CHAPTER

1

THE EFFECTS OF BIOCHAR CHARACTERISTICS, PRODUCTION METHODS, AND MECHANISMS ON ACID SOIL REMEDIATION

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Abstract

A major barrier that significantly reduces agricultural productivity on some of the world's arable land is soil acidity. The use of biochar in soil remediation has become a promising research area recently. Biochar is a carbon-rich byproduct of the pyrolysis of organic waste and has the potential to slow down climate change. The use of biochar in reclaiming acid soils shows positive impact and its long-term effect on soil health is yet to be studied. Because this can act as a guide for future study on the use of biochar to remediate polluted soils in mining locations, it is essential to methodically gather the relevant information regarding biochar remediation. This study aims to provide an in-depth review of the most recent studies on the application of biochar in soil remediation, including its possible advantages, constraints, difficulties, and prospective future applications. In particular, this review will highlight the biochar production methodology, physical, chemical and biological improvements on soil with respect to crop productivity and soil fertility.

Keywords: *Biochar, Carbon sequestration, Organic, Soil remediation, Soil acidity*

Introduction

Approximately 30% of the Earth's land surface is classified as acidic, impacting over half of all arable land, especially in tropical and subtropical regions ("Agriculture for Marginal Lands," 2000). Soil acidification is a natural process intensified by climatic and pedogenic factors, yet it is frequently accelerated by human activities, particularly long-term and excessive application of nitrogen (N) fertilizers, which lead to the production of protons (H^+) in the soil solution. Many physical properties, chemical reactions, and biological activities inside soil are impacted by soil acidity, which regulates the availability of nutrients, the toxicity of metal elements, and the metabolic processes of microbes, plants, and soil fauna (Hartemink and Barrow 2023). For example, acidic soils readily lose nutrients including calcium (Ca), magnesium (Mg), and potassium (K), which reduces soil fertility (Li *et al*. 2020).

Acidic soils have a tendency to fix phosphorus (P), which results in limited bioavailability. Long-term reliance on substantial P fertilizer application is required to guarantee crop yield, which exacerbates agricultural P pollution and P resource depletion (Kabir et al., 2023). Crop yields and quality can be negatively impacted by acidity because it can cause "aluminum (Al) toxicity" and increase the bioavailability of hazardous metals like lead (Pb) and cadmium (Cd) (Wang et al., 2015). Considering these widespread impacts, the improvement of acidic soils is vital for sustainable agriculture and food security.

The conventional approach to managing acidic soils involves the application of calcitic or dolomitic limestone (liming). Although effective, liming has limitations such as a delayed reaction time, elevated expenditures in remote agricultural areas, and possible negative effects on micronutrient balance when applied inappropriately. Meanwhile, lime has other disadvantages such as dust contamination, a tendency for soil to acidify again, easy soil compaction, short maintenance times, and inadequate improvement of deep soil layers (Xu et al. 2018). Industrial byproducts typically contain heavy metals, which raises the possibility of secondary pollution (Li et al. 2010). Water eutrophication is likely caused by organic waste, which frequently contains excessive N and P (Case et al. 2017). The effectiveness of returning straw to improve acid soil is still up for debate. So, in recent decades, biochar, a byproduct of the thermal decomposition of organic matter in limited oxygen conditions (pyrolysis), has gained more importance as an innovative soil amendment (Suresh Babu et al., 2024). Its distinctive physiochemical properties, such as elevated surface area, porous structure, and intrinsic alkalinity, act as an effective carbon-sequestering agent for soil fertility and environmental management (Khan et al., 2020). This chapter seeks to systematically analyze the mechanisms through which biochar improves acidic soil and describes its effects on various soil quality indicators.

Biochar Characteristics and Mechanisms of Amelioration

Biochar is a rich in carbon, porous substance generated through the pyrolysis of organic material in an oxygen-limited environment (He et al., 2024). The principal attributes comprise elevated surface area, alkaline properties, and the existence of functional groups that improve cation exchange capacity and nutrient retention (Zhang et al., 2013). These properties make biochar effective in improving acidic soils by neutralizing soil acidity, thereby reducing aluminum and manganese toxicity. The porous structure of biochar enhances soil aeration, water-holding capacity, and nutrient availability, while providing favorable microhabitats for beneficial microorganisms that promote soil biological activity (Klasson, 2017). Moreover, biochar adsorbs and holds essential nutrients such as nitrogen, phosphorus, and potassium, thereby reducing leaching losses and improving overall soil fertility. Biochar also serves as an effective soil ameliorant through these physical, chemical, and biological processes, improving soil structure, productivity, and sustainability, especially in acidic or degraded soil environments (Kocsis et al., 2022).

According to Ippolito et al. (2020), biochar is not a single material and its characteristics are greatly influenced by the pyrolysis conditions (such as temperature and heating rate) and feedstock (such as wood, crop residue, and manure). The material's efficacy in acidic soil environments is determined by their nature of the material and the pyrolysis conditions. Furthermore, the overview of the effects of biochar characteristics, production methods, and mechanisms on acid soil remediation were displayed in **Figure 1.1.**

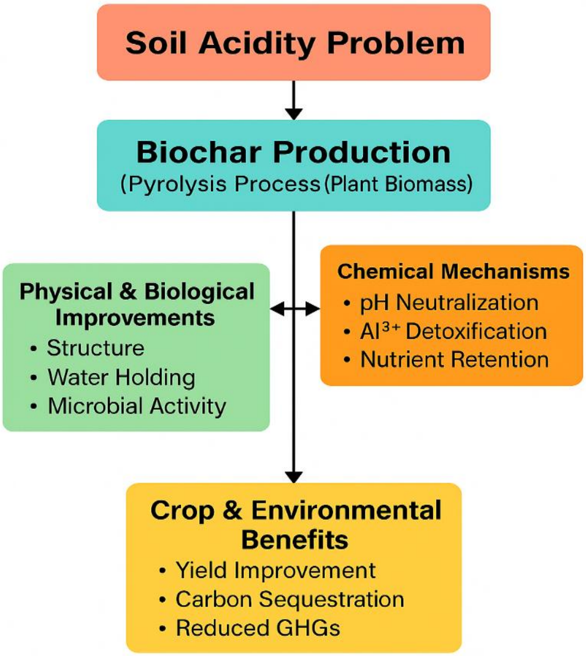

Figure 1.1. Overview of effects of biochar characteristics, production methods, and mechanisms on acid soil remediation

Table 1.1. Characteristics of biochar

Sl. No	**Bio chars**	**pH**	**EC (dSm^{-1})**	**Surface area (m^2/g)**	**Total nutrients (g/kg)**				**Nutrients (%)**	
					P	**K**	**Ca**	**Mg**	**N**	**C**
1.	Sugar cane bagasse	7.5	-	557.4	Traces	Traces	Traces	Traces	0.79	76.45
2.	Groundnut shell	6.9	-	27.1	Traces	Traces	Traces	Traces	0.94	11.26
3.	Rice straw	10.05	0.18	36.7	2.6	Traces	Traces	Traces	1.66	50.8
4.	Sugarcane straw (70^0 C)	10.2	0.05	5.0	0.9	11.7	7.7	2.0	0.9	69
5.	Wheat straw	7.2	0.25	10.0	Traces	Traces	Traces	Traces	1.1	55
6.	Saw dust	6.3	0.01	42	Traces	Traces	Traces	Traces	0.74	47
7.	Food waste	5.1	5	44	Traces	Traces	Traces	Traces	1.3	65
8.	Poultry litter	6.6	0.12	27	Traces	Traces	Traces	Traces	1.12	66

Source: Anwarzeb khan, et al., 2020

Neutralization Potential: The Chemical Mechanism

The alkaline elements and surface chemistry of biochar largely control its neutralization potential in acidic soils. Basic minerals found in biochar, including calcium, magnesium, potassium, sodium hydroxides, and carbonates, react with hydrogen ions (H^+) in acidic soils to raise the pH of the soil. This procedure uses buffering reactions and proton exchange to neutralize the acidity of the soil.

Furthermore, oxygen-containing functional groups (like carboxyl, hydroxyl, and phenolic groups) on the surface of biochar can adsorb and neutralize free protons, which helps to further stabilize pH (Li et al., 2023). It also minimizes the amount of toxic manganese (Mn^{2+}) and aluminum (Al^{3+}) ions that are available to plants by precipitating or immobilizing them (Joseph et al., 2021). Therefore, biochar's neutralization potential is based on its chemical mechanism and improves the chemical environment for plant growth by buffering soil acidity through ion exchange, proton consumption, and mineral disintegration.

a. **Direct Alkaline Input:** Generally, the mineral components are concentrated in the ash content of the biochar during the pyrolysis process. During soil application, the $CaCO_3$ dissolve and releases alkalinity (OH^- or HCO^{3-}), which consumes free H+ ions in the soil solution and raises the pH (Zubairu et al., 2023).

b. **Surface Functional Groups:** Although the carbon core of the biochar matrix is highly aromatic and resistant, its surface is coated with functional groups such as carboxyl and phenolic that can actively bind and deprotonate H^+ ions from the exchange complex, thereby lowering the acidity of the soil. This was supported by (García et al., 2021).

c. **Cation Exchange Capacity (CEC)** Enhancement: Biochar usually has a high CEC, which lowers the concentration of leachable, acid-forming H+ and Al^{3+} ions while also increasing the soil's ability to retain basic cations like Ca^{2+}, Mg^{2+}, etc. (Das et al., 2021).

Influence of Feedstock and Pyrolysis Conditions

The type of feedstock used and the pyrolysis conditions used during its production have a significant impact on the properties and remedial potential of biochar (Chintala et al., 2014; Nepal et al., 2023).

a. **Feedstock Type:** In comparison to plant or woody biomass, biochars made from manure and sewage sludge feedstocks typically have higher ash contents, alkalinity, and base cation concentrations. Thus, biochars made from animal wastes frequently have a better liming effect (Chintala et al., 2014).

b. **Pyrolysis Temperature:** When the pyrolysis temperature is raised (usually to 600°C or higher), volatile organic compounds begin to break out, which concentrates the basic mineral components and causes a significant increase in pH and ash content. Additionally, biochars that are heated to higher temperatures tend to be more stable and aromatic, which prolongs the pH-raising effect (Enders and Lehmann, 2012; García et al., 2021; Joseph et al., 2021; Zubairu et al., 2023).

On the other hand, low-temperature biochars preserve more surface functional groups and labile carbon, which may provide a less noticeable initial pH correction even though they are good for retaining nutrients.

Impacts on Soil Properties

A series of advancements in the chemical, physical, and biological aspects of soil health are triggered by the pH correction of the soil.

Chemical Parameters and Metal Detoxification

Biochar significantly affects the chemical properties of soil, enhancing nutrient dynamics and diminishing metal toxicity. Biochar application elevates soil pH, electrical conductivity (EC), and cation exchange capacity (CEC), thereby improving nutrient availability and buffering capacity. The rise in pH caused by the dissolution of basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and carbonates helps neutralize soil acidity and stabilize the chemical environment. This pH adjustment plays a vital role in metal detoxification, as it reduces the solubility and mobility of toxic metal ions such as aluminum (Al^{3+}), iron (Fe^{2+}/Fe^{3+}), manganese (Mn^{2+}), and heavy metals like cadmium (Cd^{2+}), lead (Pb^{2+}), and zinc (Zn^{2+}). Moreover, the high surface area and functional groups (carboxyl, hydroxyl, and phenolic) of biochar facilitate the adsorption and complexation of these metal ions, forming stable organo-mineral complexes that limit their bioavailability (Adamczyk-Szabela and Wolf, 2022). Biochar's negative surface charge further attracts and immobilizes positively charged metal cations through electrostatic interactions and precipitation reactions (e.g., $Al(OH)_3$, $PbCO_3$). In addition, the enhanced CEC promotes the retention of beneficial nutrients over toxic metals, contributing to overall soil fertility improvement. Thus, through its alkalinity, sorptive properties, and chemical reactivity, biochar effectively detoxifies metal-contaminated or acidic soils, ensuring a safer and more balanced soil environment conducive to plant growth (Violante et al., 2010).

Modifying Exchangeable Acidity and Al^{3+} Toxicity

Biochar is essential for reducing exchangeable acidity and alleviating aluminum (Al^{3+}) toxicity in acidic soils via various interrelated chemical mechanisms. Upon the application of biochar, its alkaline constituents predominantly carbonates, oxides, and hydroxides of calcium, magnesium, potassium, and sodium interact with free hydrogen ions (H^+) in the soil solution, effectively neutralizing acidity and elevating soil pH (Shetty and Prakash, 2020; Ur Rahman et al., 2024). The increase in pH results in a decrease in exchangeable acidity, as H+ ions on the soil's exchange sites are substituted by basic cations from the biochar. Furthermore, as soil pH rises, Al^{3+} ions become less soluble and begin to hydrolyze, forming insoluble aluminum hydroxide complexes such as $Al(OH)_3$. These reactions effectively remove toxic Al^{3+} from the soil solution, decreasing its interference with root growth and nutrient uptake. Additionally, the high cation exchange capacity (CEC) and negatively charged surfaces of biochar provide active sites for Al3+ adsorption, preventing its re-release into the soil solution (Cosgrove, 1993; Kopittke et al., 2015). Functional groups like carboxyl and phenolic moieties on biochar surfaces can also form stable complexes with Al_3+, further immobilizing it in non-toxic forms. Through these mechanisms, pH buffering, ion exchange, precipitation, and complexation, biochar substantially modifies exchangeable acidity and alleviates aluminum toxicity, fostering a more favorable chemical environment for plant root development and nutrient availability in acid soils (Lin et al., 2018).

Nutrient Availability and Retention

Biochar application dramatically influences nutrient cycling and retention. It can adsorb anions such as nitrate (NO^{3-}) and phosphate (PO_4^{3-}), helping to stabilize them within the soil matrix and improving nutrient use efficiency. It also acts synergistically with organic matter and microbial activity, promoting the mineralization of organic nutrients and enhancing biological nutrient cycling (Ighalo et al., 2025). The presence of mineral ash in biochar further contributes directly to nutrient supply, adding base cations and trace elements essential for plant growth. Overall, through its dual role in nutrient adsorption and slow release, biochar improves soil fertility, minimizes nutrient loss, and ensures sustained nutrient availability for healthier and more productive plant growth (Yan et al., 2023).

a. **Phosphorus (P) Availability:** In acidic soils, P is typically fixed (precipitated) by Al and iron (Fe). By reducing soluble Al concentrations, biochar releases bound P back into the available pool. Furthermore, the Ca and Mg in biochar can react with and complex P (forming calcium-phosphate precipitates), preventing its fixation by Al and providing a slow-release source for plants (Yang et al., 2022).

b. **Base Cations:** The enhanced CEC and direct input of Ca, Mg, and K from the biochar significantly improve the availability and retention of these essential basic cations, preventing their leaching (Ur Rahman et al., 2024; Yan et al., 2023).

c. **Micronutrients:** While generally positive, biochar application must be managed carefully, as excessive pH increases can reduce the availability of certain micronutrients, notably zinc (Zn) and copper (Cu) (Kabir et al., 2023; Shetty and Prakash, 2020; Yang et al., 2022).

Physical Quality: Structure and Hydrology

Biochar's stable, porous structure contributes mechanical stability to the soil matrix, especially in light-textured or poorly structured soils.

a. **Soil Aggregation:** Biochar particles serve as physical anchors, facilitating the binding of sand, silt, and clay into larger, stable aggregates. Chemically, the surface functional groups act as bridges to form stable organo-mineral complexes. This improved aggregation reduces soil erosion and loss (Das et al., 2021; Violante et al., 2010).

b. **Hydraulic Properties:** The internal porosity of biochar, consisting of both micro- and macropores, enhances the soil's available water holding capacity (AWHC). The macropores improve aeration and saturated hydraulic conductivity (drainage), while the micropores aid in water retention, offering a significant advantage for crop resilience, particularly in sandy or coarse-textured acid soils (Das et al., 2021; Kabir et al., 2023; Kopittke et al., 2015; Shetty et al., 2021).

Biological Activity and Soil Health

Biochar application markedly improves the physical quality of soils by enhancing both structural stability and hydrological functions. Its highly porous nature and low bulk density contribute to better soil aggregation, aeration, and reduced compaction, especially in fine-textured or degraded soils (Lehmann et al., 2011). By promoting the formation of stable soil aggregates, biochar increases pores and improves root penetration and microbial habitat. The improvement in soil structure also reduces erosion and surface crusting, thereby maintaining better tilth and long-term soil productivity (Lehmann et al., 2011; Yang et al., 2022).

a. **Microbial Biomass and Community Structure:** Correcting the low pH and Al toxicity of acid soils relieves a major stressor on native microbial communities (Elmer and Pignatello, 2011). Biochar's high surface area creates micro-habitats that protect microbes from desiccation and predation, and its carbon content provides an energy source, leading to an overall increase in soil microbial biomass and a shift toward communities more favorable for nutrient cycling (Gomez-Eyles et al., 2011).
b. **Soil Enzymes:** Key enzymes involved in the cycling of C (e.g., invertase), N (e.g., urease), and P (e.g., phosphatase) are often stimulated by biochar addition, largely due to the improved pH and substrate availability (Gomez-Eyles et al., 2011; Lehmann et al., 2011).

Broader Environmental and Agronomic Outcomes

The use of biochar in soils extends benefits beyond immediate chemical and physical improvements, producing wide-ranging environmental and agronomic impacts. Environmentally, biochar contributes to long-term carbon sequestration due to its stable aromatic carbon structure, helping mitigate greenhouse gas emissions and climate change. Its capacity to adsorb heavy metals and organic pollutants reduces soil and water contamination, improving ecosystem health (Warnock et al., 2007). By enhancing nutrient retention, biochar also minimizes nutrient leaching into groundwater and surface waters, reducing eutrophication risks. Biochar improves crop productivity by enhancing soil fertility, water retention, and microbial activity. It supports the establishment of beneficial soil microbiomes, promotes nutrient cycling, and alleviates constraints such as soil acidity and aluminum toxicity. These improvements lead to healthier root development, better nutrient uptake, and higher yields, particularly in degraded or marginal soils. Additionally, biochar's effect on water-holding capacity enhances drought resilience, while its ability to stabilize nutrients and improve soil structure supports sustainable land management and reduces dependency on chemical fertilizers. Overall, biochar integrates environmental protection with agronomic efficiency, contributing to sustainable agriculture and soil conservation (Zhang et al., 2013).

Mitigating Greenhouse Gas Emissions

Biochar application can play a significant role in mitigating greenhouse gas (GHG) emissions from soils. Its stable, carbon-rich structure sequesters carbon for long periods, preventing the rapid decomposition of organic matter into carbon dioxide (CO_2). In addition, biochar alters soil microbial activity and nutrient cycling, reducing emissions of nitrous oxide (N_2O) and methane (CH4), two potent greenhouse gases (Zhang et al., 2025).

a. **Carbon Dioxide (CO_2) Sequestration:** Unlike fresh organic matter, which decomposes rapidly and releases CO_2 back into the atmosphere, biochar resists microbial degradation and can persist in soils for decades to centuries. When applied to soils, biochar stores carbon in a stable form, effectively removing CO_2 from the carbon cycle and contributing to long-term carbon sequestration (Gui et al., 2025). Additionally, by improving soil fertility and promoting plant growth, biochar indirectly enhances carbon capture, as more atmospheric CO_2 is fixed through photosynthesis and converted into plant biomass that can eventually contribute to soil organic carbon pools (Shafawi et al., 2024).

b. **Nitrous Oxide (N_2O) Emission:** N_2O is primarily produced through microbial processes such as nitrification and denitrification, which are influenced by soil moisture, aeration, and nitrogen availability (Álvarez-Gutiérrez et al., 2017). By improving soil structure and porosity, biochar enhances aeration and reduces anaerobic microsites where denitrification occurs, thereby limiting N2O formation. Its high cation exchange capacity (CEC) and nutrient-retention properties also reduce the availability of excess nitrogen in the soil solution, preventing nitrogen loss through microbial conversion to N_2O. Additionally, biochar's surface functional groups can adsorb ammonium (NH^{4+}) and nitrate (NO^{3-}), further stabilizing nitrogen and reducing its volatilization (Álvarez-Gutiérrez et al., 2017; Dong et al., 2019).

c. **Methane Emission:** It is generated by methanogenic archaea, microbes that use organic carbon as an energy source in the absence of oxygen (Nowrouzi et al., 2018). High soil moisture, poor aeration, and abundant labile carbon increase CH4 production, which can contribute significantly to global warming (Salituro et al., 2020). Biochar provides habitat and surface area for methanotrophic bacteria, which oxidize CH_4 to CO_2 before it escapes to the atmosphere. These bacteria thrive on biochar surfaces, increasing the rate of methane consumption (Salituro et al., 2020; Violante et al., 2010; Yuan et al., 2011).

Effects on Crop Performance

The ultimate measure of biochar's success is its effect on crop yield. Numerous meta-analyses show that the largest positive yield responses occur specifically in acidic soils.

Mechanisms of Yield Increase: The increase in crop performance is a combined result of:

- Neutralization of soil acidity (pH increase).
- Reduction of Al and Mn toxicity.
- Enhanced root growth (volume, length, surface area) due to reduced toxicity.
- Improved availability and uptake of essential nutrients, particularly P and Ca.
- Better soil water retention, mitigating drought stress.

Co-Application Strategies: Biochar can be effectively combined with other soil amendments, fertilizers, or microbial inoculants to enhance soil fertility and crop productivity. Co-application with organic fertilizers such as compost, farmyard manure, or vermicompost synergistically improves nutrient availability and retention, as biochar adsorbs nutrients released from organic matter and prevents leaching. Integration with inorganic fertilizers allows more efficient nutrient use; for example, biochar can reduce nitrogen and phosphorus losses, increasing fertilizer use efficiency while lowering environmental impacts. Application along with microbial inoculants, such as nitrogen-fixing bacteria (e.g., Rhizobium, Azotobacter) or mycorrhizal fungi, is another effective strategy. Additionally, biochar combined with liming materials can further ameliorate acidic soils by synergistically raising pH and reducing aluminum toxicity.

Conclusion

Biochar is scientifically confirmed as an effective and sustainable soil amendment for the amelioration of acid soils. Its ability to neutralize pH and simultaneously enhance chemical, physical, and biological soil properties offer a holistic solution superior to traditional liming alone. The positive effects are most pronounced in highly weathered, low-pH soils with high Al toxicity. However, some future studies needed based on the long-term performance can be influenced by soil type, climate, and management practices. In, highly weathered or acidic soils may gradually alter biochar surface chemistry, affecting its cation exchange capacity and nutrient adsorption potential. Interactions with soil microorganisms can also modify biochar's physical and chemical properties over time, sometimes enhancing or slightly diminishing its effectiveness.

Disclosure Statement

The authors reported no potential conflict of interest.

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