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Biochar in Sustainable Agriculture: From Soil Amendment to Climate Mitigation

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SUMMARY

Sustainable agriculture faces two main challenges: feeding a growing global population and addressing climate change while restoring damaged farming ecosystems. Biochar is a carbon-rich, porous solid created by pyrolyzing organic biomass in a low-oxygen environment. It has become an important soil amendment and negative-emission technology. This article reviews current research on biochar, looking at its physical and chemical properties, environmental impacts, agricultural benefits, and potential for climate change mitigation. Using biochar improves soil structure, increases water retention, raises cation exchange capacity (CEC), neutralizes acidity, and decreases nutrient loss. It also boosts crop yields, especially in acidic and nutrient-poor tropical soils, and supports beneficial soil microbes. In terms of climate, biochar serves as a long-lasting carbon storage solution, lasting from hundreds to thousands of years. At the same time, it helps reduce soil emissions of nitrous oxide (N2O) and methane (CH4). However, for biochar to be widely used, challenges like feedstock variety, production costs, high application levels, and potential toxicity from heavy metals or polycyclic aromatic hydrocarbons (PAHs) must be addressed. Looking ahead, there is potential for engineered biochars, tailored mixtures for specific sites, and integration into carbon credit systems to make biochar a key part of strong global agricultural practices.

INTRODUCTION

Agriculture today is under immense pressure from ecology. Excessive dependence on artificial mineral fertilizers, heavy tillage, soil degradation, and changes in the water cycle due to climate change have endangered the food security of the future (Gyawali, 2024; Mohanty *et al.*, 2025). Loss of SOM has affected the performance of the fundamental ecosystem processes through soil structure, biodiversity, and nutrient sequestration (Tayo, 2025). Moreover, agriculture contributes significantly to the GHGs emissions on a global scale, especially CO_2, N_2O, and CH_4. For solving these two interrelated problems, sustainable agriculture should implement nature-based solutions, which could stabilize crop production and sequester carbon at the same time (Woolf *et al.*, 2010). In this regard, much research interest has been directed towards biochar. Drawing lessons from Terra Preta de Indio, the fertile dark earth produced by pre-Columbian indigenous peoples of the Amazon basin through their ancient process of biomass burning, modern biochar is regarded as a carbon-rich, charcoal-like, stable solid material that has been produced through thermal transformation of biomass (such as agricultural residues, wood wastes, animal dung or sewage sludge) through the process of pyrolysis at temperatures between 300–800°C under an anaerobic environment (Gyawali, 2024; Lehmann *et al.*, 2006). Unlike the raw biomass, which rapidly decomposes and results in the escape of stored carbon back to the atmosphere as CO_2 within weeks or years, biochar is characterized by the high stability of its aromatic carbon structure, making it resistant to biological and chemical degradation for hundreds to thousands of years (Hoque, 2025; Woolf *et al.*, 2010). This article presents a holistic understanding of biochar in sustainable agriculture as the evolution of the use of biochar from an indigenous soil additive to an essential climate change mitigation tool.

Thermochemical Production and Physicochemical Properties

Properties such as agronomic effectiveness and environmental performance of biochar depend on the feedstock used for producing biochar and the thermochemical treatment conditions that include pyrolysis temperature, heating rate, and residence time (Gyawali, 2024; Hoque, 2025). Biochars produced at high temperatures (>600°C) show larger specific surface area, aromaticity, electrical conductivity, and microporous structure while having low yields and low surface functional group density. On the contrary, biochars generated at low temperatures (<450°C) preserve oxygen-rich functional groups like carboxyl, hydroxyl, and carbonyl groups with greater CEC and higher mass yield (Hoque, 2025; Tayo, 2025).

Core Physicochemical Attributes of Biochar

High Specific Surface Area & Porosity: Provides micro-, meso-, and macroporous networks that retain moisture and harbor beneficial microorganisms.

Aromatic Carbon Structure: Condensed fused-ring polycyclic aromatic hydrocarbons confer extreme biochemical recalcitrance against microbial oxidation.
Surface Functional Groups: Phenolic, carboxylic, and hydroxylic groups provide abundant active exchange sites for mineral nutrient retention.
Alkaline Ash Content: Rich in carbonates, silicates, and oxides of Ca, Mg, K, and Na, providing liming effects for acidic soils.

Effects of Biochar Application

Soil Physical Properties

Inclusion of biochar changes the physical structure of soil. Due to the high porosity and low bulk density nature of biochar, addition of biochar results in reduced bulk density of the soil as well as increased porosity and soil aggregate stability (Gyawali, 2024; Tayo, 2025). In the case of coarse textured sandy soil, inclusion of biochar greatly enhances plant available water capacity and water holding capacity through creation of capillary pores, hence reducing drought susceptibility (Ayaz *et al.*, 2021; Hoque, 2025).

Soil Chemical Properties and Nutrient Dynamics

Biochar serves as a long-term soil amender as well as nutrient storage (Engineered Science, 2025). Biochar increases acidic soil pH via its liming property, which in turn decreases toxicity caused by aluminum (Al^{3+}) and manganese ($Mn^{2+)}$ ions, which inhibit root growth (Gyawali, 2024; Lu *et al.*, 2024). Moreover, due to high surface charge and CEC, biochar prevents nutrient leaching, which include nitrate (NO_3^-), ammonium (NH_4^+), and phosphate (PO_4^{3-}) ions and increases the FUE while avoiding eutrophication in the nearby water bodies (Mohanty *et al.*, 2025; Tayo, 2025).

Effects on Soil Biological Activity and Microbial Community

The presence of biochar in soils helps create an enabling environment ("biochar-sphere") for soil biology. The microporous nature of biochar provides a physical haven that protects the soil bacteria, AMF, and PGPR from being dried out or being preyed upon by soil protozoans (Gyawali, 2024; Hoque, 2025). In addition, biochar regulates the activity of soil enzymes (urease, phosphatase, and dehydrogenase), enhancing nutrient cycling and mineralization (Engineered Science, 2025).

Effects on Crop Yield and Agricultural Productivity

According to the meta-analysis carried out by researchers, the use of biochar leads to increased yields for crops, where the yield increase varies between 10 and 25% based on crop species, soil type, and climatic condition (Gyawali, 2024; Hoque, 2025; Tayo, 2025). The highest impact of biochar use is seen in highly weathered and low-nutrient content acidic soils found in the tropics (e.g., Ferralsols and Acrisols). In rich soils of temperate regions, yield increase is negligible, but there are stress tolerance effects (Ayaz *et al.*, 2021).

Table 1. Key Agronomic Domains, Biochar Mechanisms, and Expected Impacts Across Agroecosystems

Agricultural Domain	Primary Biochar Mechanism	Observed Outcome / Impact	Key Citations
Soil Hydrology	Micro- and mesopore creation; capillary water retention	+15% to +35% Water Holding Capacity in coarse soils	(Zulfiqar *et al.*, 2022)
Nutrient Management	High cation exchange capacity (CEC) & functional group surface adsorption	20–50% reduction in NO_3^- leaching; increased FUE	(Ali, 2025)
Soil Acidity	Ash alkalinity ($CaCO_3$ equivalence) & basic cation exchange	Elevates pH by 0.5–1.8 units; reduces toxic Al^3+	(Lu *et al.*, 2014)
Crop Yield	Enhanced root proliferation, improved water and nutrient uptake	10–25% overall yield gain (higher in degraded tropical soils)	(Zulfiqar *et al.*, 2022)
Climate Mitigation	Aromatic carbon stabilization & soil N_2O suppression	Centennial carbon storage; 20–70% lower N_2O emissions	(Woolf *et al.*, 2010)

Importance in Climate Mitigation and Environmental Sustainability

Long-Term Carbon Sequestration

Biochar is undoubtedly one of the most promising Nature-based Solutions (NbS) and Negative Emission Technologies (NETs) for mitigating climate change effects (Woolf *et al.*, 2010). Carbon dioxide in the air is fixed during photosynthesis and enters plant biomass. However, the natural decay of this biomass will release CO_2 back into the atmosphere. The pyrolysis process allows 50% of organic carbon contained in the biomass to be converted into recalcitrant aromatic carbon substances which cannot be oxidized by enzymes (Lehmann *et al.*, 2006). Biochar incorporation into the soil creates a terrestrial sink from atmospheric CO_2 and provides carbon sequestration for many centuries (Gyawali, 2024). It is believed that sustainable biochar systems can mitigate 1.8 Pg CO_2 per year, which corresponds to 12% of global anthropogenic emissions annually (Woolf *et al.*, 2010).

Reduction of Non- CO_2 Greenhouse Gas Emissions

In addition to direct carbon storage, biochar application significantly suppresses direct emissions of nitrous oxide (N_2O)—a potent greenhouse gas with a global warming potential ~273 times greater than CO_2 over a 100-year horizon (Engineered Science, 2025; Woolf *et al.*, 2010). Biochar decreases N_2O flux through multiple mechanisms: enhancing soil aeration (inhibiting anaerobic denitrification), adsorbing NO_3^- and NH_4^+ substrates, and promoting complete denitrification to harmless N_2 gas by shifting soil microbial gene expression (nosZ gene abundance) (Engineered Science, 2025). Furthermore, in flooded paddy soils, aerated biochar amendment can suppress methanogenesis, lowering CH_4 flux.

Soil Remediation and Heavy Metal Immobilization

Biochar exhibits strong sorption capacities for organic contaminants (pesticides, herbicides) and heavy metals (such as Cd, Pb, Cu, As, and Zn) (Hoque, 2025; Lu *et al.*, 2024). Through mechanisms including electrostatic attraction, surface complexation, ion exchange, and precipitation, biochar immobilizes bioavailable heavy metals in contaminated soils, preventing plant uptake and bioaccumulation in the human food chain (Hoque, 2025).

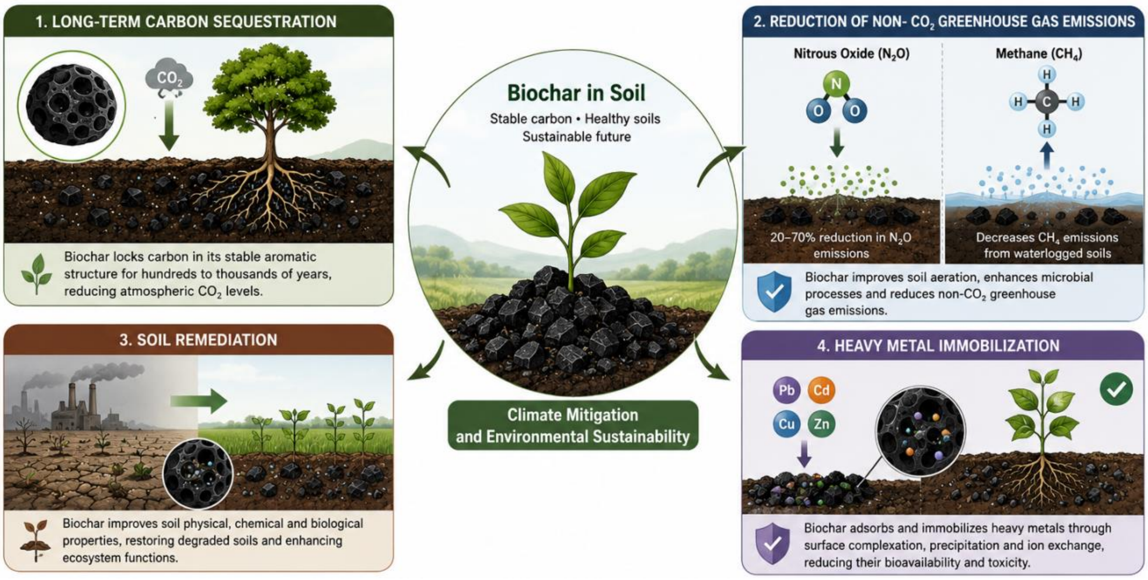

Fig. 1: A graphical abstract on Biochar and its importance in climate mitigation and environmental sustainability.

Challenges and Constraints

While the benefits of biochar in promoting sustainable agricultural practices are undeniable, there exist numerous technical and logistical obstacles that have been identified and which are currently hindering the widespread use of this technology in agricultural practice. First of all, it should be noted that the high capital cost of biochar production and delivery limits the practical application of this soil improver in the field without government subsidies or carbon credits. Besides, the high application rates of biochar, which range from 5 to 20 tons per hectare depending on the situation and the soil type, are another obstacle to the effective implementation of biochar in agriculture due to significant logistics involved in such high amounts of material being applied to the ground. High variability in the sources of feedstock used (for example, crop residues, municipal waste, or manure), as well as pyrolysis conditions, results in the inconsistency of the quality of the produced biochar. Moreover, there is the risk of ecotoxicological consequences when applying poor-quality biochar made of contaminated biomass since the presence of harmful substances such as heavy metals or dioxins might be expected.

Future Prospects and Research Directions

In order to develop biochar from an innovative soil additive to a tool that can help climate smart farming, the future work needs to emphasize more on technology, monitoring, and policy. There is still a need for research on the engineering of designer biochars like nano-biochars, biochar-compost combinations, or mineral-containing compounds in order to overcome specific deficiencies in soil, crops, and contaminants. Long-term experiments lasting several decades over different agroecological zones are required to determine the extent of structural decomposition, biological aging, and actual century-long stabilization of the carbon in soil systems. In addition, a strict and internationally recognized certification program (like the International Biochar Initiative or European Biochar Certificate) will become important to ensure product safety and quality. Including the carbon removal by biochar into the compliance and voluntary carbon market will become a needed financial mechanism to compensate the costs of its production in order to make the biochar economic for the farmers and part of NDCs for the countries.

CONCLUSION

The technology of biochar is a unique and multifunctional link between the concepts of sustainable agricultural intensification and global climate change mitigation. Using the process of transformation of volatile organic matter to a stable porous structure of carbon, biochar contributes to soil health improvement, agricultural yields growth, water and nutrients efficiency enhancement, pollutant immobilization, and carbon sequestration for hundreds of years. Though there are still some concerns regarding high production expenses, standardization issues, and ecotoxicology safety of biochar, its technological improvement and participation in carbon market make it an essential part of nature-based solutions.

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