

REVIEW ARTICLE

Impacts of Biomass-Derived Biochar on Plant Nutrition, Soil Function, and Agricultural Sustainability: A Review

Kirthana Ramesh¹ | Yuvaraj Dinakarkumar² | Koteswara Reddy Gujjula³ | Lakshmi Sowjanya Kotaru³ | Parthiban Brindha Devi¹ | Vivek Pazhamalai¹ | Sagayaraj Ivo Romauld¹

¹Department of Bioengineering, School of Engineering, Vels Institute of Science Technology and Advanced Studies (VISTAS), Pallavaram, Tamil Nadu, India |

²Department of Biotechnology, School of Life Sciences, Vels Institute of Science Technology and Advanced Studies (VISTAS), Pallavaram, Tamil Nadu, India |

³Department of Biotechnology, Koneru Lakshmaiah Education Foundation (Deemed to be University), Vaddeswram, Green Fields, Andhra Pradesh, India

Correspondence: Yuvaraj Dinakarkumar (yuvarajdinakarkumar@gmail.com) | Sagayaraj Ivo Romauld (ivoromauld@gmail.com)

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ABSTRACT

Biochar, a carbon-rich material derived from the pyrolysis of organic biomass, has emerged as a promising biotechnological solution for enhancing sustainable agricultural practices. This paper reviews the role of biochar in manure management, with a focus on its physicochemical properties and their implications for nutrient recycling and environmental impact mitigation. Biochar's large surface area and porous structure enable effective adsorption and retention of nutrients and contaminants, thereby reducing nutrient losses and enhancing nutrient availability for crops. Moreover, its integration into manure systems has shown potential in mitigating ammonia volatilization, reducing odor emissions, and inhibiting pathogenic activity, addressing key challenges in livestock waste management. The review explores biochar's interaction with microbial communities in manure, its influence on nutrient cycling, and its contribution to greenhouse gas reduction and soil health improvement. Challenges and opportunities in optimizing biochar-based biotechnological applications are also discussed, highlighting the need for advanced research and innovation to integrate biochar into sustainable agricultural systems effectively. This paper aligns with the journal's focus on novel biocatalytic and biotechnological approaches to address pressing agricultural and environmental issues.

1 | Introduction

The agricultural industry is facing an increasing difficulty in managing the environmental consequences of intensive livestock farming, particularly manure disposal and related challenges, such as the discharge of nutrients and emissions of greenhouse gases. Due to anthropogenic environmental degradation, agricultural nutrients in the soil are being depleted. The lack of microorganisms in the soil is the main reason for infertility in soil. The development of plants is significantly influenced by microbes. Biochar is used to enhance the diversity of bacteria in soil. When biomass undergoes heating in a restricted in a

vessel with minimal or no oxygen, a carbon-dense material called biochar is produced (Basanti et al. 2024). Besides improving soil fertility and sturdiness against drought and flooding, biochar also helps agriculture by detoxifying the soil of heavy metals and other impurities. By incorporating biochar into 10% of the world's crops, the equivalent of 29 billion tons of CO₂ may be stored. The capacity of soil to perform multiple agronomic and environmental tasks is referred to as soil health. These functions depend critically on agronomic/biomass output, sensitivity to practices and resources, as well as resilience against biotic and abiotic stressors (Solaiman and Anawar 2015). To trap organic matter while increasing land quality, nutrient richness, and crop

productivity, biochar is being added to the soil (Lal 2011). According to several studies soils containing biochar should last longer and hold cations more effectively than soil containing other types of organic matter (Chan and Xu 2012). While several reviews have examined the applications of biochar in agriculture and environmental management, this work advances the field by integrating recent evidence on emerging and interdisciplinary uses. In particular, we highlight novel perspectives such as biochar's role in microplastic remediation, biomedical applications, and sustainable construction materials, alongside its integration into carbon credit frameworks as a negative-emission technology. The review provides a practical decision framework that links biochar characteristics, production parameters, and application contexts, which is largely absent in earlier literature. These contributions distinguish the present work from previous reviews and underscore its relevance for advancing both fundamental understanding and real-world implementation.

Biochar, due to its porous structure, high surface area, and functional groups, can act as an efficient environmental amendment by improving soil fertility, enhancing microbial activity, sequestering stable carbon, and removing a wide range of pollutants from water and soil systems. We hypothesize that tailored applications of biochar, including engineered forms, will extend its role beyond conventional agricultural uses to novel environmental and interdisciplinary applications. This revision ensures the hypothesis is directly linked to the objectives and evidence presented in the review

1.1 | Manure: A Key to Fertile Soil

Biological soil amendments (BSAs), such as fertilizers like dung, organic matter blends, and compost teas (CTs), are essential in both traditional and organic farming systems. These additives improve soil richness and support increased crop production. However, the past decade has seen an increase in bacterial, viral, and parasitic contaminations connected to fresh produce, bringing attention to the agricultural inputs used in fruit and vegetable production. Studies have shown that repeated applications of compost improve soil microbial diversity and microbial biomass carbon (Glaser et al. 2002).

While BSAs provide significant benefits, manure has been identified as a potential source of enteric pathogens, posing risks of microbial contamination during fruit and vegetable cultivation. Manure application can enhance crop growth and quality (Agegnehu et al. 2017). Various types of manure, including green manure, farmyard manure, and composted manure, differ in their microbial populations and nutrient profiles. In many agricultural regions, the overuse of synthetic fertilizers pesticides, and insecticides has led to the depletion of soil microbial communities and essential nutrients. Manure applications are therefore crucial for restoring land productivity and maintaining land quality (Eldridge et al. 2014).

“Applying manure to the soil surface can raise the chance of phosphorus being lost through runoff.”

Applying manure to the soil surface can raise the chance of phosphorus being lost through runoff. However, manure appli-

cations often improve soil aggregate stability, which helps to reduce runoff and erosion, thereby decreasing the likelihood of phosphorus transport. To examine the impacts of untreated and processed feedlot manure, as well as the effects of continuous annual manure applications and the long-term advantages of composted manure used 5–7 years prior, conducted three field studies in Nebraska (Wortmann and Shapiro 2008). These studies focused on silt loam and silty clay loam soils, analyzing water-stable soil aggregation within the top 0–25 mm of soil. The results revealed that within 15 days of application, both manure and compost increased the presence of large macro-aggregates (>2 mm) by over 200%. These improvements were sustained for 7 months, with compost showing more pronounced and longer-lasting effects (Wortmann and Shapiro 2008).

A 37-year study investigated the impacts of various fertilizer applications practices on soil quality and bacterial community-level physiological profiles (CLPP) in a jute-rice-wheat cropping system. The experiment included several treatments: 100% of the recommended dose (RD) of NPK (Nitrogen, Phosphorus, and Potassium), 150% RD of NPK, 100% RD of nitrogen alone, 100% RD of NPK combined with 10 t/ha per year of farmyard manure (FYM), and an untreated control. Applying 150% RD of NPK significantly reduced soil pH, whereas the other treatments maintained it at nearly neutral levels. The combination of 100% RD of NPK with FYM led to the highest levels of microbial biomass carbon, organic carbon, total nitrogen, basal soil respiration, and fluorescein diacetate hydrolyzing activity. The addition of organic amendments notably enhanced microbial biomass carbon and activity; however, the combined application of organic and synthetic nutrients had a limited effect on the substrate utilization patterns of soil microbes (Chakraborty et al. 2011).

1.2 | Challenges Associated With Manure Preparation

Manures from livestock and fowl naturally harbor diverse bacteria, viruses, and protozoa. Many of these have a reputation for harming people. Some forms of *Escherichia coli*, *Salmonella*, *Listeria*, *Streptococcus*, and *Campylobacter* are among the bacteria that are known to be harmful to humans (Steiner et al. 2010). Manure contamination can cause nitrate levels in underground water to increase, and bacteria can contaminate the surface waters, causing fish deaths. Erosion or runoff from fields might keep extra phosphorus in surface water impoundments like ponds and lakes. Not all manure is beneficial to plants. Manure has a lot of bedding that absorbs nitrogen from the soil as it decomposes. This reduces the accessibility of nitrogen for plant uptake (Hammerschmiedt et al. 2022; Srinivasan et al. 2015). There are four disadvantages of manure:

- Normal Manure takes more time to production than Pleurotus manure.
- Normal manure depletes soil fertility by affecting soil bacteria.
- Normal manure only offers temporary advantages.
- Normal manure alters the soil's pH balance by turning it too acidic or too alkaline.

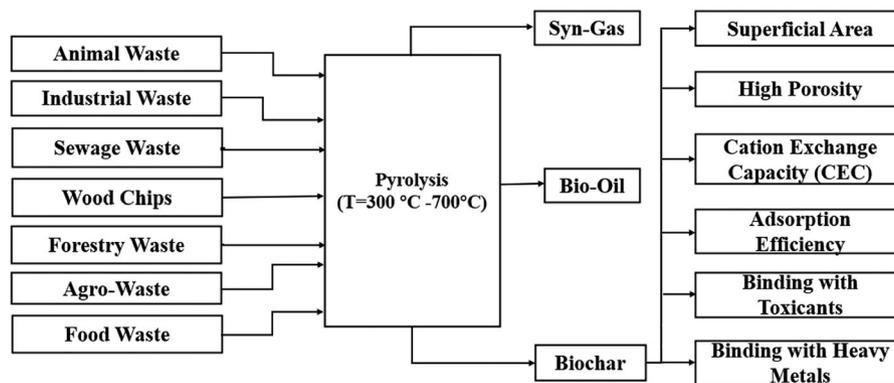


EXHIBIT 1 | Biomass-to-biochar production via pyrolysis: process overview and key characteristics (Sakhiya et al. 2020; Premchand et al. 2023; Rajput et al. 2024).

2 | Diverse Biomass to Biochar

2.1 | Biomass to Biochar Production

Research has shown that incorporating biochar into soil modifies its physicochemical characteristics while influencing the structure and function of microbial populations, ultimately enhancing soil fertility (Lehmann and Joseph 2015). Biochar is particularly advantageous for soils with poor physical properties, such as sandy soils, as it improves moisture retention and can enhance water accessibility for plants (Basso et al. 2013). Understanding the specific functions and impacts of biochar can help in selecting the most suitable types for different agricultural applications, maximizing its effectiveness as a soil amendment. Studies show that biochar improves soil integrity, particle cohesion, moisture regulation, permeability, and surface coverage (Sohi et al. 2010).

Biochar's characteristics are controlled by the feedstock used in its synthesis, and some different kinds may pose threats to soil health (Kookana et al. 2011). For example, research analyzing biochar generated from sewage sludge to unpyrolyzed sewage sludge discovered that these supplements had different effects on soil biochemical activity. Higher biochar application rates were associated with increased scaling factors for enzyme activities, whereas un-pyrolyzed sewage sludge inhibited enzyme activity. This indicates that pyrolyzed organic materials may improve soil biological activities, however the results differ based on soil type and enzyme specificity (Bailey et al. 2011; Paz-Ferreiro et al. 2012). Biochar is commonly generated via a pyrolysis method. Diverse of Biomass was used to produce the main product as biochar along with byproducts as bio-oil and gas using slow pyrolysis process (Premchand et al. 2023).

Biochar has a substantial impact on land vitality and condition through chemical and structural modifications. A study investigated at how combining bacterial culture and biochar during pig manure composting affected heavy metal (HM) stability and biological processes (Awasthi et al. 2020). Six different treatments were evaluated: T2 contained only bacterial culture, T3 and T5 incorporated 12% wood biochar (WB) and wheat-straw biochar (WSB), respectively, while T4 and T6 combined bacterial cultures with 12% WB and WSB. T1 functioned as the control. The researchers discovered that combining bacterial culture with biochar improved HM immobilization (Cu and Zn) through

better adsorption, promoted bacterial activity for decomposition, and raised the security and standard of the produced compost (Awasthi et al. 2020).

Recent studies have reported the use of various types of biomass waste such as animal waste, industrial waste, sewage waste, wood chips, forestry waste, agro-waste, and food waste to produce biochar through a slow pyrolysis process. The pyrolysis process was carried out under optimized conditions at temperatures ranging from 300°C to 900°C. This process is illustrated in **Exhibit 1** and further explained with a detailed sketch in **Exhibit 2**.

2.2 | Effects of Biochar on Soil Properties

Incorporating biochar into compost has been demonstrated to improve humification, reduce greenhouse gas emissions, enhance bacterial ecology and activity, and immobilize organic pollutants and potentially poisonous metals (PTMs) present in the compost (Guo et al. 2020). In a controlled greenhouse study examining the impact of cow dung biochar on maize growth, nitrogen absorption and utilization the physicochemical qualities of sandy soil, biochar was created by pyrolyzing dried cow dung at 500°C. It was added to sandy soil in amounts of 0, 10, 15, and 20 t/ha, with maize serving as the test crop (Uzoma et al. 2011). The findings revealed that Cow dung biochar, rich in essential plant nutrients, drastically enhanced maize development. Higher application rates, particularly Maize grain yields increased by 150% and 98% compared to the control when biochar was applied at 15 and 20 t/ha, respectively. Maize water use efficiency (WUE) improved, with increases of 6%, 139%, and 91% at application rates of 10, 15, and 20 t/ha, respectively, compared to the control. Higher application rates also enhanced maize grain nutrient uptake and the sandy soil's hydraulic conductivity, further improving WUE, post-harvest soil analysis revealed notable enhancements in pH, total carbon (C), total nitrogen (N), Olsen phosphorus (P), exchangeable cations, and cation exchange capacity (CEC). These results highlight the potential of cow dung biochar to enhance soil quality and fertility in sandy soils (Uzoma et al. 2011, Woolf et al. 2010).

Biochar derived from various feedstocks significantly improves soil properties and enhances crop productivity, as shown in **Exhibit 3**. Green waste, wood, charcoal, and agricultural residues

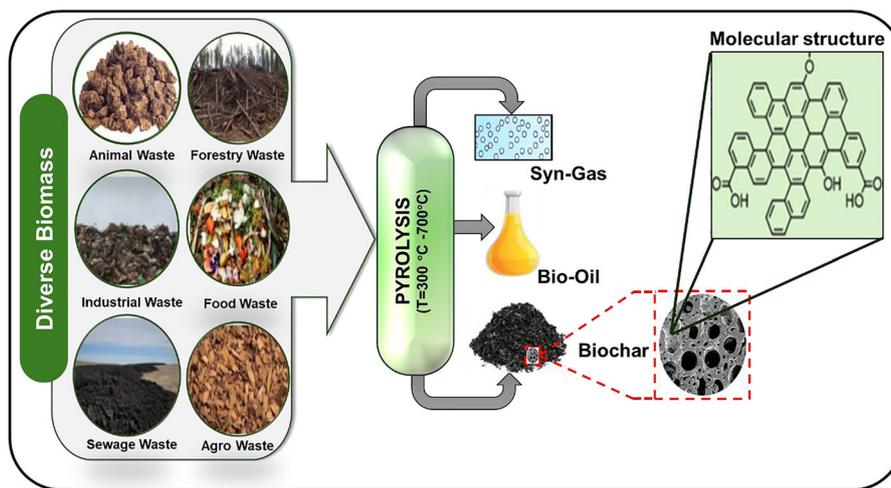


EXHIBIT 2 | Diverse biomass to biochar using slow pyrolysis process. [Color figures can be viewed at wileyonlinelibrary.com.]

have shown remarkable impacts such as increased soil organic carbon (SOC) (up to 40%), improved pH (up to 6.7), and enhanced CEC by 20%–35%. Biochar improves water retention by 15%–45% and reduces bulk density, supporting better aeration and root penetration. Specific studies, such as those by Novak et al. (2009) and Madiba et al. (2016), reveal that higher pyrolysis temperatures increase carbon content, water retention, and phosphorus and potassium availability. Charcoal-amended soils (Oguntunde et al. 2008) showed improved porosity, moisture retention, and a decrease in soil temperature. Combining biochar with nitrification inhibitors (Li et al. 2015) effectively reduced N_2O emissions by up to 70% and nitrate leaching by 45%. Overall, biochar enhances nitrogen use efficiency (NUE), crop yield, and biomass production, making it a sustainable tool for soil and environmental management.

Various types of biochar materials significantly enhance soil health and crop performance. Green waste biochar improves SOC, pH, CEC, and water retention, leading to higher biomass and crop yield. Wood-based biochar enhances nutrient availability, aeration, and reduces bulk density, promoting root growth. Charcoal biochar improves soil structure and moisture infiltration while moderating temperature fluctuations. Agricultural residue biochar boosts nitrogen availability, microbial activity, and NUE, increasing wheat biomass. When combined with nitrification inhibitors, biochar reduces N_2O emissions and nitrate leaching while improving nitrogen retention and vegetable yield. These benefits are well-supported by studies summarized in **Exhibit 4**.

2.3 | Microbial Interactions and Soil Amendments

Biochar, a substance rich in carbon and derived from organic materials, serves as an effective soil enhancer. It enhances the soil's ability to store carbon while also reducing greenhouse gas emissions, making it a valuable strategy for addressing climate change (Hou et al. 2022). The integration of biochar application with the cultivation of bioenergy crops can further enhance the greenhouse gas balance within agricultural systems.

A 500-day soil column incubation study investigated how biochar and dried swine manure affect soil bulk density (Db), total SOC, and the release of N_2O and CO_2 gases. Findings indicated that incorporating biochar led to an increase in SOC levels by 17.6%–68.8%, depending on the specific treatment, over the course of the 500-day study. The addition of biochar consistently reduced N_2O emissions during the final phase of incubation. Biochar use led to higher CO_2 emissions, which were recorded on 13 separate occasions during the study. Overall, the total CO_2 -C emissions ranged from 17% to 23% of the carbon that was added through biochar application (Rogovska et al. 2011). A specific interaction between biochar and manure indicated that biochar either contributed to the stabilization of manure-derived carbon or that the presence of manure inhibited biochar's influence on SOC mineralization. This study concluded that biochar amendments significantly sequestered stable carbon, reduced N_2O emissions, and increased CO_2 emissions from the soil. Furthermore, in the presence of manure, the system exhibited reduced rates of CO_2 emissions compared to biochar-only treatments (Rogovska et al. 2011).

Several studies have highlighted the multifaceted benefits of biochar and its interaction with soil, microbes, and environmental factors. Radhakrishnan et al. (2017) demonstrated that plant growth-promoting bacteria (PGPB) combined with biochar improved plant tolerance to salt stress, increasing plant survival by 25%–40%. Panneerselvam et al. (2021) reported that biochar enhances microbial resilience under climate-induced stress, boosting microbial biomass by 30%–50%. Scervino et al. (2010) found increased mycorrhizal colonization and enzyme activity with biochar, showing a 30%–55% rise. Madiba et al. (2016) showed that biochar improves nitrogen retention and wheat yield, raising nitrogen availability by 20%–40%. Chan et al. (2007) observed improved soil fertility and nutrient retention, with soil organic matter increasing by 15%–35%. Biochar also reduced greenhouse gas emissions, as Li et al. (2015) noted a 15%–45% reduction in N_2O and a 10%–25% yield increase. Other studies highlighted benefits like moisture retention, carbon sequestration, lignocellulose degradation, and pollutant removal up to 95% as summarized in the **Exhibit 5**.

Charcoal soil biochar	Soil used for biochar testing	Parameter	Soil quality	References			
Wood and excrement biochar	All types of soil	Water retention improvement	Biochar effect Increased plant-available water by up to 45%	Hydrochar effect Increased water retention, but less effective than biochar	Abel et al. (2013)		
		Water retention at low suction (-1 to -10 kPa)	20%-30% more water retention at 3% biochar addition	Moderate increase in water retention			
		Water repellency (hydrophobicity)—WDPT test	<5 s (hydrophilic, no significant repellency)	>300 s (strong water repellency at 5%)			
		Effect of biochar/hydrochar dose on water retention	- 1% biochar: 10%-15% increase - 5% biochar: 30%-45% increase	- 5% hydrochar: Induced significant water repellency			
		Change in soil porosity	Increased total soil porosity by 5%-10%	Increased organic matter but had a lesser effect on porosity			
		Effect on bulk density	Reduced bulk density, improving aeration	Minor reduction in bulk density			
Shells from pecans, peanuts, and poultry litter biochar	Loamy sand	Parameter	300°C biochar	500°C biochar	700°C biochar	Novak et al. (2009)	
		pH	4.8	8.3	9.9		
		Carbon content (%)	54.50%	67.30%	89.60%		
		Cation exchange capacity (CEC) (cmol/kg)	18.2	22.5	15.3	9.4	
		Water retention increase (%)	12%	18%	22%	16%	
		Bulk density reduction (%)	8%	12%	15%	10%	
		Increase in available P (%)	14%	20%	28%	22%	
		Increase in available K (%)	10%	18%	35%	28%	
Wheat straw biochar	Fimi-orthic anthrosols	Parameter	Control	Biochar only	NI only	Biochar + NI	Li et al. (2015)
		N ₂ O emissions reduction (%)	—	35%-52%	40%-58%	60%-70%	
		Crop yield increase (%)	—	8%-12%	10%-15%	12%-18%	
		Nitrate leaching reduction (%)	—	20%-35%	25%-40%	30%-45%	
		Nitrogen use efficiency improvement (%)	—	10%-20%	15%-22%	15%-28%	
		Soil pH increase	5.3	5.8	5.6	6.1	

(Continues)

Charcoal soil biochar	Soil used for biochar testing		Soil quality		References
	Charcoal soil	Haplic Acrisols	Non-charred soil	Charcoal-affected soil	
Wood and peanut shell biochar	Parameter				
	Bulk density (g/cm ³)	1.45–1.55	1.10–1.30		↓ 15%–25%
	Total soil porosity (%)	38–42	45–50		↑ 12%–20%
	Water retention capacity (%)	22–28	30–36		↑ 18%–30%
	Soil surface temperature (°C)	30–35	26–31		↓ 2°C–4°C
	Organic carbon content (%)	0.8–1.2	1.2–1.8		↑ 28%–45%
	Cation exchange capacity (CEC) (cmol/kg)	6.5–8.0	8.5–10.8		↑ 20%–35%
	Parameter	Control (no biochar)	Biochar-amended soil		Change (%)
	Nitrate (NO ₃ ⁻) increase (%)	Baseline	+25%–45%		↑ 25%–45%
	Ammonium (NH ₄ ⁺) increase (%)	Baseline	+15%–30%		↑ 15%–30%
Nitrogen use efficiency (NUE) increase (%)	Wheat biomass increase (%)	—	+20%–35%		↑ 20%–35%
	Grain yield increase (%)	—	+18%–28%		↑ 18%–28%
	Soil pH Increase	5.6	+15%–32%		↑ 15%–32%
	Water retention improvement (%)	Baseline	6.4		↑ 0.8
Wood charcoal	Parameter	Control (no biochar)	Low biochar (10 t/ha)	High biochar (50 t/ha)	Change (%)
	Soil organic carbon increase (%)	Baseline	15%	40%	↑ 15%–40%
	Soil pH increase	4.9	5.8	6.7	↑ 0.9–1.8
	Cation exchange capacity (CEC) (cmol/kg)	8.2	9.8	11.2	↑ 20%–35%
	Nitrogen, phosphorus, potassium availability (%)	Baseline	+12%–20%	+25–35%	↑ 12%–35%
	Biomass production increase (%)	—	20%	42%	↑ 20%–42%
	Crop yield increase (%)	—	10%	30%	↑ 10%–30%
	Water retention improvement (%)	Baseline	15%	25%	↑ 15%–25%
	Anthrosols and ferralsols				
					Chan et al. (2007)

EXHIBIT 4 | Effects of biochar on soil properties.

Biochar material	Key effects on soil	Impact on crop growth	References
Green waste biochar	<ul style="list-style-type: none"> - Increases soil organic carbon (15%–40%) - Improves pH (from 4.9 to 6.7) - Enhances CEC (20%–35%) - Boosts water retention (15%–25%) 	<ul style="list-style-type: none"> - Increases biomass production (20%–42%) - Improves crop yield (10%–30%) 	Chan et al. (2007)
Wood-based biochar	<ul style="list-style-type: none"> - Enhances nutrient availability - Reduces bulk density (↓10%–20%) - Increases porosity and aeration 	<ul style="list-style-type: none"> - Promotes root penetration - Supports higher crop yields 	Novak et al. (2009)
Charcoal biochar	<ul style="list-style-type: none"> - Lowers bulk density (↓15%–25%) - Increases water infiltration (↑12%–20%) - Raises organic matter content (↑28%–45%) 	<ul style="list-style-type: none"> - Improves soil structure - Reduces soil temperature fluctuations (↓2°C–4°C) 	Oguntunde et al. (2008)
Agricultural residue biochar	<ul style="list-style-type: none"> - Enhances nitrogen availability (↑25%–45% NO₃⁻, ↑15%–30% NH₄⁺) - Boosts microbial activity - Improves soil pH (from 5.6 to 6.4) 	<ul style="list-style-type: none"> - Increases wheat biomass (20%–35%) - Enhances nitrogen use efficiency (NUE) (↑15%–32%) 	Madiba et al. (2016)
Biochar + nitrification inhibitor	<ul style="list-style-type: none"> - Reduces N₂O emissions (↓60%–70%) - Improves nitrogen retention (↓30%–45% nitrate leaching) 	<ul style="list-style-type: none"> - Increases vegetable yield (12%–18%) - Enhances NUE (↑15%–28%) 	Li et al. (2015)

EXHIBIT 5 | Effects of biochar, microbial interactions, and soil amendments.

Key focus	Major findings	Statistical data	Reference
PGPB alleviating salt stress	Improved plant tolerance, enhanced microbial health	Plant survival ↑ 25%–40% under salt stress	Radhakrishnan et al. (2017)
Microbial diversity under climate stress	Biochar enhances microbial resilience	Microbial biomass ↑ 30%–50%	Panneerselvam et al. (2021)
Soil microbial interactions with biochar	Increased mycorrhizal colonization, enzyme activity	Mycorrhizal colonization ↑ 30%–55%	Scervino et al. (2010)
Biochar and nitrogen availability	Higher nitrogen retention, increased wheat yield	Nitrogen availability ↑ 20%–40%	Madiba et al. (2016)
Agronomic value of biochar	Improved soil fertility and nutrient retention	Soil organic matter ↑ 15%–35%	Chan et al. (2007)
Biochar and N ₂ O emissions	Reduced greenhouse gases, increased yield	N ₂ O emissions ↓ 15%–45%, crop yield ↑ 10%–25%	Li et al. (2015)
Charcoal production & soil properties	Increased moisture retention, nutrient availability	Soil water content ↑ 12%–30%	Oguntunde et al. (2008)
Designer biochar for carbon sequestration	Enhanced soil carbon storage, improved stability	Soil carbon sequestration ↑ 20%–50%	Novak et al. (2009)
Microbial degradation of lignocellulose	Fungal enzymes assist biochar decomposition	Lignocellulose breakdown efficiency ↑ 40%–75%	Tyskiewicz et al. (2022), Ohkuma (2003)
Biochar-based contaminant removal	Effective heavy metal and pollutant adsorption	Heavy metal removal 60%–95%, Organic pollutant removal 50%–90%	Yuanyuan et al. (2021)

2.4 | Environmental Applications

Biochar, obtained from organic sources, such as agricultural waste, forestry leftovers, or biomass, has emerged as a focus point in combating marine hydrocarbon and plastic pollution due to its extraordinary potential for remedial applications (Qiang et al. 2019). Biochar, with its porous structure and large surface area, is an exceptional adsorbent capable of absorbing various pollutants, such as hydrocarbons and plastics, in marine ecosystems disrupted by oil spills or plastic debris. Biochar effectively binds these contaminants to its surface via physical and chemical interactions, allowing them to be removed from the water column or sediment. In remediation operations aimed at contaminated marine sediments, biochar plays an essential part in minimizing the negative effects of hydrocarbon and plastic pollution. Whether applied directly to sediment layers by surface application or integrated via sediment mixing, biochar is used to remove and immobilize contaminants, reducing their bioavailability and possible harm to marine animals (Yuanyuan et al. 2021). This method not only helps to restore injured ecosystems but also improves the overall health and resilience of marine habitats. Furthermore, beyond its adsorption properties, biochar demonstrates a unique capacity to accelerate biodegradation processes in maritime environments (Li et al. 2019). Biochar, which serves as a substrate for microbial activity, promotes the growth of microorganisms capable of metabolizing adsorbed contaminants. Through this synergistic interaction between biochar and microbial populations, pollutants are digested and converted into less hazardous molecules, hence encouraging the natural attenuation of toxins in marine ecosystems. Furthermore, the intrinsic stability of biochar in marine environments makes it ideal for long-term pollutant removal initiatives. Biochar, which has the capacity to last for centuries without major deterioration, provides long-term effectiveness in pollution sequestration and removal, providing long-term solutions for environmental management and habitat restoration. Moreover, the use of biochar obtained from sustainable biomass sources not only helps pollution cleanup but also adds to carbon sequestration and climate change mitigation efforts, thereby aligning with broader sustainability objectives (Radheshyam and Wusirika 2023). To summarize, biochar's varied qualities and applications make it an asset in the search for cleaner and healthier marine habitats, providing demonstrable benefits for both environmental restoration and long-term ecosystem resilience.

The environmental scope of biochar can be contextualized within both established benefits and newly emerging applications (Oliveira et al. 2017). Biochar has been recognized as a versatile material with multifunctional environmental applications, primarily due to its porous structure, high surface area, and surface chemistry. Their study highlighted biochar's role in enhancing soil fertility, immobilizing contaminants, sequestering carbon, and supporting pollutant removal from water systems, while emphasizing its cost-effectiveness and scalability. Since then, emerging research has expanded its potential beyond these established functions. Recent developments demonstrate the use of engineered and modified biochars tailored for specific contaminants, improved performance in wastewater treatment (including dyes, pharmaceuticals, and heavy metals), and applications in mitigating greenhouse gases. Furthermore, biochar has gained

attention in carbon credit frameworks as a negative-emission technology, and novel applications such as antimicrobial activity, biosensing, concrete reinforcement, and microplastic remediation are now under exploration.

Beyond marine hydrocarbon and plastic remediation, biochar is increasingly deployed across water, soil, and air pathways as a multifunctional environmental material (Exhibit 6).

2.5 | Water and Wastewater Remediation

“Engineered and pristine biochars effectively remove dissolved contaminants heavy metals (e.g., Pb, Cd, As), dyes, pharmaceuticals, and pesticides via a combination of surface adsorption, ion exchange, complexation, and π - π interactions.”

Engineered and pristine biochars effectively remove dissolved contaminants heavy metals (e.g., Pb, Cd, As), dyes, pharmaceuticals, and pesticides via a combination of surface adsorption, ion exchange, complexation, and π - π interactions. Performance is enhanced by activation/functionalization (e.g., acid/alkali or metal-doping) and by magnetic composites that enable rapid separation and reuse. These strategies are well documented for water and soil contaminant control (Khandgave and Sreedhar 2023).

2.6 | Soil Remediation and Agroecosystem Services

In soils, biochar immobilizes trace metals and moderates pesticide bioavailability, reducing ecological risk while improving structure, moisture retention, and nutrient use efficiency. Care is needed to balance sorption benefits with potential changes in pesticide fate and to monitor any contaminant carry-over in the char itself (Jena et al. 2025). When co-applied with manures, biochar lowers ammonia volatilization and mitigates odors; it can also curb nitrous oxide and methane fluxes by altering microbial pathways and improving carbon stabilization during composting and land application (Canatoy et al. 2024).

Recent advances have highlighted the potential of engineered and modified biochars in addressing complex environmental challenges. Rizwan et al. (2024) demonstrated that steam-exploded biochar, particularly when modified with KMnO_4 or hydroxyapatite, significantly reduced lead bioavailability and improved plant growth in vegetable-grass intercropping systems. Similarly, Murtaza et al. (2024) reported that nano zero-valent iron (nZVI) loaded biochar not only alleviated the combined stresses of salinity and ciprofloxacin contamination in wheat but also enhanced biomass, photosynthetic performance, and antioxidant activity while reducing oxidative damage. These findings underscore how functionalized biochars can extend applications beyond conventional soil improvement, offering dual benefits for contaminant mitigation and crop productivity.

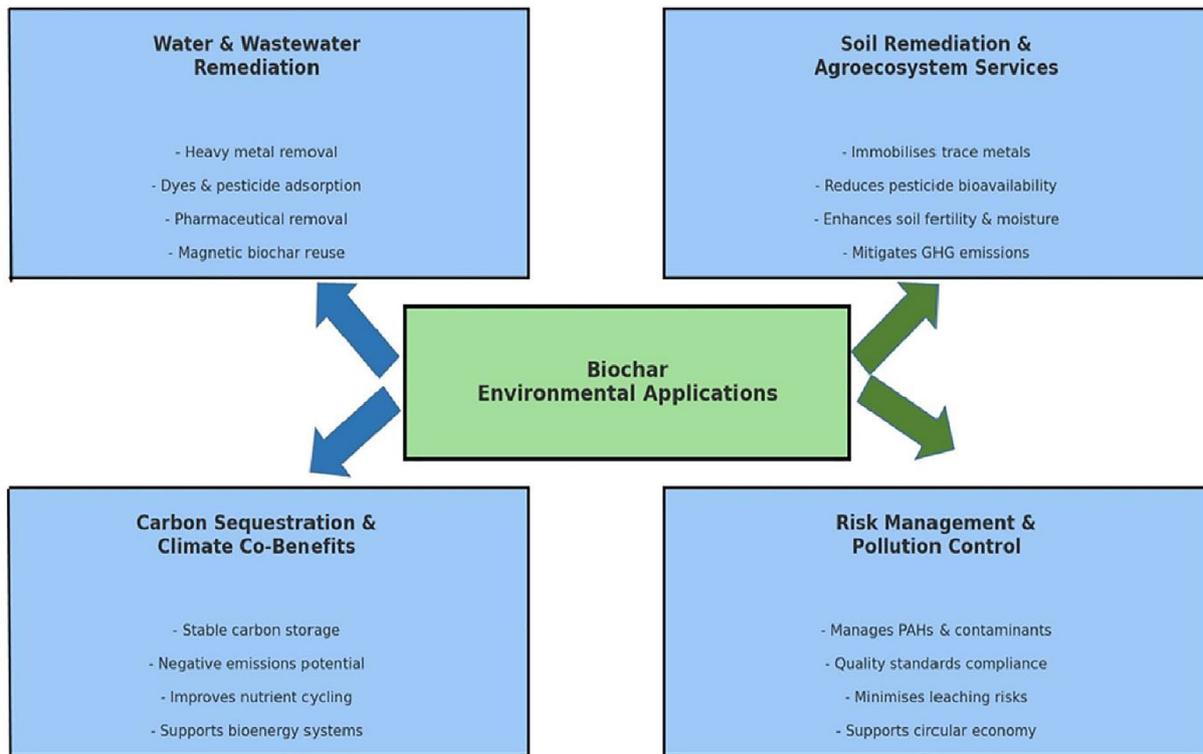


EXHIBIT 6 | Environmental applications of biochar. Biochar contributes to water and soil remediation, carbon sequestration, and pollution control, offering multifunctional environmental benefits. [Color figures can be viewed at wileyonlinelibrary.com.]

2.7 | Carbon Sequestration and Climate Co-Benefits

Biochar’s recalcitrant carbon contributes to long-term sequestration at field scale, offering negative-emissions potential alongside agronomic gains. Life-cycle assessments consistently highlight mitigation opportunities when stable, high-yield chars are produced and applied appropriately (Yin et al. 2022). Production parameters (feedstock, peak temperature, residence time, and atmosphere) strongly shape pore architecture, surface chemistry, and ash content, which in turn govern contaminant affinity and durability. Recent work under CO₂ pyrolysis and advanced activation details how tuning these levers improves remediation performance (Yaashikaa et al. 2020).

2.8 | Risk Management and Standards

While generally stable, chars may carry polycyclic aromatic hydrocarbons (PAHs) or trace metals depending on feedstock and process; application should follow quality standards with periodic monitoring to ensure environmental safety. A practical decision framework should consider: (i) target pollutant class and matrix; (ii) char specification (surface area, pH, ash, functional groups); (iii) application mode (in-situ mixing, permeable reactive media, filters); (iv) recovery/reuse (e.g., magnetic biochar); and (v) life-cycle and cost implications to ensure scalable, circular outcomes.

3 | Challenges in Incorporating Biochar in Manure

The constant loss of organic carbon from soils is a major environmental concern, and biochar has emerged as a viable solution to address this problem. This method aligns with the goals of the thematic strategy for soil protection, especially considering the important role soils play as carbon storage, which helps in mitigating climate change. Biochar is renowned for its potential to assist long-term carbon sequestration in soils, which support these strategic aims (Lehmann et al. 2006). Beyond from its role in carbon storage, biochar has a variety of agronomic benefits as a soil amendment. It’s very porous structure and wide surface area promote soil productivity, improve nutrient availability and fertilizer effectiveness, and regulate soil pH through its “liming effect” (Manya 2012; Atkinson et al. 2010; Biederman and Harpole 2013; Chan et al. 2008). More studies are required to better understand how biochar characteristics, like the source of the feedstock and how it is produced, relate to different types of soil. Furthermore, concerns have been expressed about its potential to influence the availability of heavy metals, change pesticide sorption, and introduce metal pollutants into the soil ecosystem (Kookana et al. 2011).

Biochar has shown effectiveness in trapping both organic and inorganic pollutants, especially in their most mobile forms, underscoring its potential for use in environmental restoration projects (Beesley and Marmiroli 2011). For example, experimental

studies in polluted soils found that biochar considerably reduced leachate concentrations of cadmium (Cd) and zinc (Zn), mostly through sorption mechanisms, but no equivalent reductions were observed for other metals (Beesley et al. 2011). Despite these advantages, the presence of poisonous elements (PTEs), such as copper (Cu), lead (Pb), and arsenic (As) in biochar, depending on the feedstock utilized, causes worry. This issue highlights the significance of setting regulating limits for PTE concentrations, given there are currently no national guidelines for biochar additions. Furthermore, issues exist in determining the bioavailability of PTEs using standard extraction procedures (Farrell et al. 2013).

The impact of biochar on PAHs is complex. Research has shown that using biochar in contaminated soil helps lower both the overall and available levels of PAHs and reduces the buildup of PAHs in earthworms. However, a decrease in earthworm biomass was detected, most likely due to insufficient moisture levels rather than toxicity (Gomez-Eyles et al. 2011; Alvarez 2011). Biochar also enhances the ability of soil to absorb hydrophobic organic compounds, like phenanthrene. However, the extent of this effect depends on the characteristics of both the biochar and the soil (Zhang et al. 2010). However, this higher sorption has been found to hinder the breakdown of PAHs, leading to concerns about their accumulation over time. In the context of pesticide behavior, biochar treatment has been demonstrated to prevent water contamination caused by foliar pesticides. However, when mixed into soils, greater herbicide dosages may be required for successful weed control. The degree of pesticide leaching mitigation depends on the adsorption characteristics of the biochar (Quilliam et al. 2013).

4 | Future Perspectives

Further research should insist that the development of engineered biochars tailored for specific environmental challenges represents a promising frontier. Modifications such as surface functionalization, metal-doping, and magnetic composites can significantly enhance adsorption properties, broaden contaminant selectivity, and enable material recovery and reuse. Moreover, the integration of biochar applications into carbon credit frameworks and climate mitigation policies may help establish biochar as a scalable negative-emissions technology. Standardization of quality guidelines and monitoring protocols will be essential to ensure safety, effectiveness, and reproducibility across diverse contexts.

Beyond established roles in soil improvement and pollution control, biochar research is increasingly branching into novel interdisciplinary applications. Emerging studies highlight its potential in antimicrobial and biomedical uses, biosensing platforms, concrete reinforcement for sustainable construction, and microplastic remediation in soils. At the same time, the valorization of industrial and municipal waste streams into biochar offers a circular economy pathway that supports both environmental protection and resource recovery. Addressing these directions through collaborative research and pilot-scale demonstrations will be critical for translating biochar's diverse promise into practical, long-term solutions.

5 | Conclusion

This review highlights the benefits of biochar and compost as organic amendments for improving degraded soils. Biochar has properties like high porosity, a large surface area, and the ability to exchange nutrients, which allow it to support microbial activity and interact with nutrient cycles during composting. In tropical farming systems, it helps improve soil health and acts as a long-lasting carbon storage for CO₂ from the air. When mixed with compost, biochar helps fix nutrient gaps, boosting soil fertility, water retention, and crop yields. Biochar alone is particularly effective in medium-fertility soils, contributing to carbon sequestration, crop productivity, and nutrient retention. Biochar influences composting by modifying physicochemical properties, stimulating microbial activity, and reducing greenhouse gas emissions. These processes enhance nutrient levels, organic matter content, and microbial biomass. Composting, in turn, improves biochar's properties, enriching its surface functional groups, organic matter, and nutrient availability. The combined use of biochar and compost enhances their ability to improve soil, helping with restoration, fertility, and structure. Combining biochar with compost offers a sustainable solution for degraded soils, enhancing agricultural productivity, carbon sequestration, and environmental sustainability, particularly in tropical and low-quality soils.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data are presented in the manuscript.

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