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Biochar for Remediation of Acidic Soils: Effects on Soil Chemistry, Structure, and Biological Activity

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

A major barrier that significantly reduces agricultural productivity on some of the world's arable land is soil acidity. Low microbial activity, nutrient deficiencies, and, most importantly the phytotoxicity of manganese (Mn2+) and aluminum (Al3+) are common problems in these soils. For the remediation of acid soils, the use of biochar a carbon-rich substance produced by the pyrolysis of plant biomass has shown promise as a sustainable substitute for conventional liming techniques. Current studies on the various ways that biochar can balance soil acidity and improve soil qualities are summarized in this review. We examine the main chemical, physical, and biological processes that are stimulated by the high porosity and natural alkalinity of biochar. Furthermore, the review explores the scientific knowledge about the production technology, acidity problems, and mechanism of

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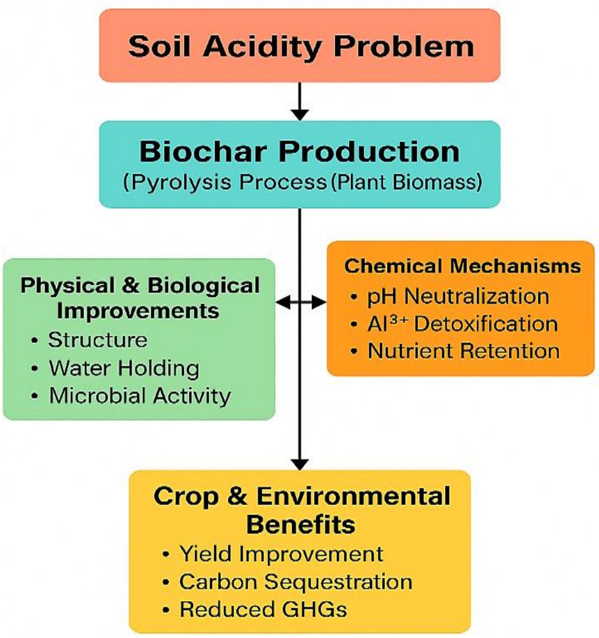
biochar in aspect of physical, chemical and biological in soil. With all the aspects this study also aims to cover the effect of biochar on crop productivity and soil fertility.

Graphical Abstract



Keywords: Acid soil; aluminum toxicity; biochar; pyrolysis; soil amelioration; soil health.

1. 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 (López-Bucio et al., 2000). Moreover, recent global assessments estimate that annual liming requirements exceed 200 million tonnes in acid-prone agricultural regions, highlighting the need for more sustainable and locally accessible alternatives. 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 (Parameshwari Y S et al., 2024). Acidic conditions (typically pH < 5.5) cause the dissolution of aluminum and manganese minerals, producing toxic concentrations of Al^{3+} and Mn^{2+} that hinder root growth and nutrient/water absorption (Wang et al., 2015). (Kabir et al., 2023) indicated that a low pH environment reduces the availability of important macronutrients such as phosphorus (P), calcium (Ca), and magnesium (Mg). 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. In recent decades, biochar, a byproduct of the thermal decomposition of organic matter in limited oxygen condition (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). Recent researches report that biochar application can increase soil pH by 0.3–1.5 units, decrease exchangeable aluminum by 20–60%, and enhance crop yields in acidic soils by 10–25%, depending on feedstock type, pyrolysis conditions, and application rate (Zhang et al., 2013; Maddila Harshith et al.,2023). This review seeks to systematically analyze the mechanisms through which biochar improves acidic soil and describe its effects on various soil quality indicators. Beyond its ameliorative effects, biochar offers practical advantages over lime: it can be produced locally from agricultural residues, lowers input dependence in resource-limited regions, and contributes to climate mitigation through its stable carbon fraction.

1.1 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 these essential properties.

1.1.1 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 (Mn2+) 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 concentrated in the ash content of the biochar during pyrolysis process. During soil application the $CaCO_3$ dissolve and release 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 have the ability to 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 ability to retain basic cations like Ca^{2+}, Mg^{2+}, etc., (Das et al., 2021).

1.2 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.

2. 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.

2.1 Chemical Parameters and Metal Detoxification

The chemical parameters of bio char was depicted in table 1. 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).

2.1.1 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 Al3+, 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).

2.1.2 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

Table 1. Characteristics of various bio char products

Feedstock Type	Pyrolysis Temperature (°C)	pH	EC (dS m⁻¹)	Organic Carbon (%)	Surface Area (m² g⁻¹)	Reference
Peanut shell biochar	400–550	7.8–9.5	1.5–4.0	55–70%	80–200	Xu et al., 2014; Sun et al., 2017
Paddy straw biochar	350–550	8.0–10.0	2.0–5.5	45–65%	50–150	Yuan et al., 2011; Singh et al., 2015
Sawdust (softwood/ hardwood) biochar	450–600	7.0–9.0	0.5–2.0	60–75%	100–300	Novak et al., 2009; Lehmann & Joseph, 2015
Mixed crop-residue biochar	400–550	7.5–9.5	1.0–4.5	50–70%	70–220	Wu et al., 2017; Santos et al., 2021
Wheat straw biochar	350–550	8.5–10.5	2.0–6.5	50–65%	60–180	Ding et al., 2016; Luo et al., 2020

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).

2.2 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).

2.3 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).

3. 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 reduced dependency on chemical fertilizers. Overall, biochar integrates environmental protection with agronomic efficiency, contributing to sustainable agriculture and soil conservation (Zhang et al., 2013). Its impact on soil structure enhances water-holding capacity, with coarse-textured soils showing up to a 45% increase in plant-available water (Omondi et al., 2019). Further some field studies demonstrated that increases in maize productivity and reductions in greenhouse gas emissions when biochar is applied to low-carbon soils (Zhang et al., 2013).

3.1 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 (CO2). In addition, biochar alters soil microbial activity and nutrient cycling, reducing emissions of nitrous oxide (N2O) 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 CO2 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.

b. Nitrous Oxide (N_2O) Emission: N2O 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 (Dai et al., 2017 and 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; Liu et al., 2025). 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).

3.2 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.

a. 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.

4. 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. Future research should therefore focus more precisely on understanding biochar longevity under diverse field conditions, particularly how microbial communities transform or degrade biochar surfaces, the persistence of its liming effect over multi-year cycles, and the mechanisms governing long-term nutrient stabilization and carbon retention. Such insights are essential to optimizing biochar formulations and application strategies for sustained soil health improvement.

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The final structure, critical evaluation, scientific interpretation, and all conclusions were carefully reviewed, validated, and approved by the authors. The responsibility for the content rests entirely with the authors, not with the AI system.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Adamczyk-Szabela, D., & Wolf, W. M. (2022). The impact of soil pH on heavy metals uptake and photosynthesis efficiency in *Melissa officinalis*, *Taraxacum officinalis*, *Ocimum basilicum*. *Molecules, 27*, 4671. https://doi.org/10.3390/molecules27154671

Álvarez-Gutiérrez, N., Gil, M. V., Rubiera, F., & Pevida, C. (2017). Kinetics of CO_2 adsorption on cherry stone-based carbons in CO_2/CH_4 separations. *Chemical Engineering Journal, 307*, 249–257. https://doi.org/10.1016/j.cej.2016.08.077

Chintala, R., Mollinedo, J., Schumacher, T. E., Malo, D. D., & Julson, J. L. (2014). Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science, 60*, 393–404. https://doi.org/10.1080/03650340.2013.789870

Cosgrove, D. J. (1993). Wall extensibility: Its nature, measurement and relationship to plant cell growth. *New Phytologist, 124*, 1–23. https://doi.org/10.1111/j.1469-8137.1993.tb03795.x

Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P. C., & Xu, J. (2017). Potential role of biochars in decreasing soil acidification—a critical review. *Science of the Total Environment, 581*, 601–611. https://www.sciencedirect.com/science/article/pii/S0048969716328583

Das, S. K., Ghosh, G. K., & Avasthe, R. (2021). Applications of biomass derived biochar in modern science and technology. *Environmental Technology & Innovation, 21*, 101306. https://doi.org/10.1016/j.eti.2020.101306

Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, Y., & Zheng, B. (2016). Biochar to improve soil fertility: A review. *Agronomy for Sustainable Development, 36*, 36. https://doi.org/10.1007/s13593-016-0372-z

Dong, Y., Wu, Z., Zhang, X., Feng, L., & Xiong, Z. (2019). Dynamic responses of ammonia volatilization to different rates of fresh and field-aged biochar in a rice–wheat rotation system. *Field Crops Research, 241*, 107568. https://doi.org/10.1016/j.fcr.2019.107568

Elmer, W. H., & Pignatello, J. J. (2011). Effect of biochar amendments on mycorrhizal associations and Fusarium crown and root rot of asparagus in replant soils. *Plant Disease, 95*, 960–966. https://doi.org/10.1094/PDIS-10-10-0741

Enders, A., & Lehmann, J. (2012). Comparison of wet-digestion and dry-ashing methods for total elemental analysis of biochar. *Communications in Soil Science and Plant Analysis, 43*, 1042–1052. https://doi.org/10.1080/00103624.2012.656167

García, R., Gil, M. V., Fanjul, A., González, A., Majada, J., Rubiera, F., & Pevida, C. (2021). Residual pyrolysis biochar as additive to enhance wood pellets quality. *Renewable Energy, 180*, 850–858. https://doi.org/10.1016/j.renene.2021.08.113

Gomez-Eyles, J. L., Sizmur, T., Collins, C. D., & Hodson, M. E. (2011). Effects of biochar and the earthworm *Eisenia fetida* on the bioavailability of polycyclic aromatic hydrocarbons and potentially toxic elements. *Environmental Pollution, 159*, 616–622. https://doi.org/10.1016/j.envpol.2010.09.037

Gui, X., Xu, X., Zhang, Z., Hu, L., Huang, W., Zhao, L., & Cao, X. (2025). Biochar-amended soil can further sorb atmospheric CO_2 for more carbon sequestration. *Communications Earth & Environment, 6*, 5. https://doi.org/10.1038/s43247-024-01985-5

He, X., Yang, Y., Huang, B., & Wang, Z., Wang, M. (2024). An overview of characteristic factors of biochar as a soil improvement tool in rice growth—A review. *Environmental Research, 242*, 117794. https://doi.org/10.1016/j.envres.2023.117794

Ighalo, J. O., Ohoro, C. R., Ojukwu, V. E., Oniye, M., Shaikh, W. A., Biswas, J. K., Seth, C. S., Mohan, G. B. M., Chandran, S. A., & Rangabhashiyam, S. (2025). Biochar for ameliorating soil fertility and microbial diversity: From production to action of the black gold. *iScience, 28*, 111524. https://doi.org/10.1016/j.isci.2024.111524

Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: A comprehensive meta-data analysis review. *Biochar, 2*, 421–438.

https://doi.org/10.1007/s42773-020-00067-x

Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., Kuzyakov, Y., Luo, Y., Ok, Y. S., Palansooriya, K. N., Shepherd, J., Stephens, S., Weng, Z. (Han), & Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy, 13*, 1731–1764. https://doi.org/10.1111/gcbb.12885

Kabir, E., Kim, K.-H., & Kwon, E. E. (2023). Biochar as a tool for the improvement of soil and environment. *Frontiers in Environmental Science, 11*. https://doi.org/10.3389/fenvs.2023.1324533

Khan, Anwarzeb, Khan, S., Lei, M., Alam, M., Khan, M. A., & Khan, Ajmal. (2020). Biochar characteristics, applications and importance in health risk reduction through metal immobilization. *Environmental Technology & Innovation, 20*, 101121. https://doi.org/10.1016/j.eti.2020.101121

Klasson, K. T. (2017). Biochar characterization and a method for estimating biochar quality from proximate analysis results. *Biomass and Bioenergy, 96*, 50–56. https://doi.org/10.1016/j.biombioe.2016.10.011

Kocsis, T., Ringer, M., & Biró, B. (2022). Characteristics and applications of biochar in soil–plant systems: A short review of benefits and potential drawbacks. *Applied Sciences, 12*, 4051. https://doi.org/10.3390/app12084051

Kopittke, P. M., Moore, K. L., Lombi, E., Gianoncelli, A., Ferguson, B. J., Blamey, F. P. C., Menzies, N. W., Nicholson, T. M., McKenna, B. A., Wang, P., Gresshoff, P. M., Kourousias, G., Webb, R. I., Green, K., & Tollenaere, A. (2015). Identification of the primary lesion of toxic aluminum in plant roots. *Plant Physiology, 167*, 1402–1411. https://doi.org/10.1104/pp.114.253229

Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for environmental management: Science, technology and implementation* (2nd ed.). Earthscan.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry, 43*, 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Li, Y., Gupta, R., Zhang, Q., & You, S. (2023). Review of biochar production via crop residue pyrolysis: Development and perspectives. *Bioresource Technology, 369*, 128423. https://doi.org/10.1016/j.biortech.2022.128423

Lin, Q., Zhang, L., Riaz, M., Zhang, M., Xia, H., Lv, B., & Jiang, C. (2018). Assessing the potential of biochar and aged biochar to alleviate aluminum toxicity in an acid soil for achieving cabbage productivity. *Ecotoxicology and Environmental Safety, 161*, 290–295. https://doi.org/10.1016/j.ecoenv.2018.06.010

Liu, S., Cen, B., Yu, Z., Qiu, R., Gao, T., & Long, X. (2025). The key role of biochar in amending acidic soil: reducing soil acidity and improving soil acid buffering capacity. *Biochar, 7*(1), 52. https://link.springer.com/article/10.1007/s42773-025-00432-8

López-Bucio, J., Guevara-García, A., Ramírez-Rodríguez, V., Nieto, M. F., de la Fuente, J. M., & Herrera-Estrella, L. (2000). Agriculture for marginal lands: transgenic plants towards the third millennium. *Developments in plant genetics and breeding*, *5*, 159-165. https://doi.org/10.1016/S0168-7972(00)80025-0

Luo, Y., Durenkamp, M., De Nobili, M., Lin, Q., & Brookes, P. C. (2020). Short-term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. *Soil Biology and Biochemistry, 43*, 230–236. https://doi.org/10.1016/j.soilbio.2010.10.005

Maddila Harshith, Sahu, A., Indrakanti, S., Reddy, R. K., & Bhutada, S. (2023). Optimizing crop yields through machine learning-based prediction. *Journal of Scientific Research and Reports, 29*(4), 27–33. https://doi.org/10.9734/jsrr/2023/v29i41741

Nepal, J., Ahmad, W., Munsif, F., Khan, A., & Zou, Z. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science, 11.* https://doi.org/10.3389/fenvs.2023.1114752

Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., & Niandou, M. A. S. (2009). Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil Science, 174*, 105–112. https://doi.org/10.1097/SS.0b013e3181981d9a

Nowrouzi, M., Younesi, H., & Bahramifar, N. (2018). Superior CO_2 capture performance on biomass-derived carbon/metal oxides nanocomposites from Persian ironwood by H_3PO_4 activation. *Fuel, 223*, 99–114. https://doi.org/10.1016/j.fuel.2018.03.035

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2019). Quantifying biochar effects on soil structure and water retention across soil textures: A meta-analysis. *Geoderma, 343*, 32–41. https://doi.org/10.1016/j.geoderma.2019.01.006

Parameshwari, Y. S., Narendar, G., Krishna Chaitanya, A., & Chandrasekhar, K. (2024). Understanding of organic fertilizers in Indian context: A review. *Journal of Advances in Biology & Biotechnology, 27*(11), 1573–1583. https://doi.org/10.9734/jabb/2024/v27i111744

Salituro, A., Westwood, A., Ross, A., & Brydson, R. (2020). Sustainable and regenerable alkali metal-containing carbons derived from seaweed for CO_2 post-combustion capture. *Sustainable Chemistry, 1*, 33–48. https://doi.org/10.3390/suschem1010003

Santos, F., Tornquist, C. G., Briedis, C., Caner, L., & Knicker, H. (2021). Biochar from different field residues: effects on soil chemical and physical properties. *Archives of Agronomy and Soil Science, 67*, 186–200. https://doi.org/10.1080/03650340.2019.1707184

Shetty, R., & Prakash, N. B. (2020). Effect of different biochars on acid soil and growth parameters of rice plants under aluminium toxicity. *Scientific Reports, 10*, 12249. https://doi.org/10.1038/s41598-020-69262-x

Shetty, R., Vidya, C. S.-N., Prakash, N. B., Lux, A., & Vaculík, M. (2021). Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review. *Science of the Total Environment, 765*, 142744. https://doi.org/10.1016/j.scitotenv.2020.142744

Singh, B., Singh, B. P., & Cowie, A. L. (2015). Characterisation and evaluation of biochars for their application as a soil amendment. *Australian Journal of Soil Research, 48*, 516–525. https://doi.org/10.1071/SR10058

Sun, H., Lu, H., Chu, L., Shao, H., & Shi, W. (2017). Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH_3 volatilization in a coastal saline soil. *Science of the Total Environment, 575*, 820–825. https://doi.org/10.1016/j.scitotenv.2016.09.137

Suresh Babu, K. K. B., Nataraj, M., Tayappa, M., Vyas, Y., Mishra, R. K., & Acharya, B. (2024). Production of biochar from waste biomass using slow pyrolysis: Studies of the effect of pyrolysis temperature and holding time on biochar yield and properties. *Materials Science for Energy Technologies, 7*, 318–334. https://doi.org/10.1016/j.mset.2024.05.002

Ur Rahman, S., Han, J.-C., Ahmad, M., Ashraf, M. N., Khaliq, M. A., Yousaf, M., Wang, Y., Yasin, G., Nawaz, M. F., Khan, K. A., & Du, Z. (2024). Aluminum phytotoxicity in acidic environments: A comprehensive review of plant tolerance and adaptation strategies. *Ecotoxicology and Environmental Safety, 269*, 115791. https://doi.org/10.1016/j.ecoenv.2023.115791

Violante, A., Cozzolino, V., Perelomov, L., Caporale, A. G., & Pigna, M. (2010). Mobility and bioavailability of heavy metals and metalloids in soil environments. *Journal of Soil Science and Plant Nutrition, 10*, 268–292. https://doi.org/10.4067/S0718-95162010000100005

Wang, W., Zhao, X. Q., Hu, Z. M., Shao, J. F., Che, J., Chen, R. F., Dong, X. Y., & Shen, R. F. (2015). Aluminium alleviates manganese toxicity to rice by decreasing root symplastic Mn uptake and reducing availability to shoots of Mn stored in roots. *Annals of Botany, 116*, 237–246. https://doi.org/10.1093/aob/mcv090

Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil – concepts and mechanisms. *Plant and Soil, 300*, 9–20. https://doi.org/10.1007/s11104-007-9391-5

Wu, W., Yang, M., Feng, Q., McGrouther, K., Wang, H., Lu, H., & Chen, Y. (2017). Chemical characterization of rice straw-derived biochar for soil amendment.

Biomass and Bioenergy, 94, 40–50. https://doi.org/10.1016/j.biombioe.2016.08.012

Xu, G., Sun, J., Shao, H., & Chang, S. X. (2014). Biochar had effects on nutrient retention and leaching in three soils with differing acidity. *Ecological Engineering, 62*, 54–62. https://doi.org/10.1016/j.ecoleng.2013.10.027

Yan, B., Zhang, Y., Wang, Y., Rong, X., Peng, J., Fei, J., & Luo, G. (2023). Biochar amendments combined with organic fertilizer improve maize productivity and mitigate nutrient loss by regulating the C–N–P stoichiometry of soil, microbiome, and enzymes. *Chemosphere, 324*, 138293. https://doi.org/10.1016/j.chemosphere.2023.138293

Yang, Z., Zhang, Y., Wang, Y., Zhang, H., Zhu, Q., Yan, B., Fei, J., Xiangmin, R., Peng, J., & Luo, G. (2022). Intercropping regulation of soil phosphorus composition and microbially-driven dynamics facilitates maize phosphorus uptake and productivity improvement. *Field Crops Research, 287*, 108666. https://doi.org/10.1016/j.fcr.2022.108666

Yuan, J. H., Xu, R. K., & Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource Technology, 102*, 3488–3498. https://doi.org/10.1016/j.biortech.2010.11.018

Zhang, A., Liu, Y., Pan, G., Hussain, Q., Li, L., Zheng, J., & Zhang, X. (2013). Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon–poor calcareous loamy soil. *Soil Biology and Biochemistry, 65*, 68–75. https://doi.org/10.1016/j.soilbio.2013.05.005

Zhang, K., Sui, Y., Gao, J., Zhang, Z., Chen, L., Tang, S., Wan, X., Jiang, H., Zhao, Y., & Zhang, W. (2025). Different roles of biochar in mitigating greenhouse gas emissions from paddy fields in northern and southern China. *Crop Environment, 4*, 203–215. https://doi.org/10.1016/j.crope.2025.04.003

Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., Bolan, N. S., Pei, J., & Huang, H. (2013). Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environmental Science and Pollution Research, 20*, 8472–8483. https://doi.org/10.1007/s11356-013-1659-0

Zubairu, A. M., Michéli, E., Ocansey, C. M., Boros, N., Rétháti, G., Lehoczky, É., & Gulyás, M. (2023). Biochar improves soil fertility and crop performance: A case study of Nigeria. *Soil Systems, 7*, 105. https://doi.org/10.3390/soilsystems7040105

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