal temperatures and from different biomass types. It helps identify and quantify functional groups and elemental composition on the biochar surface. XPS can track changes in oxygen-containing functional groups, which are linked to the short-term stability of biochar. It also allows for determining the O/C molar ratio, which serves as an indicator of biochar stability [20].

2.11. Biochar Stability

Biochar stability refers to its resistance to degradation by both biotic and abiotic factors in the soil, serving as a key indicator of its potential for carbon sequestration. Various methods have been developed to assess biochar stability, including thermal, chemical, and biochemical techniques. The temperature used during pyrolysis is a rough indicator of biochar stability, though it is not always accurate. Proximate analysis, a traditional method for assessing biochar composition, is used to determine moisture, volatile matter, and ash content, though it has limitations, especially with regard to ash content [21]. Biochar stability can be evaluated through direct or indirect measurements of carbon structures, such as aromaticity, or by using techniques like chemical oxidation and thermal degradation [22]. Incubation in soil and modeling carbon mineralization are considered the most reliable methods for determining biochar stability, though these are expensive and time-consuming**.** New approaches, including the use of radioactive 14C isotopes, are being explored to improve the assessment of biochar stability for climate change mitigation.

3. Biochar Influence on Soil Quality

Biochar interacts physically with soil fractions. Molecular-scale interactions occur between biochar and clay, silt particles, and soil organic matter (SOM) through van der Waals forces and hydrophobic interactions [23]. These interactions at the molecular scale influence biochar's impact on the physicochemical properties of the soil, as well as its interactions with cations, anions, and other organic compounds [24]. These interactions are particularly specific to biochar, with its properties being affected by the type of feedstock and pyrolysis conditions.The application of biochar can have either positive or negative effects on soil properties, including water holding capacity [25], cation exchange capacity (CEC) [26], bulk density [27], and specific surface area [28]. The stability of biochar is not only beneficial from a climate mitigation perspective but also for sustaining potential positive agronomic effects over extended periods [29].

3.1. Inorganic and organic contaminates in soil

Numerous studies have demonstrated that biochar enhances the soil's ability to adsorb heavy metals and other contaminants, which is crucial for environmental protection and management [28]. Biochars consist of both carbonized and non-carbonized fractions, which may interact with soil contaminants through oxygen-containing surface functional groups such as carboxyl, phenolic, hydroxyl, and lactonic groups. These fractions play distinct roles in the adsorption process. The carbonized fraction is analogous to the "glassy" fraction (similar to glassy polymers), while the non-carbonized fraction is similar to the "soft" fraction (comparable to rubbery polymers) . Biochar can be viewed as a soil amendment that mitigates the biotoxicity of pollutants [30].

The efficiency of contaminant removal depends on the specific surface area and CEC of biochar [31], as well as factors such as the type of interfering ions, pH of the solution, the biochar dosage [28], soil type, soil pH, contact time, metal concentration, and temperature, in addition to the biochar type. Several studies have examined heavy metal adsorption by biochars, including copper ion adsorption from water by a soil-biochar mixture at varying pH levels [28], as well as zinc, copper, and lead adsorption on zeolite and platinum (IV) ions in loess soil.These studies aim to understand how heavy metal ions are adsorbed from the liquid phase to the adsorbent's surface and how biochar influences this process in soil [32]. Colloids and organic ligands, as well as inorganic ones [33], affect the adsorption process. Cao et al. [34] found that dairy manure biochar produced at low temperatures (200 °C and 350 °C) was six times more effective at removing lead (Pb) from wastewater than commercial activated carbon. Tong et al. [35] studied the copper adsorption capacity of biochars derived from different feedstocks and found that biochar from nut straw exhibited the highest adsorption capacity, followed by soybean and rapeseed biochar. Copper adsorption occurred via the formation of complexes with surface groups, specifically –COOH and phenolic groups [35]. However, Karami et al. [36] reported that the addition of oak biochar (20.0% v/v) to soil reduced copper (Cu) sorption by approximately 69.0%. Xu et al.[37] showed that biochar from straws and peanuts (3.0% and 5.0% v/v) enhanced Cu sorption in Oxisol, Utisol, and Ultisols, while rice-derived biochar reduced Cu sorption in Ultisol derived from Quaternary red earth . Woody biochar increased Cu adsorption in Haplic Podzol at pH 3.0 and 5.0, with the most significant change occurring at pH 5.0 [28].

Biochar can also adsorb other contaminants, such as polycyclic aromatic hydrocarbons (PAHs), antibiotics, and pesticides. For instance, Chen et al. [38] investigated the effect of biochars obtained from pine needles at different pyrolysis temperatures on the sorption of PAHs, specifically naphthalene and phenanthrene. Biochar produced at high temperatures (400 and 700 °C) demonstrated higher sorption efficiency than biochar produced at low temperatures (100 and 300 °C). Phenanthrene sorption exceeded 99.0% for biochars produced at 300 and 400 °C at a concentration of 5.0%. When the biochar content was only 0.5% for biochar at 300 °C and 0.1% at 400 °C, the contributions of biochar and soil to total phenanthrene sorption were similar. At a higher biochar content (5.0%), phenanthrene sorption increased to 90.0% and 98.0% for biochar at 300 °C and 400 °C, respectively [38]. A similar trend was observed for naphthalene sorption, with enhanced sorption intensities (1.7–3.2 times, 28.3–113.0 times, 58.6–314.0 times, and 138.0–1170.0 times for biochars produced at 100, 300, 400, and 700 °C, respectively). The biochar dominated the overall sorption of naphthalene when added to soil at a minimum proportion of 0.5% for biochar produced at 300 °C and 0.1% for biochar produced at 400 °C. Overall, the saturated adsorption capacity for PAHs increased with the biochar pyrolysis temperature, following the order 100 < 300 < 400 < 700 °C [38]. Li et al. [39]studied the sorption of sulfadiazine and tetracycline on wood biochar produced at 600–800 °C. The authors found that biochar produced at higher temperatures enhanced its mesoporosity and its affinity for antibiotic sorption from the aquatic environment. Desorption studies indicated irreversible adsorption of antibiotics, suggesting that biochar adsorbs them permanently, preventing their leaching into the [39]. Furthermore, Garcia-Perez et al.[40] observed that biochars produced at temperatures exceeding 700 °C typically generate hazardous PAHs, while low-temperature biochars (pyrolyzed between 350–600 °C) produce fewer toxic substances. Therefore, biochars intended for soil fertility amendments should be produced under moist conditions and at low temperatures.

3.2. Physicochemical properties of soil

Biochar application to soils has demonstrated significant potential for mitigating climate change by enhancing soil carbon sequestration. The long-term stability of biochar in soil is a key factor in reducing CO_2 emissions into the atmosphere [41]. Recent long-term studies estimate the mean residence time of carbon in biochars to range from 90 to 1600 years, depending on the labile and intermediate stable carbon components. Biochar influences changes in functional groups and their distribution in soil microaggregates, which indicates modifications in the physical protection and processing of carbon in soil [42]. Several recent studies have shown that biochar can reduce emissions of nitrous oxide (N_2O) and methane (CH_4) from soil through both biotic and abiotic mechanisms [43]. Woolf et al. [44] proposed a sustainable biochar concept through which the emission of greenhouse gases, including CH_4 and N_2O, can be mitigated. Additionally, the bioenergy produced during the pyrolysis process offsets fossil energy consumption.

Furthermore, biochars are rich in mineral elements such as Na, K, Ca, Fe, and Mg. Their concentrations increase with the pyrolysis temperature [45] and vary according to the type of biomass [46]. In one study, the highest concentrations of P, K, and Mg (4.3, 9.9, and 2.8 g/kg, respectively) were observed in biochar obtained at 500 °C, while 400 °C yielded the highest carbon and nitrogen contents (73.6% and 1.9%, respectively) [45]. Cantrell et al. [47] suggested that metals inherent in animal litter may protect against the loss of volatile material by altering the dissociation energies of organic and inorganic carbon bonds. Adding biochar to soil is expected to increase the concentrations of micronutrients that are readily available to plants. Improving soil physical, chemical, and biological properties enhances plant productivity by increasing nutrient availability, reducing nutrient leaching, and mitigating losses of gaseous components [48]. A high cation exchange capacity (CEC) is known to correspond with high nutrient content.

Glaser et al. [49] suggested that oxidation of aromatic carbon and the formation of carboxyl groups are responsible for the high CEC of biochar. This formation of carboxyl or other negatively charged functional groups in the pH range of soils can result from two processes: (1) surface oxidation of biochar particles and (2) adsorption of highly oxidized organic matter onto biochar surfaces. Low-temperature biochars are often preferred due to better soil-biochar interactions compared to high-temperature biochars [50]. Low-temperature biochar also retains more carbon and other nutrients, which are typically lost during high-temperature pyrolysis. The main advantage of low-temperature biochar (pyrolyzed between 400 and 500 °C) is its ability to increase CEC, although it sequesters less soil carbon than high-temperature biochar. High-temperature biochars have lower reactivity in soils compared to lower-temperature biochars, which tend to have a more positive impact on soil fertility. Hass et al. [51]observed that the effect of biochar on soil pH increased with application rate and varied among different biochar types. The pH increase and corresponding reduction in exchangeable aluminum (Al) improved the chemical environment (e.g., soil pH, organic matter, phosphorus, and potassium content) for radish plants [52].

Biochar application can also positively influence soil's specific surface area [53]. Tomczyk et al. [28] showed that the specific surface area of the non-modified silty Haplic Luvisol was almost three times greater than that of the sandy Haplic Podzol. Biochar amendment increased the specific surface area of both soils, with modified Haplic Luvisol showing a higher surface area (approximately 12.7–21.9 m^2/g) compared to non-modified loamy soil, and modified Haplic Podzol also having a higher surface area (approximately 2.5–11.6 m^2/g) than non-modified sandy soil. These results suggest that Haplic Podzol has weaker interactions with biochar than Haplic Luvisol. The larger specific surface area in Haplic Luvisol may be due to its higher amounts of organic carbon, clay, and silt compared to Haplic Podzol. The effect of biochar on specific surface area varies among biochar types. Lei et al.[54] reported that wood biochar has a higher specific surface area (124.0 m^2/g) than biochar from the dairy industry (83.4 m^2/g). Biochar application increases the number of macropores (up to a 59.0% increase), and macropore content increases with pyrolysis temperature. The increased specific surface area and porosity improve water sorption [55].

Biochar fertilization also positively impacts water holding capacity [56]. Biochar can absorb water up to 5.0 times its weight [57]. It increases moisture and the content of organic and inorganic nitrogen compounds, which reduces lime in litter, lowering the pH of litter and manure, thus reducing ammonia emissions. Studies have shown that biochar alters water retention in soil. The increase in carbon content from biochar addition stimulates humification and carbon sequestration processes, improving soil density and water retention [55]. Cybulak et al. [58] reported that biochar application increased the hygroscopic moisture content of soil by approximately 1.5–3.0%, which benefits dry and degraded soils. Smaller biochar particle sizes also increase water retention but may reduce saturated flow [59]. Glaser et al. [49]found that Amazonian charcoal-rich anthrosols had an 18.0% higher field water retention capacity than surrounding soil without charcoal. The impact of charcoal on water retention depends on the original characteristics of the soil. Usowicz et al. [60]noted that biochar amendment to fallow land reduced bulk density, particle density, thermal conductivity, and thermal diffusivity. However, no significant effects were observed on soil thermal conductivity and diffusivity under grassland. Biochar application to agricultural soils can alter surface albedo, potentially counteracting its climate-mitigation potential. Greater albedo reduces the absorption of UV radiation by the soil. Biochar amendments reduced albedo in both grassland and fallow land [60].

3.3. Soil Remediation

Soil contamination, resulting from industrial, domestic activities, and the presence of various chemicals, compounds, or substances, has become a significant global concern. These contaminants can directly or indirectly affect the activities of non-target microorganisms [61]. One promising technique for cleaning contaminated soils is the application of biochar, which has been shown to effectively remediate contaminated soils. As an affordable and environmentally sustainable solution made from waste materials, biochar helps repair the soil [61]. Its large surface area, high water-holding capacity, and porous structure contribute to its ability to reduce pollutants in the soil [62]. Several studies support the use of biochar in soil remediation, especially for heavy metals and metalloids, through immobilization strategies, demonstrating positive outcomes. For instance, biochar derived from Carya species has been found to significantly adsorb and reduce the leaching of sodium bispyribac and clomazone in the soil [63].

3.4. Agronomical Importance (Crop Improvement)

The use of biochar has a positive impact on crop yield and productivity by improving nutrient availability and nutrient use efficiency. Studies have reported a 10% increase in crop yield with biochar application [64]. Biochar aids in the reduction of soil salinity, thus improving nutrient availability and leading to higher yields. Additionally, biochar has the potential to manage or eliminate diseases and pests in crop fields. Application of 3–5% biochar can slow the growth of fungal pathogens and pests [64]. Furthermore, biochar has shown a promising role in weed control in faba beans, leading to enhanced crop productivity [65]. Numerous field tests and pot experiments have demonstrated that the application of various biochars to the soil increases the growth and production of a variety of crops, such as *Phaseolus vulgaris*, *Solanum lycopersicum*, *Cucumis sativus*, *Citrullus lanatus*, *Zea mays*, and *Piper nigrum*. Additionally, the use of rice husk biochar in wheat crops has been shown to improve both yield and water-holding capacity [63].

3.5. Induces Microbial Activity in the Soil

The application of biochar alters the physical and chemical properties of soil, enhancing its ability to support microorganisms.Soil microbial activity plays a crucial role in the decomposition of organic substances, nutrient cycling, and the nutrient status and production capacity of crops [66]. Biochar has been found to increase microbial growth in the soil by providing a medium for microbes .According to Kannan et al. [67], biochar application positively influences the habitat and function of mycorrhizal fungi and other soil organisms, leading to direct improvements in soil quality and health. Furthermore, biochar produced from fresh biogas has been shown to favorably affect microbiota by modulating the suppression of arsenic and ferric ions [63].

3.6. Mitigating Greenhouse Gas Emissions

Estimates suggest that the global use of biochar could reduce greenhouse gas (GHG) emissions by up to 12% [68]. Recent studies have shown that using biochar composites, rather than virgin biochar, may help mitigate climate change in two significant ways, despite biochar's ability to cut global GHG emissions on its own [68]. First, combining biochar with compost has been hypothesized to improve decomposition by increasing the amount of stable carbon and producing a valuable byproduct (biochar-compost mix). This approach addresses potential drawbacks of biochar pyrolysis technology, such as poor macronutrient content and CH_4 emissions from composting systems [64]. Second, biochar has been linked to increases in soil organic matter and reductions in GHG emissions, particularly for gases with high global warming potential, such as CH_4 and N_2O [64]. In practice, more plant growth or lower soil GHG emissions may be needed for a biochar system to offer a better emission balance compared to biochar used as a charcoal fuel. Studies have also shown that biochar plays an essential role in reducing methane emissions from rice fields by encouraging methanotroph (methane-consuming bacteria) communities and limiting the diversity of methanogens (methane-producing bacteria) [63, 69].

3.7. Climate Change Mitigation

Global warming, caused by increasing GHG emissions, is one of the most significant environmental issues of the 21st century. The carbon (C) cycle plays a pivotal role in both the causes of and solutions to this problem [70]. Biochar offers exceptional physical and chemical properties that can be used across various fields to improve eco-natural quality. Biochar can serve as a catalyst for the degradation of contaminants by gathering transition metals (see Figure 2) [71]. Proper management of organic wastes can indirectly reduce methane emissions from landfills and industrial energy use, thus mitigating climate change. A study by Montanarella et al.[72] reported that to remove 0.49 GtC per year from the atmosphere through biochar application, approximately 2.2 GtC of feedstock would need to be converted into biochar annually. The pyrolysis of animal manures and the use of appropriate biochars to reduce the leaching of phosphates and nitrates in soil or co-applied manures can help mitigate excessive nutrient export from agricultural watersheds [64]. Reducing GHG emissions emphasizes the need to manage biochar as part of an integrated system rather than as a standalone component. Biochar has lower mineralization than its raw material, reducing CO_2 emissions and playing a crucial role in mitigating climate change [73]. Since biochar is tightly bound to soil particles, it helps decrease CO_2 emissions. The role of biochar in climate change mitigation focuses on two critical areas: carbon sequestration and GHG reduction [63, 64].

3.8. Carbon Sequestration

Biochar was initially proposed as a soil amendment to store carbon and enhance carbon sequestration, as its carbon component is generally stable [70]. Biochar represents a relatively stable form of carbon that can act as an effective long-term carbon store, significantly impacting the reduction of GHG emissions. Biomass, when used in conjunction with waste management techniques, can store organic carbon that would otherwise be burned or composted, offering a long-term solution for carbon sequestration and waste disposal. Certain biochar-based composites may enhance biochar's stability and biomass carbon retention compared to virgin biochar. Biochar created from leftover biomass from agriculture and food processing industries can contribute to long-term carbon sequestration, positively impacting both soils and environmental quality [63, 64].

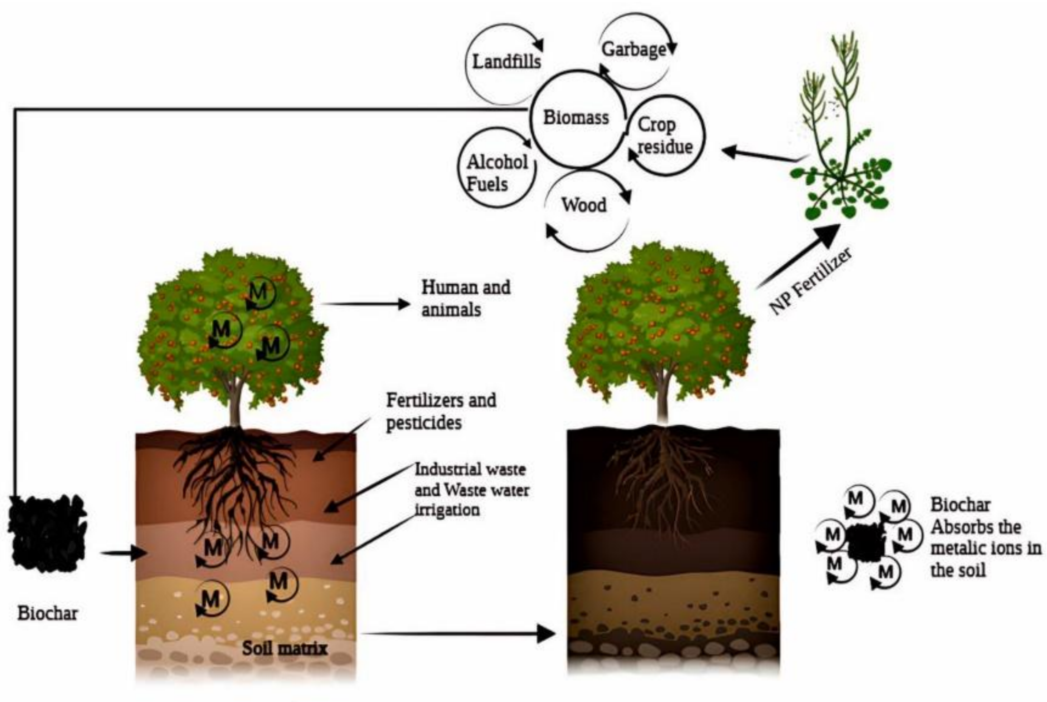

Fig.2 Schematic representation of metal pollution treatment using biochar, showing adsorption of metal impurities (reproduced with permission from Yadav et al.[63]).

4. Conclusion

Biochar represents a powerful tool for enhancing soil quality and addressing critical environmental challenges. Its physicochemical properties, elucidated through advanced characterization techniques such as BET, SEM, FTIR, Raman, XPS, NMR, XRD, and TGA, provide a foundation for its diverse applications. By improving soil physicochemical properties, remediating contaminants, enhancing microbial activity, and boosting crop productivity, biochar offers tangible benefits for sustainable agriculture. Furthermore, its capacity for carbon sequestration and greenhouse gas mitigation positions it as a vital component of climate change mitigation strategies. As research and application of biochar continue to evolve, its integration into agricultural and environmental practices holds promise for fostering resilient ecosystems and supporting global sustainability goals.

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Ethical Statement

This research does not contain any studies with human or animal subjects performed by any of the authors

Data Availability Statement

Not Applicable

Conflicts of Interest

The authors declare no conflicts of interest

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