



Biochar and Compost Effects on Soil Physico-Chemical and Biological Properties: Implications for Remediation and Climate Mitigation

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Abstract

Soil degradation driven by intensive agriculture, land-use change, and climate variability threatens global food security and ecosystem sustainability. Organic amendments such as biochar and compost are increasingly recognized as climate-smart strategies for soil restoration and sustainable agricultural production. This review evaluates the individual and combined effects of biochar and compost on soil physical, chemical, and biological properties, with emphasis on soil remediation and climate change mitigation. Published literature was synthesized to assess impacts on soil health, carbon sequestration, nutrient dynamics, greenhouse gas emissions, and contaminant remediation across diverse agroecosystems. Biochar enhances soil structure, water-holding capacity, nutrient retention, and long-term carbon stabilization because of its porous structure, large surface area, and chemical stability. Compost supplies labile organic matter, nutrients, and beneficial microorganisms, thereby improving nutrient cycling and soil fertility. Their combined application often generates synergistic benefits, including enhanced nutrient-use efficiency, microbial activity, crop productivity, and soil resilience. Co-application also mitigates methane (CH₄), nitrous oxide (N₂O), and ammonia (NH₃) emissions while increasing soil carbon sequestration. Furthermore, biochar-compost systems promote contaminant immobilization and degradation through adsorption, complexation, and microbial processes. Overall, amendment effectiveness depends on feedstock characteristics, production conditions, soil properties, climate, and application rates. Future research should prioritize long-term field studies, mechanistic investigations, and economic assessments to optimize sustainable soil management.

1. Introduction

Soil degradation and declining land quality are among the most pressing global environmental challenges, threatening food security, ecosystem stability, and long-term agricultural sustainability (Hossain et al., 2020). These problems are mainly attributed to intensive agricultural practices, deforestation, nutrient depletion, and rising climate variability, which hastens soil erosion and decreases

productivity. As a result, there is growing global interest in sustainable soil restoration strategies that can simultaneously enhance soil fertility and support climate resilience. Organic amendments have emerged as an effective and environmentally sound approach for improving degraded soils. The materials improve soil physical properties, including structure, bulk density, porosity, infiltration rate, soil water retention capacity, and cation exchange capacity (CEC) (Abdelhak, 2022). Soil structure improvement

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decreases compaction and boosts aggregate stability, which helps promote better root development and soil profile water movement (Peng et al., 2021). By improving soil physical functioning, organic amendments create favorable conditions for plant growth and long-term soil sustainability.

Among organic inputs, compost, animal manure, crop residues, and other agricultural wastes are widely used to increase soil organic matter (SOM). SOM plays a central role in regulating soil fertility by improving nutrient availability, enhancing microbial activity, and supporting plant growth. It is also directly linked to improving soil environment, which leads to improved biomass production and root development (Dămățircă et al., 2023). Also, organic matter affects the partitioning and stabilization of soil organic carbon (SOC) and nitrogen into soil fractions, which contributes to the long-term storage of carbon and nutrient cycling efficiency. The efficiency of organic amendments is markedly dependent on their composition, decomposition rate and the interaction with the soil properties. Different organic materials produce varying effects depending on their biochemical structure and degree of humification (Bahadori et al., 2021). For example, simple application of humic substances may have limited impact on soil aggregation; however, their combination with fulvic acids and other organic compounds can significantly enhance aggregate stability and soil structural integrity. Overall, organic amendments can enhance hydraulic conductivity, decrease the risk of erosion, and increase resistance to wind and water degradation.

Biochar is a highly stable carbon-rich material generated via thermochemical processes like pyrolysis and gasification of biomass like nutshells, straw, wood chips, and crop residues, and has been gaining interest in recent years (Sun et al., 2020). Due to its porous structure, large surface area, and long residence time in soil, biochar effectively improves soil physical and chemical properties. It helps maintain lower bulk density, better water holding capacity, higher adsorption capacity for nutrients, and higher cation exchange capacity, which are favorable for long-term enhancement of soil fertility. Compost, however, is a rich microbial population and organic matter that is produced under biological conditions with certain control (Aguilar-Paredes et al., 2023). Its nutrient content is typically less than the synthetic fertilizers, but compost improves many processes of soil biological activity, nutrient cycling, and aggregation processes. It also enhances absorption of soil moisture and provides a slow release of nutrients, making it an essential amendment for sustainable crop production. Recent studies indicate that both biochar and compost play important roles in climate change mitigation through carbon sequestration and reduction of greenhouse gas emissions. The application to agricultural soils helps to stabilize carbon in the soil matrix, and it decreases the emission of carbon dioxide,

methane and nitrous oxide (Ayilara et al., 2020). When applied individually, both amendments improve soil quality; however, their combined application often produces greater benefits due to complementary mechanisms.

Combination of biochar and compost has been demonstrated to have significant effects on soil water-holding capacity, nutrient retention, nitrogen use efficiency and soil structural stability (Frimpong et al., 2021). These synergistic interactions also reduce the dependency on inorganic fertilizers and improve overall soil resilience. Biochar offers long-term stability and nutrient retention, while compost brings immediate nutrients and boosts microbial activity, creating a synergistic and balanced enhancement of soil systems. Field studies further confirm that integrated application of biochar and compost improves soil nutrient availability, microbial diversity, and water retention more effectively than single amendments (Iacomino et al., 2022). These benefits are particularly important in degraded soils where both physical structure and nutrient availability are limiting factors for crop production. Modern agricultural methods have contributed to a dramatic rise in soil erosion, nutrient depletion, and ecosystem imbalance, posing a need for sustainable soil management strategies. Organic amendments offer a dual advantage by restoring soil health while contributing to climate change mitigation through enhanced carbon sequestration. Their dual role is of paramount importance in the context of climate-smart agriculture and sustainable land management.

This review, therefore, focuses on the synergistic aspects of biochar and compost by reviewing recent advances in the co-application of these two amendments from the perspectives of soil physical, chemical and biological processes. This review combines mechanistic understanding of nutrient dynamics, microbial control, contaminant retention and soil carbon stabilization, with the focus on individual amendments as in previous studies. The objectives are to elucidate interaction mechanisms, evaluate performance across different soil types and environments, and identify critical research gaps related to long-term stability, greenhouse gas mitigation, and optimized application strategies for sustainable agriculture.

2. Biochar and Compost: Production, Composition, and Functional Characteristics

2.1 Feedstocks, Production Processes, and Physicochemical Determinants

Biochar is produced from diverse organic feedstocks including wheat stalks, rice straw, sugarcane bagasse, pistachio shells, walnut shells, forestry residues, eucalyptus green waste, algal biomass, urban sewage sludge, and animal manures such as poultry and cattle waste (Ahmed et al.,

2024). The physicochemical properties and soil functionality of the biochar can greatly differ due to the different carbon contents, ash fraction, mineral content, and nutrient availability of the materials used. Pyrolysis is a thermochemical process that produces biochar from biomass in the absence of oxygen, resulting in a carbon-rich, porous and stable product. Pyrolysis removes volatiles and leaves a condensed aromatic carbon structure with high surface area, chemical stability, and a high sorption capacity. The properties of biochar are significantly influenced by the type of feedstock and the process parameters such as pyrolysis temperature, heating rate, residence time and particle size (Purakayastha et al., 2019). Of these, temperature has the largest influence, which determines the aromaticity, surface area, pH, and cation exchange capacity (CEC), and nutrient retention potential. Low-temperature biochars (~300 °C) retain more labile carbon and nutrients, enhancing short-term microbial activity, whereas high-temperature biochars are more stable, favoring long-term carbon sequestration and contaminant adsorption (Marin et al., 2025). Representative feedstocks and their associated production conditions and key properties are summarized in Table 1.

readily decomposable organic carbon, nutrients, and microbial biomass. Composting efficiency depends on proper regulation of moisture (45–60%), particle size (3.1–12.7 mm), aeration, and temperature (35–40 °C), which collectively control microbial activity and organic matter stabilization (Oshins et al., 2022). These conditions ensure efficient decomposition, humification, and nutrient stabilization. Functionally, compost enhances soil fertility by supplying labile carbon, essential nutrients, and diverse microbial communities that stimulate enzymatic activity, nutrient cycling, and soil aggregation. However, due to its low chemical stability, compost mainly contributes to short- and medium-term improvements in soil productivity.

2.3 Comparative Properties and Synergistic Basis of Biochar–Compost Systems

Biochar and compost have essentially opposed but complementary properties. Biochar offers structural stability, high surface area, nutrient-holding capacity and carbon sequestration potential, while compost contributes nutrients that are easily used by plants and labile carbon that stimulates quick soil biological processes. A comparative overview of

Table 1. Representative feedstocks for biochar production, associated pyrolysis temperature ranges, key physicochemical properties, and primary soil amendment applications.

Feedstock	Temp (°C)	Surface Area	pH	C Content (%)	Primary Soil Use
Crop Residues	Low (~300)	Moderate	6.5–7.5	45–55	Nutrient retention
Wheat straw / Rice straw	300–500	50–150 m ² g ⁻¹	7.0–8.5	50–65	N/P retention, WHC
Sugarcane bagasse	400–600	100–300 m ² g ⁻¹	7.5–9.0	55–70	CEC improvement
Wood chips / Forestry waste	500–700	200–500 m ² g ⁻¹	8.0–10.0	70–85	C sequestration, porosity
Nutshells (pistachio, walnut)	400–600	150–400 m ² g ⁻¹	7.5–9.5	65–80	Contaminant adsorption
Poultry / Cattle manure	300–500	30–100 m ² g ⁻¹	8.5–11.0	30–50	Nutrient supply, pH correction
Algal biomass	300–500	50–200 m ² g ⁻¹	7.0–9.0	35–55	N cycling, microbial activity
Sewage sludge	400–600	30–150 m ² g ⁻¹	7.5–9.5	25–45	Remediation (caution: HMs)

2.2 Compost Formation, Functional Properties, and Soil Contributions

Compost is produced through aerobic microbial decomposition of organic wastes such as crop residues, animal manures, food waste, and agro-industrial by-products. Unlike biochar, compost is biologically active and consists of

the contrasting yet complementary properties of both amendments is provided in Table 2. These materials complement each other and work synergistically to augment soil function. Biochar also functions as a sorptive matrix that will trap nutrients made available by the decomposition of compost, which will limit leaching and volatilization losses

of nitrogen and enhance nutrient availability with time (Tang, 2025). Concurrently, compost stimulates microbial synergistic role of biochar and compost in enhancing soil physical, chemical, and biological functions, and their

Table 2. Comparative physicochemical, biological, and functional properties of biochar and compost as soil amendments, with optimum co-application rates for agricultural soils.

Attribute	Biochar	Compost
Production method	Pyrolysis / gasification (300–700°C, no O ₂)	Aerobic microbial decomposition of organic waste
Carbon stability	Recalcitrant aromatic C; persists centuries	Labile C; mineralizes within months–years
Organic C content	High (25–85%)	Moderate (10–30%)
Nutrient availability	Low–moderate; slow release via desorption	High; rapid mineralization and plant uptake
pH	Alkaline (7–11, feedstock dependent)	Slightly acidic to near neutral (5.5–7.5)
Surface area	High (50–500 m ² g ^{−1})	Low (1–10 m ² g ^{−1})
CEC	Moderate–high; improves with aging	Moderate; from humus formation
Microbial content	Low initially; colonized over time	High; diverse active microbial communities
Water-holding effect	Increase via microporosity and surface adsorption	Increase via organic matter and hygroscopicity
GHG effect	Inhibits CH ₄ and N ₂ O; sequesters C	Variable; can emit CO ₂ during decomposition
Persistence in soil	Centuries to millennia	Months to a few years
Contaminant remediation	Strong adsorption of metals and PAHs	Enhances microbial degradation of organics
Cost / Availability	Variable; depends on production scale	Widely available; low cost from organic waste
Optimum combined rate	7–10 t ha ^{−1}	20–40 t ha ^{−1}

colonization of biochar surfaces, and hastens biochar aging, thereby further augmenting nutrient cycling and soil biogeochemical processes. The three main methods for integration include: co-composting biochar with organic waste, pre-incubating biochar with compost before use, and direct blending before soil application. Of these, co-composting is frequently the most successful for enhancing nutrient stabilization and compost maturity, while direct application remains common. Overall, biochar–compost integration results in the betterment of soil organic carbon, water retention, nutrient availability and CEC, and better crop performance in various soil types. However, responses vary depending on soil conditions, crop species, and environmental factors, highlighting the need for site-specific management strategies (Teodoro et al., 2020). The

collective contributions to crop productivity, carbon sequestration, and greenhouse gas mitigation, are illustrated in Figure 1.

3. Effects of Biochar and Compost on Soil Physical Properties

3.1 Soil Bulk Density and Porosity Dynamics

Soil bulk density (BD) is a key indicator of soil compaction and overall structural condition, directly influencing root penetration, aeration, and water movement. Biochar, due to its inherently low density and highly porous structure (0.05–0.57 g cm^{−3}), significantly reduces soil bulk density while enhancing total soil porosity and structural stability (Ayilara et al., 2020). It directly contributes to soil aggregation,

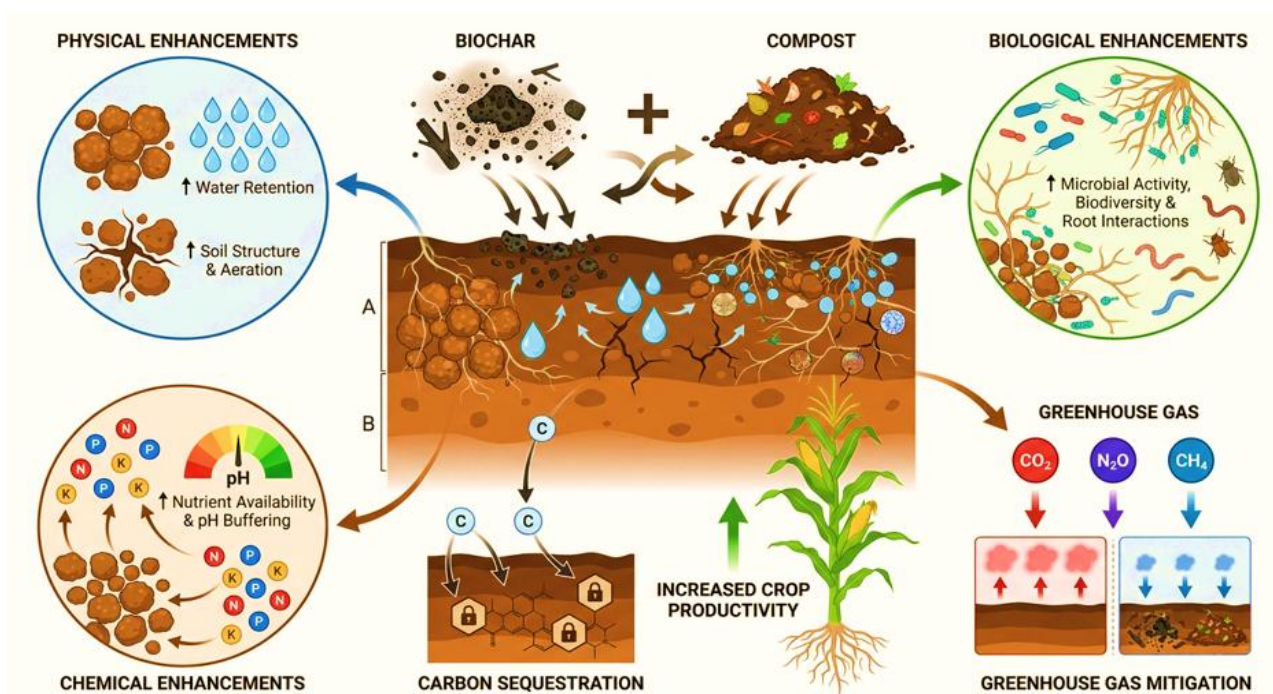


Figure 1. illustrates the synergistic role of biochar and compost in enhancing soil physical, chemical, and biological functions, leading to improved crop productivity, carbon sequestration, and greenhouse gas mitigation.

enhances pore connectivity and enhances microbial habitat quality which in turn improves root growth and hyphal development. Compost also helps to improve soil structure by increasing organic matter and decreasing compaction of the soil, which would otherwise limit crop productivity and root growth. Compost applications of the organic fraction can improve the aggregate stability, resulting in better pore continuity, aeration and permeability (Botta et al., 2022). Improved macroporosity also promotes root oxygenation and drainage processes crucial for plant development. Both amendments show similar trends, which include lower bulk density and higher porosity, but their mechanisms and permanence are different. The recalcitrant nature of biochar can help provide long-term structural stability, while compost can provide more immediate, but temporary benefits, due to its being more easily decomposed. Consequently, sustained improvements in soil physical structure often require repeated compost applications, while biochar contributes to longer-term stabilization (Singh et al., 2022).

3.2 Soil Water-Holding Capacity and Moisture Regulation

Soil water-holding capacity (WHC) is governed by soil texture, structure, and environmental conditions, and is critical for regulating plant water availability. Biochar improves WHC by raising the internal porosity and specific

surface area, which increases water adsorption and retention in soil micropores (Chen et al., 2023). This improves the balance between water retention and drainage, particularly in coarse-textured soils such as sandy soils where water loss is typically high. Biochar enhances root penetration and soil bulk volume available for plant water uptake by decreasing bulk density and increasing soil porosity. Such structural changes also promote hydraulic connection and improve water re-distribution through water shortage periods, while minimizing plant water stress. Compost also enhances soil water dynamics by increasing organic matter content, improving aggregation and soil pore network stabilization. Compost amended soils have better infiltration, better moisture distribution and reduced compaction which promotes root development and water absorption (Lal, 2020). Due to its hygroscopic properties, it can absorb water and retain it in the root zone, which enhances its drought resistance and lowers irrigation needs (Hassan et al., 2023). The combination of biochar and compost increases drought resistance and maintains soil physiological activity under drought stress by improving both soil water storage capacity and infiltration efficiency.

3.3 Saturated Hydraulic Conductivity and Water Flow Regulation

Saturated hydraulic conductivity (K_{sat}) is a measure of the capacity for soil to conduct water when it is saturated and highly influenced by pore structure. The impact of biochar on K_{sat} varies across studies depending on the soil type, biochar application rate, and biochar properties (Rabbi et al., 2021). Biochar often improves infiltration and drainage, especially in fine-textured soils, through increased soil porosity and decreased soil compaction, which also increases pore connectivity. The increase in hydraulic conductivity promotes fast percolation of water through the soil profile which decreases surface runoff and encourages drainage. But, too much infiltration can also lead to nutrient leaching concerns, and therefore, balanced application strategies are required. Overall, biochar tends to improve long-term hydraulic response, but the magnitude and direction of this effect is highly context dependent. Compost improves saturated hydraulic conductivity through its ability to increase the formation of macropores and soil aggregation. These structural changes promote greater infiltration, decrease surface runoff, and prevent erosion, especially under high rainfall or irrigated conditions (Vijay et al., 2021). Simultaneously, composting promotes the development of micropores, increasing the water holding capacity, a dual effect on soil water regulation (Rivier et al., 2022). Such a dual effect can help composted soils to also reduce drainage while providing better moisture holding capacity to make soil water more available for plant uptake. The intensity of these impacts is dependent on soil type, compost quality, and environmental factors, however, and must be managed to maximize positive impact.

3.4 Soil Color, Temperature Regulation, and Microclimatic Effects

Biochar application generally induces a temporary darkening of soil due to its high carbon content and black coloration, which enhances soil heat absorption (Tsolis & Barouchas, 2023). This effect is reduced over time due to the weathering and incorporation of biochar into the soil matrix (Mandal et al., 2021). Soil surface darkening can lead to greater heat retention and a slight rise in soil temperature, potentially favoring crop growth in cooler climates or early phases. Compost, however, has a cooling effect on soil, retaining moisture and providing insulation. This helps buffer temperature fluctuations and create more stable microclimatic conditions for root development (Tsai & Chang, 2020). Biochar and compost may work synergistically to influence soil thermal regimes, with the direction and magnitude of the change varying according to application rates, climate conditions and soil properties (Linh et al., 2023). In addition to their physical effects, these amendments also have indirect impacts on soil chemical and biological processes, due to their ability to buffer soil pH, retain nitrogen and add organic matter. Overall, the

integration of biochar and compost supports improved soil structure, enhanced moisture regulation, and more stable thermal conditions, ultimately contributing to increased soil fertility and crop productivity.

4. Effects of Biochar and Compost on Soil Chemical Properties

4.1 Soil Organic Matter Dynamics and Carbon Enrichment

Biochar plays a significant role in enhancing soil organic matter (SOM) by increasing carbon inputs and improving the stabilization of organic compounds within the soil matrix. This improvement in SOM contributes to enhanced nutrient efficiency, better nutrient uptake, and improved plant growth performance (Hou et al., 2022). The level of SOM enrichment will be influenced significantly by biochar type and source, since manure-based biochars tend to have higher levels of N, P, K, Ca, Mg and S than plant-based biochars (Bolan et al., 2023). These nutrient-rich biochars also provide catalytic surfaces that facilitate organic matter formation and stabilization processes (Bagheri et al., 2023). Compost also provides direct inputs of organic carbon and nutrients, and is quickly added to soil fertility and soil structure. Its breakdown results in the production of labile organic compounds that benefit SOM building and to promote nutrient availability. Moreover, microbial communities from compost can increase the decomposition of complex organic residues, thereby enhancing SOM formation and nutrient cycling (Guo et al., 2020). The extent of SOM improvement depends on the type of amendment, amendment rate, and material properties, and both amendments affect the short- and long-term carbon soil turnover differently (Malone et al., 2023).

4.2 Nitrogen Availability and Nutrient Cycling Processes

The primary mechanism by which biochar improves nitrogen retention is by adsorption of ammonium (NH_4^+) and by decreasing nitrate (NO_3^-) leaching, especially in coarse-textured and highly permeable soils (Alkharabsheh et al., 2021). Biochar can initially immobilize plant available ammonium by sorptive processes but may also help to conserve nitrogen over the long term and increase uptake efficiency by plants, thereby reducing loss from the soil system (Lyu et al., 2024). Additionally, biochar influences microbial mediated nitrogen transformations, including nitrification processes, which can help to manage nitrate buildup in soil. It also has structural stability that can help in soil aggregation and water regulation, which indirectly supports the retention of N by decreasing runoff and leaching pathways (Hossain et al., 2020). Compost, on the other hand, releases readily mineralizable nitrogen by rapid degradation of organic matter thereby allowing for rapid mobilization of

nitrogen for the use of plants. It also promotes microbial activity and enzymatic processes to manage nitrogen cycling and enhance soil fertility. Compost nitrogen, however, tends to lose its nitrogen more rapidly, resulting in greater potential for short-term losses than biochar-associated nitrogen retention. Biochar and compost are complementary nutrients, as biochar improves nutrient retention and compost provides available nitrogen at the time of application. This interaction contributes to sustain soil fertility, to increase nutrient-use efficiency and to minimize nitrogen losses (Tortosa et al., 2023).

4.3 Soil pH Regulation and Buffering Capacity

Biochar typically has neutral to mild alkaline properties and when applied to soil can lead to an increase in the soil pH depending on the ash content and source of the biochar. The pH modification not only increases the solubility of nutrients but also increases the buffering capacity of the soil in the long term (Qi et al., 2022). Compost usually has a slightly acidic to near neutral pH, and when applied has a more moderate and gradual effect on soil pH. Its effect on soil pH is largely dependent on feedstock composition and degree of decomposition. The pH changes induced by compost biofertilizers are typically transient as they mineralize quickly. Biochar and compost can be used together to regulate the pH of soils by offsetting the alkaline or acid properties of the soil to optimize nutrient availability and microbial activity. This regulatory effect, however, may be reduced over time due to degradation and alteration of both materials in the soil system. Therefore, it is crucial that application rates and combinations are managed properly to ensure the soil chemical conditions remain stable for sustained plant growth and soil productivity (Alkharabsheh et al., 2021). The directional changes in key soil physical and chemical parameters under individual and combined amendments are consolidated in Table 3.

5. Effects of Biochar and Compost on Soil Biological Properties

5.1 Microbial Community Structure and Functional Activity

Biochar significantly influences soil microbial ecology by modifying habitat conditions and altering soil physico-chemical environments, leading to rapid shifts in microbial community structure and ecological functioning (Lv et al., 2022). The porous structure creates a microhabitat that can host bacterial, fungal and algal growth which increases microbial diversity and stabilizes soil biological processes (Kumar & Bhattacharya, 2021). These habitat effects are closely related to the increased nutrient cycling and soil aggregation processes. The addition of compost further promotes microbial activity by adding a variety of microbial

populations and organic substrates that are readily available. This facilitates an increase in soil microbial biomass, promotes degradation of organic matter, and enhances soil structure by increasing aggregation and porosity development (Xu et al. 2022). Further, compost associated microbial consortia play a disease suppression role by fostering antagonistic interactions with soil-borne pathogens, thereby enhancing the health and productivity of plants (Aguilar-Paredes et al., 2023).

5.2 Bacterial Dynamics and Nutrient Cycling Processes

Biochar increases labile carbon fractions and provides adsorption surfaces that promote the proliferation and metabolic activity of bacteria (Dai et al., 2020). Its porous structure promotes the bacterial colonization and decreases loss of microorganisms due to leaching. Some bacterial groups are also able to convert the carbon associated with biochar into humus-like compounds, which leads to long-term soil carbon stabilization (Lu et al., 2020). Nitrogen fixing bacteria has been reported to be more abundant, and microbial diversity has increased, leading to better nitrogen cycling and soil fertility (Das et al., 2023). Compost acts as a rich substrate for bacterial growth due to its high content of decomposable organic matter and nutrients (Siedt et al., 2021). It fosters functional specialization and diversity of microorganisms, especially in the process of transforming nutrients. Additionally, compost promotes the growth of beneficial bacteria used in nitrogen fixation and the mineralization of nutrients and the suppression of the pathogens (Singha & Singha, 2023). Moreover, the microbial community found in compost plays a role in soil bioremediation processes, which includes the degradation of natural and organic contaminants (Manea et al., 2024).

5.3 Fungal Communities, Mycorrhizae, and Soil Aggregation

Organic amendments strongly promote the growth of fungus, especially the proliferation of hyphae which improves soil aggregation and structural stability. Volatile matter content and pore structure are known to regulate the fungal retention and activity in biochar. Compost further enhances fungal diversity and abundance by supplying continuous organic substrates and nutrients, leading to improved soil biological functioning (Oni et al., 2019). Fungi are major agents in decomposition processes, which enzymatically convert complex organic compounds to simpler ones, hence contributing to humus formation and long-term carbon stabilization (Frimpong et al., 2021). They form hyphal networks that increase soil particle aggregation and enhance the structural coherence of the soil. Mycorrhizal associations also improve plant nutrient uptake, especially phosphorous uptake, and overall plant resilience under nutrient-poor environments. Compost application has been shown to

Table 3. Summary of changes in soil physical and chemical properties under individual and combined biochar and compost amendments.

Soil Parameter	Biochar Only	Compost Only	Biochar + Compost	Primary Mechanism
A. Soil Physical Properties				
Bulk Density	Reduction (10–30%) due to low-density carbon	Reduction (5–15%) via organic matter addition	Reduction (15–35%) via synergistic aggregation and dilution	Pore space expansion, improved soil structure, and dilution of mineral fraction
Total Porosity	Increase (10–25%) from porous structure	Increase (5–12%) via organic aggregation	Increase (15–30%) from combined pore formation	Development of biochar micro–mesopores and organic matter-induced aggregation
Water-Holding Capacity	Increase (15–40%) via adsorption and capillarity	Increase (10–25%) via organic colloids	Increase (20–50%) via complementary retention mechanisms	Micropore water adsorption and hydrophilic organic matter interactions
Aggregate Stability	Long-term improvement via stable carbon structure	Short-term improvement via microbial binding agents	Strong and sustained stability via organo-mineral binding	Hyphal proliferation, microbial exudates, and stable organo-mineral complexes
Saturated Hydraulic Conductivity	Variable improvement via pore connectivity	Moderate improvement in soil tilth	Consistent improvement in macro- and microporosity	Enhanced pore connectivity and reduced compaction
B. Soil Chemical Properties				
Soil Organic Matter	Increase via recalcitrant carbon stabilization	Increase via labile organic matter addition and decomposition	Substantial increase via complementary carbon fractions (≈15–25%)	Integration of stable and labile carbon pools
Soil pH	Tendency toward alkalization due to ash content	Minimal change toward near-neutral conditions	Buffered and stabilized pH through acid–base interactions	Acid–base neutralization and buffering capacity
Cation Exchange Capacity (CEC)	Moderate to high increase via surface functional groups	Moderate increase via humified organic matter	Strong synergistic increase via functional groups and humus formation	Surface charge development and humification processes
Available Nitrogen	Initial immobilization followed by slow release	Rapid mineralization and nutrient release	Sustained nitrogen availability via controlled release dynamics	Nutrient adsorption, microbial immobilization–mineralization cycling
Available Phosphorus	Increase via pH effects and sorption regulation	Increase via organic matter mineralization	Strong enhancement via synergistic release and retention	Microbial phosphorus cycling and adsorption–desorption balance
Nitrogen Use Efficiency	Improved via reduced leaching losses	Improved via direct nutrient supply	Maximized efficiency via combined retention and release processes	Synchronization of nutrient supply with plant demand

enhance mycorrhizal activity and plant nutrient uptake efficiency, particularly nitrogen and phosphorus acquisition (Shakoor et al., 2021). Moreover, some of these fungal taxa in compost help in the biological control of soil-borne pathogens and degrade pollutants, thus enhancing soil health and ecological rehabilitation potential (Wahab et al., 2023).

5.4 Microbial Biomass and Soil Enzymatic Activity

Microbial biomass is a key indicator of soil fertility and ecosystem functioning, reflecting changes in microbial growth and metabolic activity. Biochar alters the pH, aeration, and nutrient levels in microbial habitats, influencing microbial biomass and the nitrogen transformation process (Pandian et al., 2024). Controlling organic matter availability helps to establish a more stable microbial community and enhance microbial colonization. The labile organic substrates and nutrients in compost significantly improve microbial biomass, respiration rate, and enzymatic activity (Rastogi et al., 2020). It improves soil enzymatic processes such as oxidoreductase and hydrolase activities, which are key in the breakdown of organic matter and the release of nutrients (Lata et al., 2023). These processes are interdependent to improve soil nutrient and fertility. Enzymes are recognized as key biogeochemical regulators, primarily synthesized by microbial communities, and soil biochemical reaction indicators, (Jamir et al., 2019). Improvements of up to 27% in enzyme activity such as dehydrogenase have been observed, indicating enhanced metabolic activity of microorganisms. When combined, biochar and compost increase the efficiency of enzymes and ensure long-term soil health and productivity.

6. Effects of Biochar–Compost Co-Application in Agricultural Soils

The combined application of biochar and compost produces synergistic effects that exceed the benefits of individual amendments by integrating structural stability with biological activity (Shifa et al., 2024). Biochar offers a long-lasting porous matrix that improves nutrient holding capacity and provides microbial habitat, while compost offers labile carbon, nutrients, and active microbial populations. This interaction enhances the efficiency of the nutrient cycling and minimizes nutrient losses by leaching and volatilization. The application strategies are different, such as direct mixing, pre-incubation, and co-composting, and are known to affect nutrient dynamics and soil response (Le Guyader et al., 2025). Typical application rates of 7–10 t ha⁻¹ biochar combined with 20–40 t ha⁻¹ compost have demonstrated improved soil fertility and crop productivity across multiple soil types. It has been reported that it has beneficial effects such as increasing the chlorophyll content, biomass production and improving the chemical properties of soils, such as total nitrogen, available phosphorus, cation exchange

capacity, soil organic carbon and water-holding capacity (Manolikaki & Diamadopoulos, 2019). However, the outcomes are not always clear, as they are significantly dependent on soil type, crop species and environmental conditions, with some studies reporting no effect at all (Teodoro et al., 2020). In addition to field use, biochar can also be used to improve composting processes by increasing nutrient retention during composting and decreasing nutrient losses.

6.1 Biochar Application Strategies and Soil Process Interactions

Biochar interactions with the soil system are dependent on application methods. Surface spreading, plow-layer incorporation, and deep banding are common practices and can sometimes be applied at rates greater than 5 t ha⁻¹ (Amonette et al., 2021). These techniques change the soil aeration, microbial distribution and mobility of nutrients with depth and mixing intensity. The fate of biochar when added to soils depends on the placement method, particularly for nitrogen leaching, transport of dissolved organic carbon, and hydraulic properties. Plow-layer incorporation can increase the response capacity to environmental changes but excessive mechanical action can promote the degradation of organic matter and decrease the efficiency of microorganisms (Ding et al., 2019). Overall, application approach is a key factor influencing the agricultural effectiveness of biochar.

6.2 Compost Application Strategies and Nutrient Release Dynamics

Compost applications in agriculture, horticulture, forestry and land restoration are widely used in order to enhance soil fertility and structure (Ciavatta et al., 2022). Compost is a slow-release source of nutrients due to microbial mineralization. Typically, only a fraction of total nitrogen (8–12%) and phosphorus (25–40%) becomes plant-available in the first year of application, with measurable soil improvements continuing over long-term use (Głąb et al., 2025). Compost gives long-term nutrient cycles and soil fertility to the soil due to its abilities to improve organic matter, microbiology and soil fertility. It accumulates with time and repeated applications are important for ensuring soil productivity and stability.

7. Role of Biochar–Compost Co-Application in Greenhouse Gas Mitigation

Application of biochar and compost together is identified as a promising approach to lower greenhouse gas (GHG) emissions with synergistic physical, chemical and microbial effects. Biochar's porous structure and its ability to interact with nutrient-enriched compost affect nitrogen transformation, enhance aeration and stabilize carbon and nitrogen cycling, which lowers the release of methane (CH₄),

nitrous oxide (N₂O) and ammonia (NH₃) (Ferdous et al., 2023). Figure 2 illustrates the key pathways through which biochar and compost mitigate CH₄, N₂O, and NH₃ emissions, including methanotrophic stimulation, redox modification of denitrification processes, and NH₄⁺ adsorption mechanisms, alongside the associated reduction ranges.

7.3. Ammonia (NH₃) Volatilization Control

The NH₃ emissions reduction effect of biochar is due to its high surface area and cation exchange capacity, which adsorbs the ammonium (NH₄⁺) to the biochar and reduces the amount available to be volatilized to NH₃. Compost improves microbial immobilization of nitrogen to biomass. It is

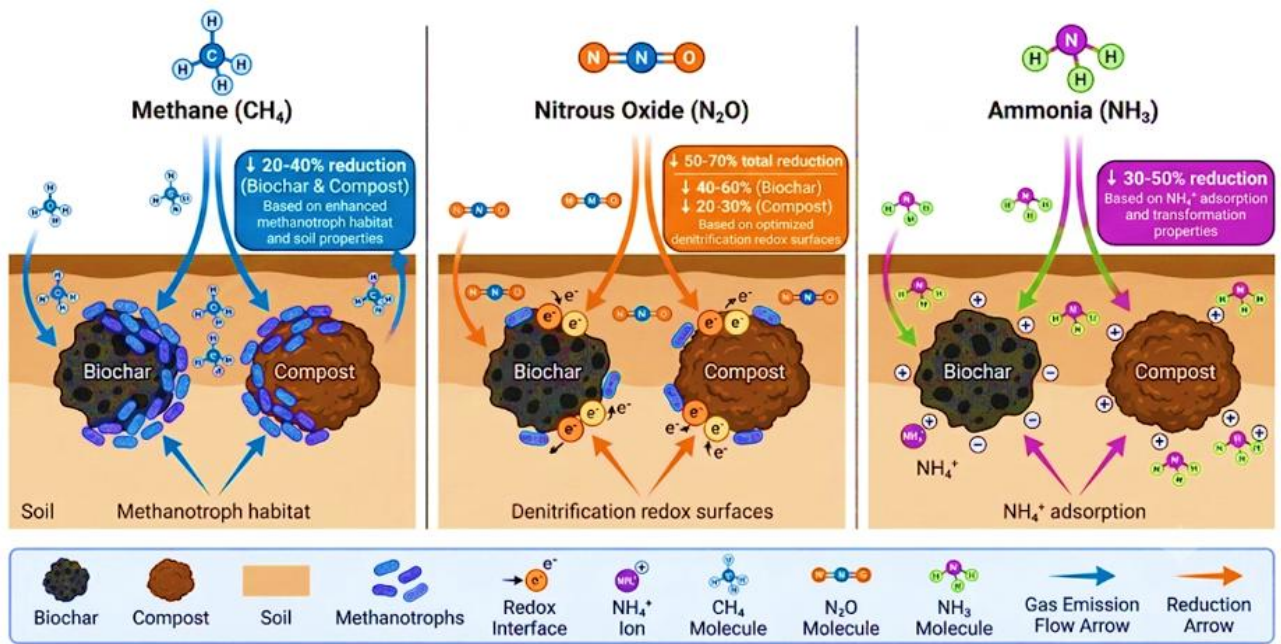


Figure 2. Schematic representation of greenhouse gas (GHG) reduction pathways under biochar and compost application.

7.1. Methane (CH₄) Mitigation

Biochar improves soil aeration and provides microhabitats that support the growth of methanotrophic bacteria and inhibit methanogenic bacteria. Compost provides labile carbon substrates that support balanced microbial communities. These effects combined can lower CH₄ emissions by 20-40% relative to compost-only systems (Wu et al., 2019).

7.2. Nitrous Oxide (N₂O) Reduction

The mitigation effect is the most significant for N₂O, with reductions of 50-70% for combined application. Biochar promotes complete denitrification to N₂ rather than N₂O through redox-active surfaces and improved soil aeration, while also adsorbing nitrogen compounds and limiting substrate availability for incomplete denitrification pathways (Javanmard et al., 2026). In addition, compost provides a steady nitrogen pool with little change in the microbial infrastructure, resulting in more stable nitrogen cycling (Maier et al., 2022).

reported that NH₃ volatilization decreased by 30–50% under the co-application systems compared to conventional compost amendments (Field studies; An et al., 2023).

7.4. Carbon Sequestration and Climate Function

Biochar contributes stable, recalcitrant carbon that persists for centuries, whereas compost supplies labile carbon that supports short-term microbial activity. This dual carbon system enhances both immediate and long-term soil carbon storage, increasing soil organic carbon by 15–25% over time (Li & Tasnady, 2023). Additionally, improved microbial habitat diversity within biochar pores promotes efficient nutrient cycling while minimizing GHG by-products (Palansooriya et al., 2019). Overall, the system simultaneously reduces emissions and enhances soil fertility, aligning with climate-smart agricultural goals. The magnitude of emission reductions and underlying mechanisms for each greenhouse gas are summarized in Table 4.

Table 4. Greenhouse gas mitigation and carbon sequestration responses under biochar–compost co-application, with associated biochar, compost, and microbial/biochemical mechanisms (values relative to compost-only or conventional amendments).

GHG / Emission	Reduction (%)	Biochar Mechanism	Compost Mechanism	Microbial / Biochemical Basis
CH₄ (Methane)	20–40% reduction	Improved aeration; suppression of methanogenesis; enhanced methanotroph habitat	Labile C supports balanced microbial activity	Increased CH ₄ oxidation by methanotrophic bacteria
N₂O (Nitrous oxide)	50–70% reduction	Redox-active surfaces; improved aeration favoring complete denitrification	Gradual N release reducing excess substrate	Enhanced <i>nosZ</i> activity and N ₂ O → N ₂ reduction
NH₃ (Ammonia)	30–50% reduction	High CEC; NH ₄ ⁺ adsorption reducing volatilization	Microbial N immobilization	Reduced NH ₄ ⁺ availability and pH-driven volatilization
CO₂ (Soil respiration)	Net reduction (system-dependent)	Recalcitrant carbon resists decomposition	Short-term microbial respiration from labile OM	Long-term SOC gain offsets respiration losses
SOC sequestration	15–25% increase	Stable aromatic carbon formation	Humus and microbial necromass formation	Organo-mineral stabilization and aggregate protection

8. Soil Remediation and Ecosystem Restoration Using Biochar–Compost Systems

The use of biochar–compost co-application offers a holistic remediation solution that links contaminant immobilization to biological restoration of contaminated soils. The high surface area, functional groups, and porosity of biochar allow it to adsorb and immobilize heavy metals like Pb, Cd, and as, through complexation and precipitation reactions, making it a stable sorbent (Akhtar et al., 2024). Its alkaline nature also contributes to pH neutralization in acidic and polluted soils. Compost complements this process by supplying organic matter and diverse microbial populations that enhance biodegradation of organic pollutants and promote formation of stable metal–organic complexes (Gao et al., 2023). Further, compost enhances soil structure, moisture and microbial habitat qualities which promote faster ecological recovery and establishment of plant life in degraded systems (Sayara et al., 2020). For organic contaminants such as polycyclic aromatic hydrocarbons (PAHs), combined amendments significantly enhance remediation efficiency (Gusiatin & Rouhani, 2023). Biochar has an increasing sorption capacity with a decrease in bioavailability, and compost has an enhancing effect on microbial degradation pathways. It has been demonstrated that when combined with compost, they can enhance PAH sorption by up to 100% compared to compost alone and may promote degradation by

providing more microbial activity. In some instances, however, the bioavailability may decrease but the contaminants may not be fully removed and degraded, depending upon the type of contaminant, soil properties, and amendment characteristics. A conceptual framework linking biochar and compost remediation mechanisms to contaminant immobilization and ecosystem restoration outcomes is presented in Figure 4.

9. Environmental Risks and Potential Trade-Offs

While useful, applications of biochar and compost can present environmental hazards if not managed properly. The quality and pyrolysis conditions of the feedstock can result in the presence of residual contaminants like heavy metals, PAHs, or persistent organic compounds in biochar (Alharbi et al., 2023). Similarly, compost may introduce pathogens, pesticide residues, or industrial contaminants when derived from untreated waste streams. However, improper or excessive composting may result in nutrient imbalance, accumulation of salt and immobilization of nitrogen, thereby temporarily limiting the availability of nutrients to plant growth and microbial activity (Oyebiyi et al., 2026). Anaerobic decomposition can produce unwanted gases like methane or hydrogen sulfide, which have a negative impact on soil quality and plant health. Thus, caution should be exercised in choosing feedstocks, compost maturity, and

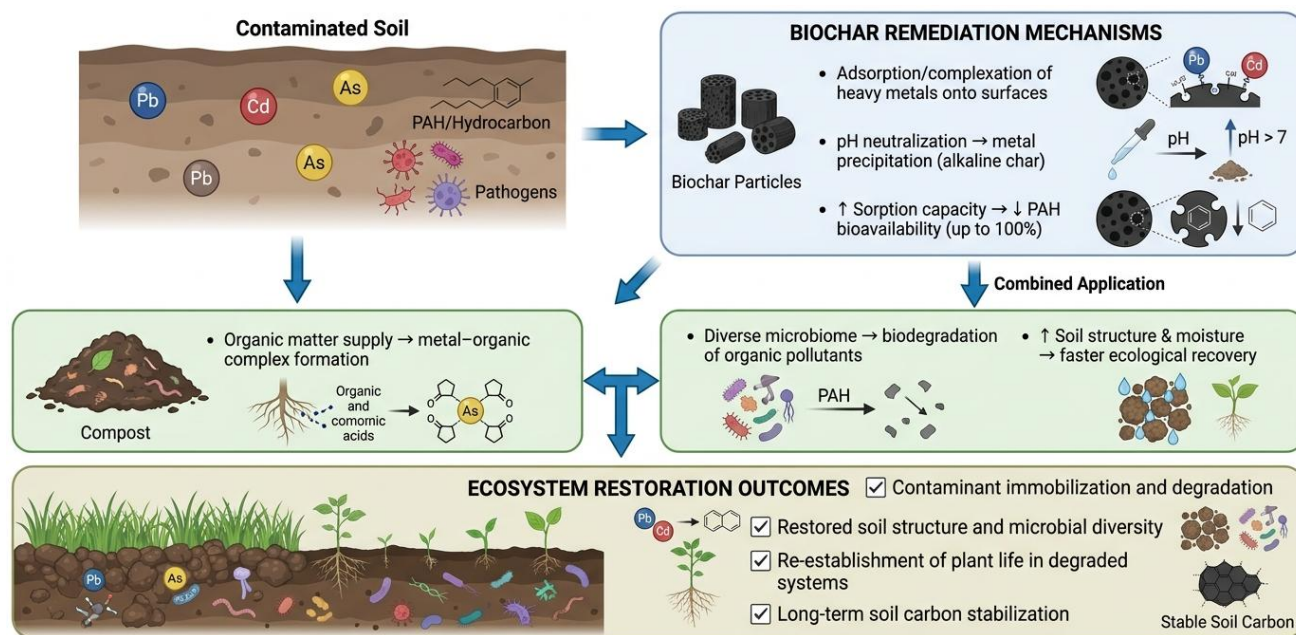


Figure 4. Conceptual framework of biochar–compost co-application for contaminated soil remediation. Biochar immobilizes heavy metals and reduces PAH bioavailability, while compost enhances microbial degradation and soil recovery.

biochar production conditions for safe application. Both amendments can have a beneficial effect on soil health, nitrate retention, and crop productivity when properly managed, especially in the first few years after they are applied.

10. Future Directions

Standardized production and application guidelines for biochar and compost co-application should be developed for future studies, to ensure uniformity, safety, and the repeatability of biochar production and application across agroecosystems. Quality control of biochar feedstocks and pyrolysis conditions is critical because these parameters have a significant impact on soil properties. Optimization of biochar integration strategies, especially co-composting systems, optimizing nutrient retention, microbial efficiency and GHG mitigation potential is a key research priority. Real-world performance, sustainability and scalability require long-term field trials under varying climatic and soil conditions beyond short-term lab results. Further mechanistic research is required to better understand plant–soil–microbe interactions, including nutrient sorption–desorption dynamics, microbial functional shifts, and rhizosphere processes. Special attention should be given to water-limited and drought-prone environments where soil amendment effects on hydraulic properties are critical. In an applied way, guidelines should be designed according to soil texture, crop

type and environmental conditions for each region. Integration of biochar and compost with conservation agriculture practices, precision nutrient management, and climate-smart farming systems will further enhance their effectiveness. Finally, future work should integrate agronomic performance with environmental risk assessment and socio-economic feasibility to ensure that biochar–compost systems are not only scientifically effective but also practically viable and policy-relevant for sustainable agricultural transformation.

11. Conclusion

Soil degradation is a persistent problem that poses a threat to agricultural productivity and ecosystem stability around the world. The combination of biochar and compost is an emerging climate-smart strategy to improve soil health through physical structure, nutrient cycling, microbial activity and water-holding capacity. These amendments also contribute to long-term carbon sequestration and significant reductions in greenhouse gas emissions, particularly N_2O , CH_4 , and NH_3 . Their effectiveness is, however, greatly dependent on the characteristics of the materials, soil conditions, climate and management. Although the short- and medium-term benefits have been well established, there is a limited number of long-term field data. Future research should therefore focus on mechanistic understanding, standardized application strategies, and long-term

sustainability assessment to fully realize their potential in global soil restoration and climate mitigation strategies.

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8. Conflict of Interest

The authors declare no conflict of interest.

9. Authors' Contribution

Laraib Saeed conceived the study, conducted the literature review, and prepared the original manuscript draft. Akaninyene Joseph contributed to manuscript writing, critical revision, and intellectual content. Sania Saeed assisted with literature collection, data organization, and manuscript editing. Raana Fahim supervised the study, provided guidance throughout the research process, and reviewed the final manuscript. All authors read and approved the final manuscript.

10. SDGs Addressed

This study supports SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) by promoting sustainable soil restoration, improved soil fertility, enhanced carbon sequestration, and reduced greenhouse gas emissions through the use of biochar and compost amendments.

References

- Abdelhak, M. (2022). Soil improvement in arid and semiarid regions for sustainable development. In *Natural Resources Conservation and Advances for Sustainability* (pp. 73–90). Elsevier. <https://doi.org/10.1016/B978-0-12-822976-7.00026-0>
- Aguilar-Paredes, A., Valdés, G., Araneda, N., Valdebenito, E., Hansen, F., & Nuti, M. (2023). Microbial community in the composting process and its positive impact on the soil biota in sustainable agriculture. *Agronomy*, 13(2), 542. <https://doi.org/10.3390/agronomy13020542>
- Ahmed, S. F., Mehejabin, F., Chowdhury, A. A., Almomani, F., Khan, N. A., Badruddin, I. A., & Kamangar, S. (2024). Biochar produced from waste-based feedstocks: Mechanisms, affecting factors,

economy, utilization, challenges, and prospects. *GCB Bioenergy*, 16(8), e13175. <https://doi.org/10.1111/gcbb.13175>

- Akhtar, M. S., Ali, S., & Zaman, W. (2024). Innovative adsorbents for pollutant removal: Exploring the latest research and applications. *Molecules*, 29(18), 4317. <https://doi.org/10.3390/molecules29184317>
- Alharbi, H. A., Alotaibi, K. D., El-Saeid, M. H., & Giesy, J. P. (2023). Polycyclic aromatic hydrocarbons (PAHs) and metals in diverse biochar products: Effect of feedstock type and pyrolysis temperature. *Toxics*, 11(2), 96. <https://doi.org/10.3390/toxics11020096>
- Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., Almutairi, K. F., & Al-Saif, A. M. (2021). Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy*, 11(5), 993. <https://doi.org/10.3390/agronomy11050993>
- Amonette, J. E., Archuleta, J. G., Fuchs, M. R., Hills, K. M., Yorgey, G. G., Flora, G., ... Wheeler, E. (2021). *Biomass to biochar: Maximizing the carbon value*. Pullman, WA: Washington State University, Center for Sustaining Agriculture and Natural Resources. <https://csanr.wsu.edu/biomass2biochar/>
- An, H., Lee, Y., Lee, J., Yoon, S., Park, S.-J., Hong, S.-C., Kim, J.-H., & Kim, S. Y. (2023). Does co-application of compost and mineral fertilizers reduce gaseous nitrogen (NH₃ and N₂O) losses and improve nitrogen use efficiency from maize-growing soil? *Korean Journal of Soil Science and Fertilizer*, 56(1), 119–125. <https://doi.org/10.7745/KJSSF.2023.56.1.119>
- Ayilara, M. S., Olanrewaju, O. S., Babalola, O. O., & Odeyemi, O. (2020). Waste management through composting: Challenges and potentials. *Sustainability*, 12(11), 4456. <https://doi.org/10.3390/su12114456>
- Bagheri Novair, S., Cheraghi, M., Faramarzi, F., Asgari Lajayer, B., Senapathi, V., Astatkie, T., & Price, G. W. (2023). Reviewing the role of biochar in paddy soils: An agricultural and environmental perspective. *Ecotoxicology and Environmental Safety*, 263, 115228. <https://doi.org/10.1016/j.ecoenv.2023.115228>
- Bagheri Novair, S., Cheraghi, M., Faramarzi, F., Asgari Lajayer, B., Senapathi, V., Astatkie, T., & Price, G. W. (2023). Reviewing the role of biochar in paddy

- soils: An agricultural and environmental perspective. *Ecotoxicology and Environmental Safety*, 263, 115228. <https://doi.org/10.1016/j.ecoenv.2023.115228>
- Bahadori, M., Chen, C., Lewis, S., Boyd, S., Rashti, M. R., Esfandbod, M., Garzon-Garcia, A., Van Zwieten, L., & Kuzyakov, Y. (2021). Soil organic matter formation is controlled by the chemistry and bioavailability of organic carbon inputs across different land uses. *Science of the Total Environment*, 770, 145307. <https://doi.org/10.1016/j.scitotenv.2021.145307>
- Bolan, S., Hou, D., Wang, L., Hale, L., Egamberdieva, D., Tammeorg, P., Li, R., Wang, B., Xu, J., Wang, T., Sun, H., Padhye, L. P., Wang, H., Siddique, K. H. M., Rinklebe, J., Kirkham, M. B., & Bolan, N. (2023). The potential of biochar as a microbial carrier for agricultural and environmental applications. *Science of the Total Environment*, 886, 163968. <https://doi.org/10.1016/j.scitotenv.2023.163968>
- Botta, G. F., Antille, D. L., Nardon, G. F., Rivero, D., Bienvenido, F., Contessotto, E. E., Ezquerra-Canalejo, A., & Ressler, J. M. (2022). Zero and controlled traffic improved soil physical conditions and soybean yield under no-tillage. *Soil and Tillage Research*, 215, 105235. <https://doi.org/10.1016/j.still.2021.105235>
- Burgos, P., Madejón, E., Pérez-de-Mora, A. and Cabrera, F., 2008. Horizontal and vertical variability of soil properties in a trace element contaminated area. *International Journal of Applied Earth Observation and Geoinformation*, 10(1), pp.11-25.
- Chen, X., Li, L., Li, X., Kang, J., Xiang, X., Shi, H., & Ren, X. (2023). Effect of biochar on soil-water characteristics of soils: A pore-scale study. *Water*, 15(10), 1909. <https://doi.org/10.3390/w15101909>
- Ciavatta, C., Centemero, M., Toselli, M., Zaccone, C., & Senesi, N. (2022). Compost production, analysis and applications in agriculture. In Y. Yang, M. Keiluweit, N. Senesi, & B. Xing (Eds.), *Multi-Scale Biogeochemical Processes in Soil Ecosystems: Critical Reactions and Resilience to Climate Changes* (pp. 297–321). John Wiley & Sons. <https://doi.org/10.1002/9781119480419.ch13>
- Cowan-Ellsberry, C., Belanger, S., Dorn, P., Dyer, S., McAvoy, D., Sanderson, H., Versteeg, D., Ferrer, D. and phosphorus. *Journal of Cleaner Production*, 257, 120573. <https://doi.org/10.1016/j.jclepro.2020.120573>
- Dămătîrcă, C., Moretti, B., Bertora, C., Ferrarini, A., Lerda, C., Mania, I., Celi, L., Gorra, R., & Zavattaro, L. (2023). Residue incorporation and organic fertilisation improve carbon and nitrogen turnover and stabilisation in maize monocropping. *Agriculture, Ecosystems & Environment*, 342, 108255. <https://doi.org/10.1016/j.agee.2022.108255>
- Das, S. K., Ghosh, G. K., & Avasthe, R. (2023). Application of biochar in agriculture and environment, and its safety issues. *Biomass Conversion and Biorefinery*, 13(2), 1359–1369. <https://doi.org/10.1007/s13399-020-01013-4>
- Ding, Y., Gao, X., Qu, Z., Jia, Y., Hu, M., & Li, C. (2019). Effects of biochar application and irrigation methods on soil temperature in farmland. *Water*, 11(3), 499. <https://doi.org/10.3390/w11030499>
- Ferdous, J., Mumu, N. J., Hossain, M. B., Hoque, M. A., Zaman, M., Müller, C., Jahiruddin, M., Bell, R. W., & Jahangir, M. M. R. (2023). Co-application of biochar and compost with decreased N fertilizer reduced annual ammonia emissions in wetland rice. *Frontiers in Sustainable Food Systems*, 6, 1067112. <https://doi.org/10.3389/fsufs.2022.1067112>
- Frimpong, K. A., Abban-Baidoo, E., & Marschner, B. (2021). Can combined compost and biochar application improve the quality of a highly weathered coastal savanna soil? *Heliyon*, 7(5), e07089. <https://doi.org/10.1016/j.heliyon.2021.e07089>
- Gao, J., Han, H., Gao, C., Wang, Y., Dong, B., & Xu, Z. (2023). Organic amendments for in situ immobilization of heavy metals in soil: A review. *Chemosphere*, 335, 139088. <https://doi.org/10.1016/j.chemosphere.2023.139088>
- Głąb, T., Gondek, K., & Mierzwa-Hersztek, M. (2025). Enhancing soil physical quality with compost amendments: Effects of particle size and additives. *Agronomy*, 15(2), 458. <https://doi.org/10.3390/agronomy15020458>
- Guo, X., Liu, H., & Zhang, J. (2020). The role of biochar in organic waste composting and soil improvement: A review. *Waste Management*, 102, 884–899. <https://doi.org/10.1016/j.wasman.2019.12.003>

- Gusiatin, M. Z., & Rouhani, A. (2023). Application of selected methods to modify pyrolyzed biochar for the immobilization of metals in soil: A review. *Materials*, 16(23), 7342. <https://doi.org/10.3390/ma16237342>
- Hassan, S. H., Chafik, Y., Sena-Velez, M., Lebrun, M., Scippa, G. S., Bourgerie, S., Trupiano, D., & Morabito, D. (2023). Importance of application rates of compost and biochar on soil metal(loid) immobilization and plant growth. *Plants*, 12(11), 2077. <https://doi.org/10.3390/plants12112077>
- Hossain, A., Krupnik, T. J., Timsina, J., Mahboob, M. G., Chaki, A. K., Farooq, M., Bhatt, R., Fahad, S., & Hasanuzzaman, M. (2020). Agricultural land degradation: Processes and problems undermining future food security. In M. Hasanuzzaman (Ed.), *Environment, Climate, Plant and Vegetation Growth* (pp. 17–61). Springer International Publishing. https://doi.org/10.1007/978-3-030-49732-3_2
- Hou, J., Pugazhendhi, A., Sindhu, R., Vinayak, V., Thanh, N. C., Brindhadevi, K., Lan Chi, N. T., & Yuan, D. (2022). An assessment of biochar as a potential amendment to enhance plant nutrient uptake. *Environmental Research*, 214, 113909. <https://doi.org/10.1016/j.envres.2022.113909>
- Iacomino, G., Sarker, T. C., Ippolito, F., Bonanomi, G., Vinale, F., Staropoli, A., & Idbella, M. (2022). Biochar and compost application either alone or in combination affects vegetable yield in a volcanic Mediterranean soil. *Agronomy*, 12(9), 1996. <https://doi.org/10.3390/agronomy12091996>
- Jamir, E., Kangabam, R. Das, Borah, K., Tamuly, A., Deka Boruah, H. P., & Silla, Y. (2019). Role of soil microbiome and enzyme activities in plant growth nutrition and ecological restoration of soil health. In *Soil Health and Sustainable Agriculture* (pp. 99–132). Springer. https://doi.org/10.1007/978-981-13-9117-0_5
- Javanmard, A., Zuki, F. M., Wan Daud, W. M. A., & Abdul Patah, M. F. (2026). Biochar for sustainable soil management: A review of production technologies, functionalization strategies, and environmental synergies. *BioEnergy Research*, 19(1), 66. <https://doi.org/10.1007/s12155-026-10995-4>
- Kumar, A., & Bhattacharya, T. (2021). Biochar: a sustainable solution. *Environment, Development and Sustainability*, 23(5), 6642–6680. <https://doi.org/10.1007/s10668-020-00970-0>
- Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, 112(5), 3265–3277. <https://doi.org/10.1002/agi2.20282>
- Le Guyader, E., Oueriemmi, H., Clivot, H., El Mazlouzi, M., Guillaneuf, A., Gommeaux, M., Marin, B., Zoghalmi, I. R., Alavoine, G., Sbih, M., Boumaraf, B., & Morvan, X. (2025). Influence of biochar and compost and their interaction on carbon and nitrogen mineralization in a Saharan sandy soil. *Geoderma Regional*, 42, e01002. <https://doi.org/10.1016/j.geodrs.2025.e01002>
- Li, S., & Tasnady, D. (2023). Biochar for soil carbon sequestration: Current knowledge, mechanisms, and future perspectives. *C*, 9(3), 67. <https://doi.org/10.3390/c9030067>
- Linh, D. T. T., Khoi, C. M., Ritz, K., Sinh, V. N., Phuong, N. T. K., My, H. M. T., Linh, T. B., Minh, D. D., Linh, T. T., & Toyota, K. (2023). Effects of rice husk biochar and compost amendments on soil phosphorus fractions, enzyme activities and rice yields in salt-affected acid soils in the Mekong Delta, Viet Nam. *Agronomy*, 13(6), 1593. <https://doi.org/10.3390/agronomy13061593>
- Lu, H., Yan, M., Wong, M. H., Mo, W. Y., Wang, Y., Chen, X. W., & Wang, J.-J. (2020). Effects of biochar on soil microbial community and functional genes of a landfill cover three years after ecological restoration. *Science of the Total Environment*, 717, 137133. <https://doi.org/10.1016/j.scitotenv.2020.137133>
- Lv, Y., Xu, L., Guo, X., Liu, J., Zou, B., Guo, Y., Zhang, Y., Li, H., Zheng, G., Guo, Y., & Zhao, M. (2022). Effect of biochar on soil physiochemical properties and bacterial diversity in dry direct-seeded rice paddy fields. *Agronomy*, 13(1), 4. <https://doi.org/10.3390/agronomy13010004>
- Lyu, H., Li, Y., Wang, Y., Wang, P., Shang, Y., Yang, X., Wang, F., & Yu, A. (2024). Drive soil nitrogen transformation and improve crop nitrogen absorption and utilization—A review of green manure applications. *Frontiers in Plant Science*, 14, 1305600. <https://doi.org/10.3389/fpls.2023.1305600>
- Maier, R., Soja, G., Friesl-Hanl, W., Zechmeister-Boltenstern, S., Michel, K., Tatzber, M., & Kitzler, B. (2022). Biochar-compost additions have strong short-term effects on carbon and nitrogen emissions from an agricultural soil. *Agronomy*, 12(12), 2959. <https://doi.org/10.3390/agronomy12122959>

- Malone, Z., Berhe, A. A., & Ryals, R. (2023). Impacts of organic matter amendments on urban soil carbon and soil quality: A meta-analysis. *Journal of Cleaner Production*, 419, 138148. <https://doi.org/10.1016/j.jclepro.2023.138148>
- Mandal, S., Pu, S., Adhikari, S., Ma, H., Kim, D.-H., Bai, Y., & Hou, D. (2021). Progress and future prospects in biochar composites: Application and reflection in the soil environment. *Critical Reviews in Environmental Science and Technology*, 51(3), 219–271. <https://doi.org/10.1080/10643389.2020.1713030>
- Manea, E. E., Bumbac, C., Dinu, L. R., Bumbac, M., & Nicolescu, C. M. (2024). Composting as a sustainable solution for organic solid waste management: Current practices and potential improvements. *Sustainability*, 16(15), 6329. <https://doi.org/10.3390/su16156329>
- Manolikaki, I., & Diamadopoulos, E. (2019). Positive effects of biochar and biochar-compost on maize growth and nutrient availability in two agricultural soils. *Communications in Soil Science and Plant Analysis*, 50(5), 512–526. <https://doi.org/10.1080/00103624.2019.1566468>
- Marin, F., Tanislav, O. M., Constantinescu, M., Roman, A., Bucura, F., Oancea, S., & Zaharioiu, A. M. (2025). Biochar for soil fertility and climate mitigation: Review on feedstocks, pyrolysis conditions, functional properties, and applications with emerging AI integration. *Agriculture*, 15(22), 2345. <https://doi.org/10.3390/agriculture15222345>
- Oni, B. A., Oziegbe, O., & Olawole, O. O. (2019). Significance of biochar application to the environment and economy. *Annals of Agricultural Sciences*, 64(2), 222–236. <https://doi.org/10.1016/j.aos.2019.12.006>
- Oshins, C., Michel, F., Louis, P., Richard, T. L., & Rynk, R. (2022). The composting process. In *The Composting Handbook* (pp. 51–101). Elsevier. <https://doi.org/10.1016/B978-0-323-85602-7.00008-X>
- Oyebiyi, O. O., Laezza, A., Hoque, M. M., Thammavongsa, S., Li, M., Tspas, S., Tasiopoulos, A. J., Scopa, A., & Drosos, M. (2026). Organic amendments for sustainable agriculture: Effects on soil function, crop productivity and carbon sequestration under variable contexts. *C*, 12(1), 7. <https://doi.org/10.3390/c12010007>
- Palansooriya, K. N., Wong, J. T. F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., Bolan, N., Wang, H., & Ok, Y. S. (2019). Response of microbial communities to biochar-amended soils: A critical review. *Biochar*, 1(1), 3–22. <https://doi.org/10.1007/s42773-019-00009-2>
- Pandian, K., Vijayakumar, S., Mustaffa, M. R. A. F., Subramanian, P., & Chitraputhirapillai, S. (2024). Biochar – a sustainable soil conditioner for improving soil health, crop production and environment under changing climate: a review. *Frontiers in Soil Science*, 4, 1376159. <https://doi.org/10.3389/fsoil.2024.1376159>
- Peng, Y., Sun, Y., Fan, B., Zhang, S., Bolan, N. S., Chen, Q., & Tsang, D. C. W. (2021). Fe/Al (hydr)oxides engineered biochar for reducing phosphorus leaching from a fertile calcareous soil. *Journal of Cleaner Production*, 279, 123877. <https://doi.org/10.1016/j.jclepro.2020.123877>
- Purakayastha, T. J., Bera, T., Bhaduri, D., Sarkar, B., Mandal, S., Wade, P., Kumari, S., Biswas, S., Menon, M., Pathak, H., & Tsang, D. C. W. (2019). A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: Pathways to climate change mitigation and global food security. *Chemosphere*, 227, 345–365. <https://doi.org/10.1016/j.chemosphere.2019.03.170>
- Qi, Y., Fu, P., & Volmer, D. A. (2022). Analysis of natural organic matter via Fourier transform ion cyclotron resonance mass spectrometry: An overview of recent non-petroleum applications. *Mass Spectrometry Reviews*, 41(5), 647–661. <https://doi.org/10.1002/mas.21634>
- Rabbi, S. M. F., Minasny, B., Salami, S. T., McBratney, A. B., & Young, I. M. (2021). Greater, but not necessarily better: The influence of biochar on soil hydraulic properties. *European Journal of Soil Science*, 72(5), 2033–2048. <https://doi.org/10.1111/ejss.13105>
- Rastogi, M., Nandal, M., & Khosla, B. (2020). Microbes as vital additives for solid waste composting. *Heliyon*, 6(2), e03343. <https://doi.org/10.1016/j.heliyon.2020.e03343>
- Rivier, P.-A., Jamniczky, D., Nemes, A., Makó, A., Barna, G., Uzing, N., Rékási, M., & Farkas, C. (2022). Short-term effects of compost amendments to soil on soil structure, hydraulic properties, and water regime. *Journal of Hydrology and Hydromechanics*,

- 70(1), 74–88. <https://doi.org/10.2478/johh-2022-0004>
- Sayara, T., Basheer-Salimia, R., Hawamde, F., & Sánchez, A. (2020). Recycling of organic wastes through composting: Process performance and compost application in agriculture. *Agronomy*, 10(11), 1838. <https://doi.org/10.3390/agronomy10111838>
- Shakoor, A., Arif, M. S., Shahzad, S. M., Farooq, T. H., Ashraf, F., Altaf, M. M., Ahmed, W., Tufail, M. A., & Ashraf, M. (2021). Does biochar accelerate the mitigation of greenhouse gaseous emissions from agricultural soil? A global meta-analysis. *Environmental Research*, 202, 111789. <https://doi.org/10.1016/j.envres.2021.111789>
- Shifa, S., Worku, M., & Beyene, A. (2024). Co-application of compost and biochar improves soil properties and Desho grass growth on acidic soils in a tropical environment of Southwestern Ethiopia. *Cogent Food & Agriculture*, 10(1), 2290338. <https://doi.org/10.1080/23311932.2023.2290338>
- Siedt, M., Schäffer, A., Smith, K. E. C., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, 751, 141607. <https://doi.org/10.1016/j.scitotenv.2020.141607>
- Singh, H., Northup, B. K., Rice, C. W., & Prasad, P. V. V. (2022). Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: A meta-analysis. *Biochar*, 4(1), 8. <https://doi.org/10.1007/s42773-022-00138-1>
- Singha, R., & Singha, S. (2023). *Composting for a sustainable future: Turning waste into nutrient-rich soil*. In *Water–Soil–Plant–Animal Nexus in the Era of Climate Change* (pp. 279–297). Springer. <https://doi.org/10.1007/978-1-6684-9838-5.ch013>
- Sun, Y., Yang, J., Yao, R., Chen, X., & Wang, X. (2020). Biochar and fulvic acid amendments mitigate negative effects of coastal saline soil and improve crop yields in a three-year field trial. *Scientific Reports*, 10(1), 8946. <https://doi.org/10.1038/s41598-020-65730-6>
- Tang, K. H. D. (2025). Biochar amendments for soil restoration: Impacts on nutrient dynamics and microbial activity. *Environments*, 12(11), 425. <https://doi.org/10.3390/environments12110425>
- Teodoro, M., Trakal, L., Gallagher, B. N., Šimek, P., Soudek, P., Pohořelý, M., Beesley, L., Jačka, L., Kovář, M., Seyedsadr, S., & Mohan, D. (2020). Application of co-composted biochar significantly improved plant-growth relevant physical/chemical properties of a metal-contaminated soil. *Chemosphere*, 242, 125255. <https://doi.org/10.1016/j.chemosphere.2019.125255>
- Tsai, C.-C., & Chang, Y.-F. (2020). Effects of biochar to excessive compost-fertilized soils on the nutrient status. *Agronomy*, 10(5), 683. <https://doi.org/10.3390/agronomy10050683>
- Tsolis, V., & Barouchas, P. (2023). Biochar as soil amendment: The effect of biochar on soil properties using VIS-NIR diffuse reflectance spectroscopy, biochar aging and soil microbiology—A review. *Land*, 12(8), 1580. <https://doi.org/10.3390/land12081580>
- Vijay, V., Shreedhar, S., Adlak, K., Payyanad, S., Sreedharan, V., Gopi, G., Van der Voort, T. S., Malarvizhi, P., Yi, S., Gebert, J., & Aravind, P. (2021). Review of large-scale biochar field-trials for soil amendment and the observed influences on crop yield variations. *Frontiers in Energy Research*, 9, 710766. <https://doi.org/10.3389/fenrg.2021.710766>
- Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., Khizar, C., & Reddy, S. P. P. (2023). Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. *Plants*, 12(17), 3102. <https://doi.org/10.3390/plants12173102>
- Wu, Z., Song, Y., Shen, H., Jiang, X., Li, B., & Xiong, Z. (2019). Biochar can mitigate methane emissions by improving methanotrophs for prolonged period in fertilized paddy soils. *Environmental Pollution*, 253, 1038–1046. <https://doi.org/10.1016/j.envpol.2019.07.073>
- Xu, Y., Gao, Y., Tan, L., Wang, Q., Li, Q., Wei, X., Liu, F., Li, Y., & Zheng, X. (2022). Exploration of bacterial communities in products after composting rural wastes with different components: Core microbiome and potential pathogenicity. *Environmental Technology & Innovation*, 25, 102222. <https://doi.org/10.1016/j.eti.2021.102222>

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