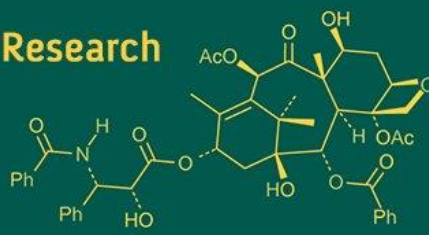


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Biochar and rhizosphere engineering: Emerging strategies for enhancing soil plant microbe interactions in sustainable agriculture

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Abstract

Biochar and rhizosphere engineering have emerged as promising approaches for improving soil health, enhancing nutrient cycling, and strengthening soil plant microbe interactions in sustainable agriculture. Biochar, a carbon-rich material produced through thermochemical conversion of biomass, improves soil physicochemical and biological properties by enhancing nutrient retention, water holding capacity, microbial colonization, and carbon sequestration. Rhizosphere engineering focuses on manipulating root-associated biological processes to optimize plant productivity and soil ecosystem functioning. The integration of biochar with rhizosphere management strategies significantly influences microbial diversity, root architecture, enzymatic activities, and plant stress tolerance under adverse environmental conditions. Recent advances in microbial ecology, molecular biology, and nanotechnology have further expanded the potential applications of engineered biochar in climate-resilient agriculture. This review comprehensively discusses the mechanisms of biochar-mediated rhizosphere engineering, its effects on soil microbial communities and plant performance, and its role in sustainable crop production systems. Furthermore, current challenges, environmental implications, and future research perspectives related to biochar-assisted rhizosphere manipulation are critically highlighted to support the development of eco-friendly and resilient agricultural practices.

Keywords: Biochar, Rhizosphere engineering, Soil microbiome, Sustainable agriculture, Plant growth-promoting rhizobacteria

1. Introduction

Modern agriculture is facing serious challenges due to soil degradation, declining soil fertility, climate change, and the excessive use of chemical fertilizers and pesticides (Joseph *et al.*, 2021) [18]. These factors negatively affect crop productivity, soil biodiversity, and environmental sustainability. Therefore, the development of sustainable and eco-friendly agricultural practices has become essential for maintaining long-term soil health and food security (Mustafa *et al.*, 2026) [27]. The rhizosphere, the narrow region of soil surrounding plant roots, is one of the most biologically active zones in the soil ecosystem. It serves as an important site for interactions among plant roots, soil, and microorganisms (Murtaza *et al.*, 2023) [26]. Root exudates released by plants influence nutrient availability, microbial colonization, and biochemical activities in the rhizosphere. Beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi play vital roles in nutrient cycling, disease suppression, and plant stress tolerance (Ali *et al.*, 2025) [3]. Biochar, a stable carbon-rich material produced through pyrolysis of organic biomass under limited oxygen conditions, has gained considerable attention as a sustainable soil amendment (Idbella *et al.*, 2024) [17]. Owing to its high porosity, large surface area, and strong adsorption capacity, biochar improves soil structure, water holding capacity, nutrient retention, and microbial activity. In addition, biochar provides favorable habitats for beneficial microorganisms, thereby enhancing soil biological functions and rhizosphere interactions (Joseph *et al.*, 2021; Murtaza *et al.*, 2023) [18, 26]. Abiotic stresses such as drought, salinity, and heavy metal toxicity. Recent advances in soil microbiology, molecular biology, and engineered biochar technologies have further expanded the potential applications of biochar

In climate-resilient agriculture (Ali *et al.*, 2025) ^[3]. Therefore, understanding the mechanisms through which biochar influences rhizosphere dynamics is essential for developing sustainable crop production systems (Yang *et al.*, 2025) ^[43].

This review aims to critically discuss the role of biochar in rhizosphere engineering, focusing on its mechanisms, effects on soil physical, chemical, and biological properties, influence on soil microbial communities, and contributions to sustainable and climate-smart agriculture. Additionally, current challenges and future research perspectives related to biochar-assisted rhizosphere management are highlighted.

2. Biochar: properties and production technologies

Biochar is a stable carbon-rich material produced through the thermochemical conversion of biomass under oxygen-limited conditions. Its physicochemical properties vary depending on the feedstock source and production conditions (Joseph *et al.*, 2021; Murtaza *et al.*, 2023) ^[18, 26]. Due to its porous structure, high surface area, and nutrient retention capacity, biochar has become an important amendment for improving soil fertility, microbial activity, and sustainable agricultural productivity (Idbella *et al.*, 2024) ^[17].

2.1 Feedstocks used for biochar production

Various organic materials are used as feedstocks for biochar production. The nature of the feedstock greatly influences the physical, chemical, and biological characteristics of the resulting biochar (Parastesh *et al.*, 2025) ^[30]. Different feedstocks and their physicochemical properties influencing biochar performance in agricultural systems are presented in Table 1.

2.1.1 Crop residues

Agricultural residues are among the most commonly used feedstocks because of their abundance and low cost. Materials such as rice husk, wheat straw, maize stalk, sugarcane bagasse, cotton stalk, and coconut shell are widely utilized (Fan *et al.*, 2023; Pathak *et al.*, 2024) ^[10]. Biochar derived from crop residues generally contains high carbon content and good porosity, making it suitable for improving soil structure and water retention (Ali *et al.*, 2025; Murtaza *et al.*, 2023) ^[3, 26].

2.1.2 Animal manure

Animal manures including poultry litter, cow dung, pig manure, and sheep manure are nutrient-rich feedstocks for biochar production (Yang *et al.*, 2025; Sarma *et al.*, 2024) ^[34, 43]. Manure-based biochar usually contains higher levels of nitrogen, phosphorus, potassium, calcium, and micronutrients. Such biochar is particularly effective in enhancing soil fertility and nutrient availability (Sarma *et al.*, 2024) ^[34].

2.1.3 Forestry waste

Forestry residues such as wood chips, sawdust, bark, and tree pruning waste are extensively used for producing high-quality biochar. Wood-derived biochar generally possesses high stability, large surface area, and greater carbon sequestration potential due to its lignin-rich composition.

2.1.4 Municipal biomass

Municipal organic wastes including sewage sludge, food waste, paper waste, and green waste are increasingly being explored for biochar production (Idbella *et al.*, 2024) ^[17].

Utilizing municipal biomass not only reduces waste disposal problems but also supports recycling of organic resources into sustainable agricultural inputs (Joseph *et al.*, 2021) ^[18].

2.2 Biochar production methods

Biochar is mainly produced through thermochemical conversion technologies under limited oxygen conditions. Different production methods influence the yield, stability, and properties of biochar (Parastesh *et al.*, 2025) ^[30].

2.2.1 Pyrolysis

Pyrolysis is the most widely used method for biochar production. In this process, biomass is heated in the absence or limited presence of oxygen at temperatures generally ranging from 300-700°C (Parastesh *et al.*, 2025) ^[30]. Slow pyrolysis produces higher biochar yield and stable carbon structures, whereas fast pyrolysis mainly favors bio-oil production (Anbuganesan *et al.*, 2024) ^[4].

2.2.2 Gasification

Gasification involves partial oxidation of biomass at high temperatures, usually above 700°C. This process primarily produces syngas along with a smaller quantity of biochar. Gasification-derived biochar often contains higher ash content and alkaline properties (Wen *et al.*, 2024) ^[40].

2.2.3 Hydrothermal carbonization

Hydrothermal carbonization is performed under high pressure and moderate temperatures in the presence of water (Hakim *et al.*, 2021; Ali *et al.*, 2025) ^[3, 13]. This technique is particularly suitable for wet biomass feedstocks and produces hydrochar with unique surface chemistry and nutrient characteristics (Ali *et al.*, 2025) ^[3].

2.3 Physicochemical properties of biochar

The effectiveness of biochar in soil systems depends largely on its physicochemical properties.

2.3.1 Surface area and porosity

Biochar possesses a highly porous structure with large surface area that improves soil aeration, water holding capacity, and microbial habitat formation. The porous surfaces also facilitate adsorption of nutrients and organic compounds (Fan *et al.*, 2023; Pathak *et al.*, 2024) ^[10].

2.3.4 Ph and cation exchange capacity

Most biochars are alkaline in nature and can help ameliorate acidic soils. Biochar also enhances soil cation exchange capacity (CEC), thereby improving nutrient retention and reducing nutrient leaching (Mustafa *et al.*, 2026; Ali *et al.*, 2025) ^[3, 27].

2.3.5 Nutrient retention capacity

Biochar adsorbs and retains essential nutrients such as ammonium, nitrate, phosphorus, potassium, and calcium. This property increases nutrient use efficiency and promotes sustained nutrient availability for plants (Anbuganesan *et al.*, 2024) ^[4].

2.3.6 Stability and carbon content

Biochar contains highly stable aromatic carbon structures that resist microbial decomposition (Wen *et al.*, 2024) ^[40]. This stability enables long-term carbon sequestration and contributes to climate change mitigation by storing carbon in soil for extended periods (Anbuganesan *et al.*, 2024) ^[4].

2.4 Factors influencing biochar characteristics

Several factors determine the final properties and performance of biochar in agricultural systems.

2.4.1 Temperature

Pyrolysis temperature strongly influences biochar properties. Higher temperatures generally increase surface area, porosity, pH, and carbon stability, whereas lower temperatures preserve more functional groups and nutrients (Yang *et al.*, 2024) ^[44].

2.4.2 Residence time

Residence time during pyrolysis affects the degree of carbonization. Longer residence times usually enhance aromatic carbon formation and structural stability of biochar (Parastesh *et al.*, 2025; Murtaza *et al.*, 2023) ^[26, 30].

2.4.3 Feedstock composition

The chemical composition of feedstocks significantly affects nutrient content, ash content, porosity, and carbon stability of biochar (Parastesh *et al.*, 2025; Murtaza *et al.*, 2023) ^[26, 30]. Lignin-rich materials typically produce more stable biochar, while manure-based feedstocks produce nutrient-rich biochar suitable for fertility enhancement (Fan *et al.*, 2023) ^[10].

3. Rhizosphere engineering: concepts and mechanisms

The rhizosphere is a narrow zone of soil directly influenced by plant roots and associated microbial communities. It is considered one of the most dynamic and biologically active regions in terrestrial ecosystems, where complex interactions among roots, soil, and microorganisms regulate nutrient availability, plant growth, and soil health (Pathak *et al.*, 2024; Mustafa *et al.*, 2026) ^[27]. Rhizosphere engineering involves the deliberate manipulation of these interactions to improve crop productivity, nutrient efficiency, and environmental sustainability.

3.1 Rhizosphere ecology

Rhizosphere ecology focuses on the biological and biochemical processes occurring around plant roots. Plant roots continuously interact with soil microorganisms through the release of organic compounds and signaling molecules that influence microbial diversity and nutrient transformations.

3.1.1 Root exudates

Plant roots release a variety of compounds including sugars, amino acids, organic acids, vitamins, enzymes, and secondary metabolites into the rhizosphere (et *al.*, 2025) ^[22]. These root exudates serve as energy sources for microorganisms and play important roles in microbial attraction, nutrient mobilization, and plant defense mechanisms (Shi *et al.*, 2023; Liu *et al.*, 2024) ^[24, 35].

3.1.2 Nutrient cycling

The rhizosphere is an active site for nutrient cycling processes such as nitrogen fixation, phosphorus solubilization, mineralization, and decomposition of organic matter (Yang *et al.*, 2025; Sarma *et al.*, 2024) ^[34, 43]. Soil Microorganisms convert unavailable nutrients into plant-accessible forms, thereby improving nutrient uptake and soil fertility (Joseph *et al.*, 2021; Idbella *et al.*, 2024) ^[17, 18].

3.1.3 Microbial colonization

The rhizosphere supports diverse microbial populations including bacteria, fungi, actinomycetes, algae, and protozoa (Liao *et al.*, 2019) ^[23]. Beneficial microbes colonize root surfaces and establish interactions that enhance plant growth, stress tolerance, and disease resistance (Yang *et al.*, 2025) ^[43].

3.2 Soil-plant-microbe interactions

Interactions among soil, plants, and microorganisms are fundamental for maintaining ecosystem functioning and agricultural productivity. These interactions can be beneficial, neutral, or harmful depending on environmental conditions and microbial composition (Ali *et al.*, 2025; Fan *et al.*, 2023) ^[3, 10].

3.2.1 Symbiotic relationships

Symbiotic associations between plants and microorganisms help improve nutrient acquisition and plant health (Fan *et al.*, 2023) ^[10]. In these relationships, plants provide carbohydrates to microorganisms, while microbes assist in nutrient mobilization and protection against pathogens.

3.2.2 Plant growth-promoting rhizobacteria (pgpr)

PGPR are beneficial bacteria that stimulate plant growth through various mechanisms such as nitrogen fixation, phytohormone production, phosphorus solubilization, siderophore production, and pathogen suppression. Common PGPR genera include *Azotobacter*, *Pseudomonas*, *Bacillus*, and *Rhizobium* (Ali *et al.*, 2025) ^[3].

3.2.3 Mycorrhizal associations

Mycorrhizal fungi form symbiotic associations with plant roots and significantly enhance nutrient and water uptake, especially phosphorus absorption (Ali *et al.*, 2025) ^[3]. These fungi also improve soil aggregation, root growth, and plant tolerance against drought and salinity stress (Gu *et al.*, 2023) ^[12].

3.3 Rhizosphere manipulation strategies

Rhizosphere engineering strategies aim to optimize beneficial interactions within the root zone to improve plant productivity and soil sustainability (Gu *et al.*, 2023) ^[12].

3.3.1 Organic amendments

Organic materials such as compost, farmyard manure, vermicompost, and biochar are widely used to enhance soil organic matter, microbial activity, nutrient availability, and soil structure (Yan *et al.*, 2022) ^[42]. These amendments improve rhizosphere conditions and support beneficial microbial communities (Joseph *et al.*, 2021) ^[18].

3.3.2 Microbial inoculants

Application of beneficial microbial inoculants including PGPR, mycorrhizal fungi, and biofertilizers helps improve nutrient uptake, stress tolerance, and disease resistance in crops. Microbial inoculation is an eco-friendly alternative to chemical fertilizers and pesticides.

3.3.3 Root architecture modification

Manipulating root system architecture through breeding, biotechnology, or agronomic practices can improve root penetration, nutrient absorption, and water use efficiency. Enhanced root development also promotes stronger rhizosphere interactions and better adaptation to

environmental stresses (Ali *et al.*, 2025; Gu *et al.*, 2023) ^[3, 12].

4. Mechanisms of biochar-mediated rhizosphere engineering

Biochar-mediated rhizosphere engineering involves the modification of soil physical, chemical, and biological processes within the rhizosphere to enhance soil fertility, microbial activity, and plant growth (Ali *et al.*, 2025; Joseph *et al.*, 2021) ^[3, 18]. Owing to its unique physicochemical characteristics, including high porosity, large surface area, and stable carbon structure, biochar significantly influences soil-plant-microbe interactions (Yan *et al.*, 2022; Gu *et al.*, 2023) ^[12, 42]. These modifications improve nutrient dynamics, microbial colonization, root development, and soil biochemical activities, thereby contributing to sustainable agricultural productivity and environmental resilience (Murtaza *et al.*, 2023; Chew *et al.*, 2020) ^[7, 26]. The mechanisms through which biochar influences soil physical, chemical, and biological properties within the rhizosphere are illustrated in Fig. 1.

4.1 Improvement in soil physical properties

Biochar application substantially improves soil physical properties, which are critical for root growth, water availability, and microbial functioning in the rhizosphere.

4.1.1 Soil aggregation

Biochar promotes the formation and stabilization of soil aggregates through interactions with soil particles, organic matter, and microbial exudates (He *et al.*, 2024) ^[14]. Improved aggregation enhances soil structure, porosity, and aeration while reducing soil erosion and compaction. Stable soil aggregates also provide favorable microhabitats for microbial colonization and nutrient retention (Dong *et al.*, 2026) ^[8].

4.1.2 Water holding capacity

The highly porous structure of biochar increases soil water retention by enhancing pore connectivity and moisture storage capacity (Dong *et al.*, 2026) ^[8]. Biochar-amended soils exhibit improved water availability, particularly in coarse-textured and degraded soils, thereby improving plant drought tolerance and reducing irrigation requirements (Wen *et al.*, 2024; Chew *et al.*, 2020) ^[7, 40].

4.1.3 Bulk density reduction

Biochar incorporation decreases soil bulk density due to its low density and porous nature. Reduced bulk density improves root penetration, gas exchange, and soil aeration, which collectively enhance root growth and microbial activity within the rhizosphere (Egamberdieva *et al.*, 2016; Li *et al.*, 2023) ^[9].

4.2 Enhancement of soil chemical properties

Biochar significantly modifies soil chemical properties and nutrient dynamics, thereby improving soil fertility and nutrient use efficiency.

4.2.1 Nutrient availability

Biochar acts as a nutrient reservoir by adsorbing and retaining essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium (Chew *et al.*, 2020) ^[7]. This nutrient retention capacity enhances nutrient availability and reduces nutrient losses from the soil system.

4.2.2 PH buffering

Most biochars possess alkaline characteristics that help neutralize acidic soils and stabilize soil pH (Egamberdieva

et al., 2016) ^[9]. Improved soil pH conditions favor nutrient solubility, microbial activity, and overall rhizosphere functioning.

4.2.3 Reduced nutrient leaching

The high cation exchange capacity and adsorption potential of biochar reduce nutrient leaching, particularly of nitrate and ammonium ions (Li *et al.*, 2023). Consequently, biochar application improves fertilizer use efficiency and minimizes environmental contamination associated with nutrient runoff.

4.3 Biochar as a microbial habitat

Biochar provides a favorable environment for microbial survival, colonization, and activity within the rhizosphere.

4.3.1 Biofilm formation

The porous surfaces of biochar facilitate microbial attachment and biofilm formation. These biofilms enhance microbial stability, nutrient exchange, and protection against environmental stress conditions (Ali *et al.*, 2025; Joseph *et al.*, 2021) ^[3, 18].

4.3.2 Microbial refuge and colonization

Biochar pores function as protective microhabitats that shelter microorganisms from predation and environmental fluctuations. Such conditions promote microbial colonization and long-term survival of beneficial microbial populations.

4.3.3 Enhanced microbial diversity

Biochar application often increases soil microbial biomass and diversity by improving soil habitat conditions and nutrient availability (Yan *et al.*, 2022) ^[42]. Enhanced microbial diversity contributes to improved nutrient cycling, organic matter decomposition, and suppression of soil-borne pathogens (Dong *et al.*, 2026; Yan *et al.*, 2022) ^[8, 42].

4.4 Influence on root growth and exudation

Biochar significantly affects root morphology and root-mediated biochemical interactions in the rhizosphere.

4.4.1 Root morphology

Improved soil aeration, moisture retention, and nutrient availability associated with biochar application enhance root length, root biomass, and root branching (Yan *et al.*, 2022) ^[42]. Enhanced root architecture improves nutrient and water uptake efficiency.

4.4.2 Root signaling compounds

Biochar influences the production and release of root signaling molecules, including phytohormones, flavonoids, and secondary metabolites (Gu *et al.*, 2023; Murtaza *et al.*, 2023) ^[12, 26]. These compounds regulate plant-microbe communication and microbial recruitment within the rhizosphere (Wu *et al.*, 2024) ^[41].

4.4.3 Rhizodeposition dynamics

Biochar alters rhizodeposition patterns by influencing the quantity and composition of root exudates released into the soil (Wu *et al.*, 2024) ^[41]. Modified rhizodeposition dynamics affect microbial activity, nutrient transformations, and soil biochemical processes (Chew *et al.*, 2020) ^[7].

4.5 Regulation of soil enzymatic activities

Biochar plays a significant role in regulating soil enzyme activities involved in nutrient mineralization and microbial metabolism.

4.5.1 Dehydrogenase activity

Dehydrogenase activity is widely considered an indicator of overall microbial metabolic activity in soil (Fan *et al.*, 2023) ^[10]. Biochar application generally enhances dehydrogenase activity by stimulating microbial growth and respiration.

4.5.2 Phosphatase activity

Biochar can increase phosphatase activity, thereby facilitating the mineralization of organic phosphorus into plant-available forms and improving phosphorus availability in soil (Ali *et al.*, 2025; Fan *et al.*, 2023) ^[3, 10].

4.5.3 Urease and catalase activity

Enhanced urease activity following biochar application improves nitrogen transformation processes, while increased catalase activity helps regulate oxidative stress within the soil environment (Joseph *et al.*, 2021) ^[18]. These enzymatic responses collectively improve soil fertility and microbial functioning.

4.6 Carbon sequestration and climate mitigation

Biochar contributes significantly to long-term carbon sequestration and mitigation of greenhouse gas emissions.

4.6.1 Stable carbon pools

Biochar contains highly recalcitrant aromatic carbon structures that resist microbial decomposition (Murtaza *et al.*, 2023) ^[26]. Consequently, biochar incorporation into soil creates stable carbon pools capable of storing carbon for extended periods (Yan *et al.*, 2022; Murtaza *et al.*, 2023) ^[26, 42].

4.6.2 Greenhouse gas mitigation

Biochar application has been reported to reduce emissions of greenhouse gases such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) through improved nutrient retention and altered microbial processes.

4.6.3 Soil carbon dynamics

Biochar influences soil organic carbon dynamics by stabilizing soil organic matter and enhancing carbon accumulation within the soil matrix. These processes improve soil fertility while contributing to climate-resilient and sustainable agricultural systems.

5. Impact of biochar on soil microbiome

The soil microbiome plays a fundamental role in maintaining soil fertility, nutrient cycling, organic matter decomposition, and plant health (Ibrahim *et al.*, 2020) ^[16]. Biochar application significantly influences the structure, diversity, and functioning of soil microbial communities by altering soil physicochemical properties, nutrient availability, moisture dynamics, and habitat conditions (Ibrahim *et al.*, 2020; Chew *et al.*, 2020) ^[7, 16]. Due to its porous structure and large surface area, biochar creates favorable ecological niches for microbial colonization and activity within the rhizosphere. Consequently, biochar-mediated changes in the soil microbiome contribute to improved soil health, enhanced nutrient use efficiency, and sustainable agricultural productivity (Yang *et al.*, 2025) ^[43]. The major effects of biochar on soil microbial communities and enzymatic activities are summarized in Table 2.

5.1 Bacterial community dynamics

Biochar application strongly affects bacterial abundance, diversity, and community composition in soil ecosystems.

5.1.1 Beneficial bacteria enrichment

Biochar enhances the proliferation of beneficial bacterial populations by improving soil aeration, moisture retention, and nutrient availability (Fan *et al.*, 2023) ^[10]. The porous surfaces of biochar provide suitable habitats for microbial attachment and biofilm formation, thereby supporting microbial survival and activity (Dong *et al.*, 2026) ^[8]. Several studies have reported increased populations of plant growth-promoting rhizobacteria (PGPR) such as *Pseudomonas*, *Bacillus*, *Azospirillum*, and *Rhizobium* following biochar amendment. These bacteria contribute to nutrient solubilization, phytohormone production, pathogen suppression, and improved plant growth (Yan *et al.*, 2022) ^[42].

5.1.2 Nitrogen-fixing bacteria

Biochar application has been shown to stimulate nitrogen-fixing bacterial communities in soil. Improved soil conditions and enhanced root-microbe interactions promote the activity of free-living and symbiotic nitrogen-fixing microorganisms (Gu *et al.*, 2023; Li *et al.*, 2020) ^[12]. Increased populations of diazotrophic bacteria improve biological nitrogen fixation and contribute to enhanced nitrogen availability for plants, thereby reducing dependence on synthetic nitrogen fertilizers (Wu *et al.*, 2024; Chew *et al.*, 2020) ^[7, 41].

5.2 Fungal community responses

Biochar also exerts significant effects on soil fungal communities, including beneficial symbiotic fungi and pathogenic fungi.

5.2.1 Arbuscular mycorrhizal fungi

Arbuscular mycorrhizal fungi (AMF) establish symbiotic associations with plant roots and enhance nutrient and water uptake, particularly phosphorus acquisition (Egamberdieva *et al.*, 2016) ^[9]. Biochar improves soil habitat conditions that support AMF colonization, hyphal development, and symbiotic efficiency. Enhanced mycorrhizal associations contribute to improved plant growth, soil aggregation, and stress tolerance under adverse environmental conditions.

5.2.2 Pathogenic fungi suppression

Biochar application can suppress soil-borne pathogenic fungi through several mechanisms, including improved microbial competition, adsorption of toxic compounds, and stimulation of antagonistic microorganisms (Yang *et al.*, 2025) ^[43]. Enhanced populations of beneficial microbes may inhibit pathogen growth through competition for nutrients and production of antimicrobial compounds. Consequently, biochar contributes to reduced disease incidence and improved plant health (Dong *et al.*, 2026) ^[8].

5.3 Biochar and soil enzyme activities

Soil enzymes are essential indicators of microbial activity and soil biochemical functioning. Biochar significantly influences the activity of enzymes involved in nutrient transformation and organic matter decomposition (Yan *et al.*, 2022) ^[42].

5.3.1 Nutrient mineralization

Biochar stimulates microbial processes associated with nutrient mineralization by improving microbial habitat conditions and nutrient retention (Li *et al.*, 2020). Enhanced activities of enzymes such as urease, phosphatase, and dehydrogenase facilitate nitrogen and phosphorus cycling,

thereby increasing nutrient availability for plants (Liao *et al.*, 2019) ^[23].

5.3.2 Organic matter decomposition

Biochar influences the decomposition of soil organic matter by regulating microbial activity and enzyme production (Ali *et al.*, 2025) ^[3]. Improved microbial colonization and favorable rhizosphere conditions enhance the breakdown of organic substrates and promote soil carbon turnover. However, the extent of decomposition may vary depending on biochar type, soil properties, and environmental conditions (Fan *et al.*, 2023) ^[10].

5.4 Molecular approaches for microbial analysis

Recent advances in molecular biology and microbial ecology have improved the understanding of biochar-induced changes in soil microbial communities.

5.4.1 Metagenomics

Metagenomic approaches enable comprehensive analysis of microbial community composition and functional genes directly from soil samples (Yan *et al.*, 2022) ^[42]. These techniques provide valuable insights into microbial diversity, metabolic pathways, and functional potential in biochar-amended soils (Murtaza *et al.*, 2023) ^[26].

5.4.2 Metatranscriptomics

Metatranscriptomics focuses on the analysis of actively expressed microbial genes and provides information regarding microbial functional activity under different environmental conditions (Wu *et al.*, 2024; Ibrahim *et al.*, 2020) ^[16, 41]. This approach helps identify microbial responses to biochar application at the transcriptional level (Li *et al.*, 2020).

5.4.3 Microbial sequencing tools

High-throughput sequencing technologies such as 16S rRNA gene sequencing and internal transcribed spacer (ITS) sequencing are widely used to characterize bacterial and fungal communities in soil ecosystems (Dong *et al.*, 2026) ^[8]. These tools enable detailed investigation of microbial diversity, community shifts, and ecological interactions associated with biochar-mediated rhizosphere engineering (Yan *et al.*, 2022) ^[42].

6. Biochar-induced plant responses

Biochar application significantly influences plant growth, physiological performance, nutrient acquisition, and stress tolerance through its effects on soil properties and rhizosphere interactions (Murtaza *et al.*, 2023) ^[26]. By improving soil structure, nutrient retention, microbial activity, and water availability, biochar creates favorable conditions for plant development and productivity. In addition, biochar-mediated modulation of plant physiological and biochemical processes enhances plant resilience against various abiotic and biotic stresses (Wu *et al.*, 2024) ^[41].

6.1 Seed germination and early growth

Biochar positively affects seed germination and early seedling establishment by improving soil aeration, moisture retention, and nutrient availability (Chew *et al.*, 2020) ^[7]. Enhanced soil porosity and water-holding capacity provide favorable conditions for seed imbibition and root emergence. Furthermore, biochar reduces soil compaction and improves root penetration, thereby promoting vigorous seedling growth (Yang *et al.*, 2025) ^[43]. Several studies have

reported increased germination percentage, seedling vigor, root length, shoot growth, and biomass accumulation in biochar-amended soils (Yan *et al.*, 2022; Li *et al.*, 2020). However, the effects may vary depending on biochar type, application rate, feedstock source, and crop species.

6.2 Nutrient uptake and use efficiency

Biochar improves nutrient uptake and nutrient use efficiency by increasing nutrient retention, reducing nutrient leaching, and enhancing microbial-mediated nutrient transformations (Liao *et al.*, 2019) ^[23]. The high cation exchange capacity and adsorption surfaces of biochar facilitate the retention of essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium within the root zone (Chew *et al.*, 2020) ^[7]. Enhanced microbial activity and improved rhizosphere conditions further stimulate nutrient mineralization and nutrient availability (Yang *et al.*, 2025) ^[43]. Biochar application has also been associated with improved root development and increased root surface area, which enhance nutrient absorption efficiency. Consequently, biochar can reduce dependence on synthetic fertilizers while improving crop productivity (Fan *et al.*, 2023; Dong *et al.*, 2026) ^[8, 10].

6.3 Photosynthesis and physiological responses

Biochar-mediated improvements in nutrient availability and water status positively influence plant physiological processes, including photosynthesis, transpiration, and stomatal conductance. Increased chlorophyll content and enhanced photosynthetic efficiency are commonly observed in biochar-treated plants (Gu *et al.*, 2023) ^[12].

Improved water relations and nutrient supply support higher rates of carbon assimilation and biomass production. Biochar application may also enhance antioxidant enzyme activities and regulate phytohormone balance, thereby improving plant metabolic performance under both normal and stress conditions (Yan *et al.*, 2022) ^[42].

6.4 Stress tolerance mechanisms

Biochar plays an important role in enhancing plant tolerance to various abiotic stresses through physical, chemical, and biological modifications within the soil-plant system (Li *et al.*, 2020; Fu *et al.*, 2022) ^[11].

6.4.1 Drought stress

Biochar improves drought tolerance primarily through enhanced soil water retention and improved root growth. Increased water-holding capacity and soil moisture availability reduce water deficit stress and maintain plant physiological activities during drought conditions (Li *et al.*, 2020). Biochar also promotes osmotic adjustment, antioxidant activity, and stomatal regulation, thereby improving plant survival under limited water availability (Fu *et al.*, 2022) ^[11].

6.4.2 Salinity stress

Biochar alleviates salinity stress by reducing sodium toxicity, improving soil structure, and enhancing nutrient balance (Liao *et al.*, 2019) ^[23]. The adsorption capacity of biochar helps immobilize excess sodium ions and reduce their uptake by plants (Ibrahim *et al.*, 2020) ^[16]. Improved potassium retention and enhanced microbial activity further support plant growth under saline conditions.

6.4.3 Heavy metal toxicity

Biochar can immobilize toxic heavy metals such as cadmium, lead, arsenic, and chromium through adsorption,

precipitation, and complexation mechanisms. Reduced metal bioavailability limits heavy metal uptake and toxicity in plants (Liao *et al.*, 2019) ^[23]. In addition, biochar-induced enhancement of antioxidant defense systems helps protect plants against oxidative damage caused by heavy metal stress (Egamberdieva *et al.*, 2016; Li *et al.*, 2023) ^[9].

6.5 Disease suppression and plant immunity

Biochar contributes to plant health by enhancing disease resistance and suppressing soil-borne pathogens through multiple biological and biochemical mechanisms.

6.5.1 Induced systemic resistance

Biochar application can activate induced systemic resistance (ISR) pathways in plants by stimulating beneficial microbial populations and signaling mechanisms (Ali *et al.*, 2025) ^[3]. Enhanced ISR improves plant defense responses against a broad range of pathogens and environmental stresses (Fan *et al.*, 2023; Yan *et al.*, 2022) ^[10, 42].

6.5.2 Pathogen suppression mechanisms

Biochar suppresses plant pathogens through improved microbial competition, enhanced populations of antagonistic microorganisms, adsorption of phytotoxic compounds, and modification of soil environmental conditions (Murtaza *et al.*, 2023; Li *et al.*, 2020) ^[26]. Increased microbial diversity and beneficial microbial activity reduce pathogen colonization and disease incidence, thereby improving overall plant health and productivity (Wu *et al.*, 2024; Ibrahim *et al.*, 2020) ^[16, 41].

7. Biochar in sustainable and climate-resilient agriculture

Biochar has emerged as an important component of sustainable and climate-resilient agricultural systems due to its multifunctional role in improving soil health, enhancing resource use efficiency, reducing environmental pollution, and promoting carbon sequestration (Joseph *et al.*, 2021) ^[18]. Its application supports environmentally sustainable crop production while contributing to climate change mitigation and adaptation strategies (Joseph *et al.*, 2021) ^[18]. The integration of biochar into modern agricultural systems is increasingly being recognized as a viable approach for achieving long-term agricultural sustainability and ecosystem resilience (He *et al.*, 2024) ^[14]. The integrated role of biochar in sustainable and climate-resilient agriculture is summarized in Fig. 2.

7.1 Biochar in organic farming

Organic farming systems rely heavily on natural soil amendments and environmentally friendly practices for maintaining soil fertility and crop productivity (Fu *et al.*, 2022) ^[11]. Biochar serves as an effective organic amendment by improving soil structure, nutrient retention, microbial activity, and water holding capacity without causing adverse environmental impacts (He *et al.*, 2024) ^[14].

Biochar application in organic farming enhances nutrient availability and reduces nutrient losses through leaching, thereby improving nutrient use efficiency (Yang *et al.*, 2025) ^[43]. It also promotes beneficial microbial populations and supports biological nutrient cycling within the rhizosphere. Furthermore, biochar can be integrated with compost, vermicompost, and biofertilizers to improve soil fertility and crop performance in organic production systems (Joseph *et al.*, 2021) ^[18].

7.2 Role in precision agriculture

Precision agriculture focuses on efficient resource management through site-specific crop and soil management

practices. Biochar has significant potential in precision agriculture due to its ability to improve soil nutrient dynamics, water retention, and fertilizer efficiency (He *et al.*, 2024) ^[14]. The use of engineered or customized biochar formulations can support targeted nutrient delivery and controlled nutrient release in different soil environments. Biochar-based technologies may also be integrated with sensor-based nutrient management systems to optimize fertilizer application and minimize nutrient losses (Sarfraz *et al.*, 2019) ^[33]. Such approaches contribute to enhanced crop productivity while reducing environmental contamination associated with excessive fertilizer use (Murtaza *et al.*, 2023).

7.3 Biochar for regenerative agriculture

Regenerative agriculture aims to restore soil health, improve biodiversity, enhance ecosystem services, and promote sustainable crop production. Biochar contributes to regenerative agriculture by improving soil organic carbon content, microbial diversity, soil aggregation, and nutrient cycling (Wen *et al.*, 2024) ^[40]. The incorporation of biochar into regenerative farming systems enhances soil resilience against erosion, drought, and nutrient depletion (Pathak *et al.*, 2024). In addition, biochar supports long-term carbon sequestration and improves soil biological functioning, which are essential components of regenerative agricultural practices. The synergistic use of biochar with cover crops, reduced tillage, and crop diversification further strengthens soil ecosystem stability and sustainability (Wen *et al.*, 2024) ^[40].

7.4 Integration with circular bioeconomy

Biochar production supports the principles of circular bioeconomy by converting agricultural residues, forestry waste, animal manure, and municipal biomass into value-added soil amendments (Prochnow *et al.*, 2024) ^[31]. This approach promotes efficient utilization of organic waste materials while reducing waste disposal problems and environmental pollution (Neogi *et al.*, 2021) ^[28]. The conversion of biomass waste into biochar contributes to resource recycling, renewable energy generation, and sustainable waste management (Singh *et al.*, 2022) ^[37]. Moreover, biochar-based systems facilitate nutrient recovery and carbon recycling within agricultural ecosystems, thereby enhancing overall resource efficiency and environmental sustainability (Yrjälä *et al.*, 2022) ^[45].

7.5 Contribution to sustainable development goals (sdgs)

Biochar application contributes directly and indirectly to several United Nations Sustainable Development Goals (SDGs), particularly those related to food security, climate action, sustainable resource management, and ecosystem restoration (Neogi *et al.*, 2021) ^[28].

Biochar supports SDG 2 (Zero Hunger) by improving soil fertility and agricultural productivity. Its role in carbon sequestration and greenhouse gas mitigation contributes to SDG 13 (Climate Action) (Ali *et al.*, 2025; Yrjälä *et al.*, 2022) ^[3, 45]. The recycling of biomass waste into biochar supports SDG 12 (Responsible Consumption and Production), while improvements in soil health and ecosystem functioning contribute to SDG 15 (Life on Land). Furthermore, biochar-mediated enhancement of water retention and nutrient efficiency supports sustainable agricultural intensification and resilience under changing climatic conditions, making biochar an important tool for achieving long-term sustainability goals (Kurniawan *et al.*, 2023) ^[19].

8. Biochar combined with other technologies

The integration of biochar with advanced agricultural technologies has gained significant attention for improving soil fertility, nutrient efficiency, microbial activity, and crop productivity (Neogi *et al.*, 2021) ^[28]. Combining biochar with microbial inoculants, compost, nanotechnology, and engineered materials enhances its functional properties and broadens its applications in sustainable agriculture (Hu *et al.*, 2024). These integrated approaches improve rhizosphere functioning, nutrient delivery, and environmental sustainability while supporting climate-resilient agricultural systems (Shoudho *et al.*, 2024; & Mofatteh, 2024) ^[1, 36].

8.1 Biochar + microbial inoculants

The combined application of biochar and microbial inoculants has shown promising results in enhancing soil biological activity and plant growth. Biochar provides a favorable habitat for beneficial microorganisms due to its porous structure, high surface area, and protective microenvironments (Neogi *et al.*, 2021; Ali *et al.*, 2025) ^[3, 28]. These characteristics improve microbial survival, colonization, and activity in the rhizosphere. Beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR), nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi exhibit enhanced establishment and persistence when applied with biochar (Hu *et al.*, 2024; Wang *et al.*, 2022) ^[38, 39]. This synergistic interaction improves nutrient cycling, phytohormone production, disease suppression, and stress tolerance in plants. Consequently, biochar-based microbial inoculants are increasingly being explored as eco-friendly alternatives to chemical fertilizers and pesticides (Ramesh & Raghavan, 2024) ^[32].

8.2 Biochar + compost

The integration of biochar with compost enhances the agronomic and environmental benefits of both amendments. Compost supplies readily available nutrients and organic matter, whereas biochar improves nutrient retention, moisture conservation, and long-term carbon stability (Neogi *et al.*, 2021; Prochnow *et al.*, 2024) ^[28, 31]. Biochar-compost mixtures reduce nutrient leaching losses and enhance microbial activity by creating favorable conditions for microbial proliferation (Singh *et al.*, 2022; Yrjälä *et al.*, 2022) ^[37, 45]. The addition of biochar during composting also improves compost maturity, reduces greenhouse gas emissions, and minimizes nutrient volatilization (Kurniawan *et al.*, 2023) ^[19]. Furthermore, biochar-compost formulations improve soil structure, nutrient availability, and crop productivity more effectively than either amendment applied alone (Neogi *et al.*, 2021; Hu *et al.*, 2024) ^[28].

8.3 Nano-biochar applications

Nanotechnology-based modifications of biochar have led to the development of nano-biochar with enhanced physicochemical properties and agricultural applications (Shoudho *et al.*, 2024) ^[36]. Nano-biochar possesses smaller particle size, increased surface area, higher adsorption capacity, and improved reactivity compared to conventional biochar (He *et al.*, 2022) ^[15]. Nano-biochar has shown potential in improving nutrient delivery, contaminant adsorption, soil remediation, and water retention (Afshar & Mofatteh, 2024) ^[1]. It can also enhance seed germination, nutrient uptake, and stress tolerance in plants. Additionally, nano-biochar is being explored as a carrier for agrochemicals, microbial inoculants, and controlled-release fertilizers. However, further research is needed to evaluate

its long-term environmental safety and ecological impacts (Neogi *et al.*, 2021; Ali *et al.*, 2025) ^[3, 28].

8.4 Engineered and functionalized biochar

Engineered or functionalized biochar refers to biochar modified through physical, chemical, or biological treatments to enhance its performance for specific agricultural or environmental applications. Surface modification techniques may include nutrient enrichment, mineral impregnation, oxidation, magnetic modification, or microbial loading (Afshar & Mofatteh, 2024; Ramesh & Raghavan, 2024) ^[1, 32]. Functionalized biochar exhibits improved adsorption capacity, nutrient retention, contaminant immobilization, and microbial compatibility. Nutrient-enriched biochar can serve as a slow-release fertilizer, while magnetized biochar may facilitate pollutant removal and recovery processes (Shoudho *et al.*, 2024) ^[36]. Engineered biochar also enhances rhizosphere interactions and improves the efficiency of sustainable soil management strategies (He *et al.*, 2022) ^[15].

8.5 Biochar-based fertilizer carriers

Biochar is increasingly being utilized as a carrier material for fertilizers due to its high porosity, adsorption capacity, and nutrient retention properties. Biochar-based fertilizer carriers improve nutrient use efficiency by reducing nutrient leaching, volatilization, and fixation in soil systems (Afshar & Mofatteh, 2024) ^[1]. The incorporation of nutrients into biochar matrices allows controlled and gradual nutrient release, thereby improving nutrient availability over extended periods. Biochar-based slow-release fertilizers can reduce the frequency of fertilizer application and minimize environmental pollution associated with excessive fertilizer use (Ramesh & Raghavan, 2024) ^[32]. In addition, biochar-supported fertilizer formulations may enhance root nutrient uptake and microbial activity within the rhizosphere, contributing to improved crop growth and sustainable agricultural productivity (Neogi *et al.*, 2021) ^[28].

9. Applications in different cropping systems

Biochar has been widely applied across diverse cropping systems due to its ability to improve soil fertility, enhance nutrient use efficiency, promote microbial activity, and increase crop productivity (Ali *et al.*, 2025) ^[3]. The effectiveness of biochar varies depending on crop type, soil conditions, climatic factors, and management practices. Its integration into different agricultural systems has shown significant potential for improving sustainability, resource conservation, and climate resilience (Wang *et al.*, 2022) ^[38, 39].

9.1 Cereal crops

Biochar application has demonstrated positive effects on the growth and productivity of major cereal crops such as rice, wheat, maize, barley, and sorghum. Improved soil structure, enhanced water retention, and increased nutrient availability contribute to higher germination rates, biomass accumulation, and grain yield in cereal-based systems (Bolan *et al.*, 2023; Bamdad *et al.*, 2021) ^[6]. In rice cultivation, biochar has been reported to improve nitrogen use efficiency and reduce methane emissions from flooded soils (Ali *et al.*, 2025). In wheat and maize systems, biochar enhances root development, nutrient uptake, and drought tolerance, particularly in degraded and nutrient-deficient soils (Neogi *et al.*, 2021) ^[28]. Furthermore, biochar application improves soil organic carbon content and

microbial activity, thereby supporting long-term soil fertility in cereal production systems (Ajeng *et al.*, 2020)^[2].

9.2 Horticultural crops

Biochar has gained considerable attention in horticultural production systems including fruits, vegetables, ornamental plants, and plantation crops. In horticultural soils, biochar improves water holding capacity, nutrient retention, root growth, and microbial activity, which collectively enhance crop quality and yield (Hu *et al.*, 2024). Several studies have reported improved growth, flowering, fruit set, and fruit quality in crops such as tomato, cucumber, pepper, strawberry, citrus, mango, and guava following biochar application (Wang *et al.*, 2022)^[38, 39]. Biochar also enhances nutrient uptake and stress tolerance in horticultural crops under drought and salinity conditions. Additionally, its use in nursery media and potting substrates improves seedling establishment and root development (Osman *et al.*, 2022; Marcińczyk & Oleszczuk, 2022)^[25, 29].

9.3 Legumes and oilseeds

Leguminous crops and oilseeds respond positively to biochar application due to enhanced nutrient availability and improved biological nitrogen fixation. In legumes such as soybean, chickpea, lentil, and pea, biochar promotes nodulation, rhizobial activity, and nitrogen fixation efficiency (Neogi *et al.*, 2021; Wang *et al.*, 2022)^[38, 39]. Oilseed crops including mustard, sunflower, groundnut, linseed, and sesame also benefit from improved soil fertility and nutrient retention associated with biochar amendment. Enhanced phosphorus availability, improved microbial activity, and better moisture retention contribute to increased seed yield, oil content, and overall crop performance in oilseed production systems (Yuan *et al.*, 2023; He *et al.*, 2022; Ramesh & Raghavan, 2024)^[15, 32, 46].

9.4 Protected cultivation systems

Protected cultivation systems such as greenhouses, polyhouses, and net houses require efficient management of water, nutrients, and growing media for optimal crop production. Biochar is increasingly being used as a component of potting media and soil amendments in protected cultivation due to its high porosity and moisture retention capacity (Osman *et al.*, 2022)^[29]. Biochar incorporation improves substrate aeration, nutrient availability, and microbial stability within controlled environments. It also reduces nutrient losses from intensive fertigation systems and supports sustainable production of high-value crops such as tomato, cucumber, lettuce, capsicum, and ornamental flowers (Marcińczyk & Oleszczuk, 2022)^[25]. Furthermore, biochar-based substrates may reduce the dependence on peat-based growing media and contribute to environmentally sustainable protected cultivation practices (Wang *et al.*, 2022)^[38, 39].

9.5 Agroforestry systems

Agroforestry systems integrate trees with crops and livestock to enhance biodiversity, soil fertility, and ecosystem sustainability. Biochar application in agroforestry systems improves soil carbon storage, nutrient cycling, microbial diversity, and water retention (Ramesh & Raghavan, 2024)^[32].

Tree-based systems benefit from enhanced root development and improved nutrient availability in biochar-amended soils. Biochar also supports long-term carbon sequestration and reduces greenhouse gas emissions, making it highly suitable for climate-resilient agroforestry

practices. The combined use of biochar with organic residues and tree litter further enhances soil productivity and ecosystem functioning in agroforestry systems.

10. Environmental and economic implications

Biochar technology has gained considerable attention due to its environmental and economic benefits in sustainable agricultural systems (Hu *et al.*, 2024). In addition to improving soil fertility and crop productivity, biochar contributes to waste management, resource recycling, climate change mitigation, and reduction in external agricultural inputs. However, certain environmental risks and economic limitations associated with biochar production and application also require careful consideration (Wang *et al.*, 2022)^[38, 39].

10.1 Waste recycling and resource recovery

Biochar production provides an effective approach for converting agricultural residues, forestry waste, animal manure, and municipal biomass into valuable soil amendments. This process supports sustainable waste management by reducing the accumulation and open burning of organic wastes, which are major sources of environmental pollution and greenhouse gas emissions (Wang *et al.*, 2022)^[38, 39]. The conversion of biomass into biochar promotes resource recovery through recycling of nutrients and organic carbon back into agricultural soils (Ali *et al.*, 2025)^[3]. Biochar production systems may also generate bioenergy and bio-oil as valuable by-products, thereby enhancing overall resource utilization efficiency within circular bioeconomy frameworks (Hu *et al.*, 2024).

10.2 Reduction in chemical fertilizer dependency

Biochar improves nutrient retention, nutrient availability, and microbial-mediated nutrient cycling, thereby enhancing nutrient use efficiency in agricultural soils. These improvements reduce nutrient losses through leaching and volatilization and increase the effectiveness of applied fertilizers (Bolan *et al.*, 2023)^[6]. Enhanced nutrient use efficiency associated with biochar application can lower the dependence on synthetic chemical fertilizers, reducing production costs and minimizing environmental pollution caused by excessive fertilizer application. Furthermore, biochar-supported microbial activity and biological nitrogen fixation contribute to sustainable nutrient management in cropping systems (Bamdad *et al.*, 2021).

10.3 Economic feasibility and farmer adoption

The economic feasibility of biochar application depends on factors such as feedstock availability, production technology, transportation costs, application rates, and crop response. In regions with abundant agricultural biomass residues, biochar production can provide an economically viable option for improving soil fertility and crop productivity (Ajeng *et al.*, 2020)^[2]. Long-term benefits such as improved soil health, increased yield stability, reduced fertilizer requirements, and enhanced water retention may offset the initial costs associated with biochar production and application (Osman *et al.*, 2022)^[29]. However, large-scale adoption among farmers remains limited in some regions due to lack of awareness, technical knowledge, standardized production methods, and initial investment requirements. Government support, policy incentives, extension services, and development of low-cost production technologies are important for promoting farmer adoption of biochar-based agricultural practices (Neogi *et al.*, 2021)^[28].

10.4 Environmental risks and safety concerns

Despite its numerous benefits, biochar application may pose certain environmental and safety concerns depending on feedstock type and production conditions (Ali *et al.*, 2025). Biochar produced from contaminated biomass or sewage sludge may contain potentially toxic substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (He *et al.*, 2022) ^[15]. Excessive biochar application may alter soil pH, nutrient balance, and microbial community composition, potentially

affecting soil ecosystem functioning (Ajeng *et al.*, 2020) ^[2]. Additionally, variations in biochar quality and lack of standardized production protocols may lead to inconsistent agronomic responses (Bamdad *et al.*, 2021). Therefore, careful selection of feedstocks, optimization of production parameters, and long-term field evaluations are essential to ensure the safe and sustainable use of biochar in agricultural systems (Neogi *et al.*, 2021; Ali *et al.*, 2025; He *et al.*, 2022) ^[15, 28].

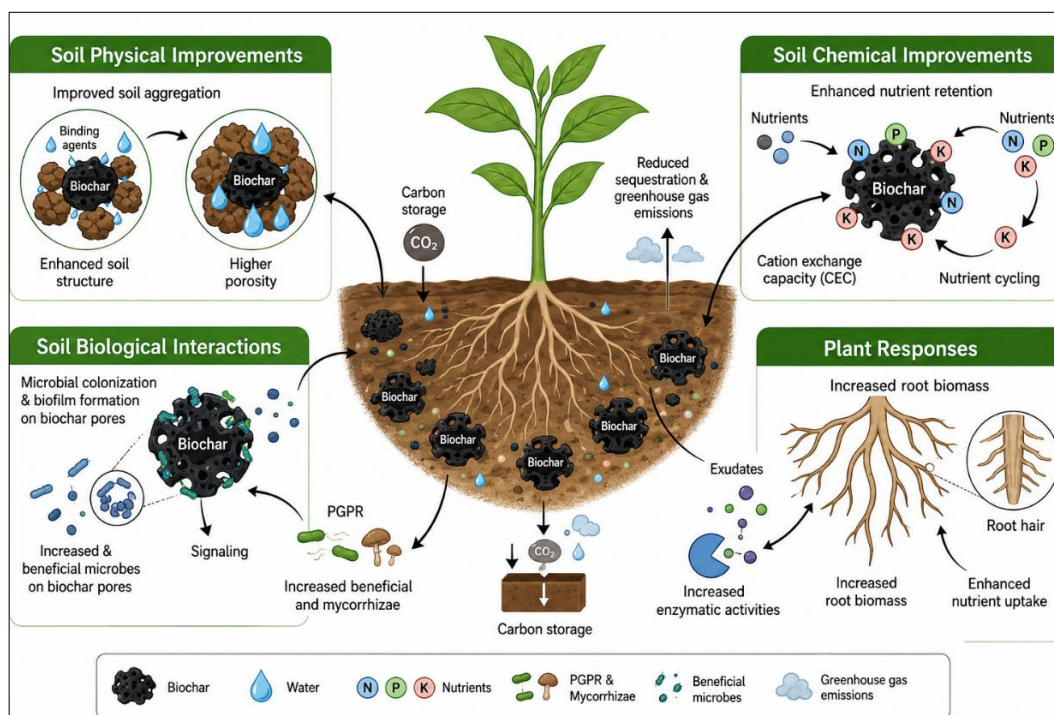


Fig 1: Mechanisms of biochar-mediated rhizosphere engineering in soil plant microbe system

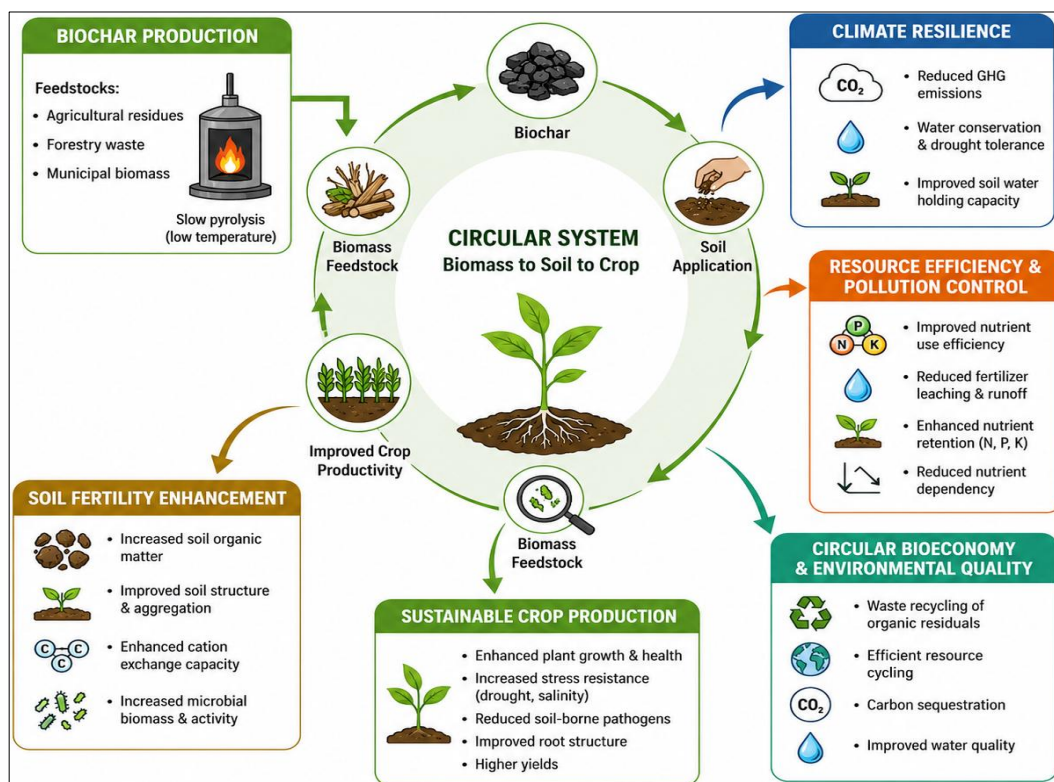


Fig 2: Integrated framework of biochar for sustainable and climate-resilient agriculture

Table 1: Different Feedstocks and Physicochemical Properties of Biochar

Feedstock source	Major characteristics of biochar	pH range	Nutrient content	Surface area/porosity	Major agricultural benefits	Citations
Rice husk	Silica-rich, lightweight, porous	Neutral to alkaline	Moderate K and Si	High porosity	Improves water retention and soil aeration	Ali <i>et al.</i> , 2025
Wheat straw	High carbon content, stable structure	Slightly alkaline	Moderate N and K	Moderate to high	Enhances soil aggregation and microbial activity	Wang <i>et al.</i> , 2022 ^[38, 39]
Sugarcane bagasse	High cellulose and lignin content	Alkaline	Moderate nutrient content	High surface area	Improves nutrient retention and carbon sequestration	Bolan <i>et al.</i> , 2023 ^[6]
Maize stalk	Porous and carbon-rich	Neutral to alkaline	Moderate nutrients	Moderate porosity	Enhances soil fertility and root growth	Bamdad <i>et al.</i> , 2021
Poultry manure	Nutrient-rich biochar	Highly alkaline	High N, P, and K	Moderate	Improves nutrient availability and crop productivity	Ajeng <i>et al.</i> , 2020 ^[2]
Cow dung	Ash-rich and nutrient-dense	Alkaline	High organic nutrients	Moderate	Supports microbial activity and nutrient cycling	Neogi <i>et al.</i> , 2021 ^[28]
Wood chips	Highly stable aromatic carbon	Slightly acidic to neutral	Low nutrient content	Very high porosity	Excellent for long-term carbon sequestration	Hu <i>et al.</i> , 2024
Sawdust	High fixed carbon and stability	Neutral	Low nutrients	High surface area	Improves soil structure and moisture retention	Wang <i>et al.</i> , 2022 ^[38, 39]
Sewage sludge	Mineral-rich biochar	Variable	High P and micronutrients	Moderate	Nutrient recovery and waste recycling	Osman <i>et al.</i> , 2022 ^[29]
Green waste	Organic matter-rich	Neutral to alkaline	Moderate nutrients	Moderate	Enhances composting efficiency and soil fertility	Marciniczyk & Oleszczuk, 2022 ^[25]

Table 2: Effects of Biochar on Soil Microbial Communities and Enzyme Activities

Biochar effect	Target microbial/enzymatic component	Mechanism involved	Observed outcome in soil-plant system	Citations
Enhanced microbial colonization	Beneficial rhizobacteria (PGPR)	Porous habitat formation and nutrient retention	Increased microbial biomass and plant growth	Neogi <i>et al.</i> , 2021 ^[28]
Improved nitrogen fixation	Diazotrophic bacteria	Favorable rhizosphere conditions	Enhanced nitrogen availability	Wang <i>et al.</i> , 2022 ^[38, 39]
Increased mycorrhizal association	Arbuscular mycorrhizal fungi (AMF)	Improved root-fungal interaction	Better phosphorus uptake and stress tolerance	Yuan <i>et al.</i> , 2023 ^[46]
Suppression of pathogenic fungi	Soil-borne pathogens	Competition and adsorption of toxic compounds	Reduced disease incidence	He <i>et al.</i> , 2022 ^[15]
Increased dehydrogenase activity	Soil microbial metabolism	Enhanced microbial respiration	Improved biological soil activity	Ramesh & Raghavan, 2024 ^[32]
Enhanced phosphatase activity	Phosphorus mineralization	Greater microbial and enzyme stimulation	Increased phosphorus availability	Osman <i>et al.</i> , 2022 ^[29]
Improved urease activity	Nitrogen transformation	Enhanced microbial enzymatic processes	Better nitrogen cycling	Marciniczyk & Oleszczuk, 2022 ^[25]
Increased catalase activity	Oxidative stress regulation	Enhanced microbial stability	Improved soil biochemical functioning	Wang <i>et al.</i> , 2022 ^[38, 39]
Enhanced organic matter decomposition	Decomposer microbial communities	Improved microbial habitat and carbon availability	Faster nutrient cycling	Ramesh & Raghavan, 2024 ^[32]
Increased microbial diversity	Soil bacterial and fungal communities	Improved soil moisture and nutrient balance	Greater soil ecosystem stability	Hu <i>et al.</i> , 2024

11. Conclusion

Biochar-mediated rhizosphere engineering has emerged as a promising strategy for improving soil health, enhancing nutrient cycling, and strengthening soil-plant-microbe interactions in sustainable agriculture. Due to its unique physicochemical properties, biochar significantly improves soil physical structure, nutrient retention, microbial activity, water holding capacity, and carbon sequestration. These improvements positively influence plant growth, nutrient uptake, stress tolerance, and overall crop productivity across diverse agricultural systems. The integration of biochar with microbial inoculants, compost, engineered materials, and advanced agricultural technologies further enhances its effectiveness in sustainable and climate-resilient farming

practices. Biochar also contributes to waste recycling, reduction in chemical fertilizer dependency, greenhouse gas mitigation, and long-term soil carbon stabilization, thereby supporting environmental sustainability and circular bioeconomy approaches. Recent advances in molecular biology, microbial ecology, nanotechnology, and engineered biochar development have expanded the understanding and applications of biochar-assisted rhizosphere engineering. However, challenges related to variability in biochar properties, economic feasibility, large-scale adoption, and long-term environmental impacts still require further investigation. Overall, biochar represents a multifunctional and eco-friendly tool with significant potential for improving agricultural sustainability and climate resilience.

Future research should focus on standardization of biochar production, optimization of application strategies, development of engineered biochar systems, and long-term field-based evaluations to maximize its agronomic and environmental benefits in modern agricultural systems.

References

1. Afshar M, Mofatteh S. Biochar for a sustainable future: environmentally friendly production and diverse applications. *Results Eng.* 2024;22:102433. DOI:10.1016/j.rineng.2024.102433.
2. Ajeng A, Abdullah R, Ling TC, Ismail S, Lau BF, Ong HC, *et al.* Bioformulation of biochar as a potential inoculant carrier for sustainable agriculture. *Environ Technol Innov.* 2020;20:101168. DOI:10.1016/j.eti.2020.101168.
3. Ali A, Jabeen N, Chachar Z, Chachar S, Ahmed S, Ahmed N, *et al.* The role of biochar in enhancing soil health and interactions with rhizosphere properties and enzyme activities in organic fertilizer substitution. *Front Plant Sci.* 2025;16. DOI:10.3389/fpls.2025.1595208.
4. Anbuganesan V, Vishnupradeep R, Bruno L, Sharmila K, Freitas H, Rajkumar M. Combined application of biochar and plant growth-promoting rhizobacteria improves heavy metal and drought stress tolerance in *Zea mays*. *Plants.* 2024;13. DOI:10.3390/plants13081143.
5. Bamdad H, Papari S, Lazarovits G, Berruti F. Soil amendments for sustainable agriculture: microbial organic fertilizers. *Soil Use Manag.* 2022;38:120-194. DOI:10.1111/sum.12762.
6. Bolan S, Hou D, Wang L, Hale L, Egamberdieva D, Tammeng P, *et al.* The potential of biochar as a microbial carrier for agricultural and environmental applications. *Sci Total Environ.* 2023;163968. DOI:10.1016/j.scitotenv.2023.163968.
7. Chew J, Zhu L, Nielsen S, Graber ER, Mitchell DRG, Horvat J, *et al.* Biochar-based fertilizer: supercharging root membrane potential and biomass yield of rice. *Sci Total Environ.* 2020;713:136431. DOI:10.1016/j.scitotenv.2019.136431.
8. Dong W, Qin J, Chun J, Yang X, Ou L, Zhou T, *et al.* Synergistic effects of biochar and arbuscular mycorrhizal fungi on maize growth: insights into nutrient uptake and microbial community shifts. *Ind Crops Prod.* 2026. DOI:10.1016/j.indcrop.2025.122467.
9. Egamberdieva D, Wirth S, Behrendt U, Abd_Allah EF, Berg G. Biochar treatment resulted in a combined effect on soybean growth promotion and a shift in plant growth-promoting rhizobacteria. *Front Microbiol.* 2016;7. DOI:10.3389/fmicb.2016.00209.
10. Fan C, Cui Y, Zhang Q, Yin N, Cai X, Yuan X, *et al.* A critical review of the interactions between rhizosphere and biochar during the remediation of metal(loid)-contaminated soils. *Biochar.* 2023;5:1-33. DOI:10.1007/s42773-023-00278-y.
11. Fu Y, Luo Y, Auwal MA, Singh BP, Van Zwieten L, Xu J. Biochar accelerates soil organic carbon mineralization via rhizodeposit-activated Actinobacteria. *Biol Fertil Soils.* 2022;58:565-577. DOI:10.1007/s00374-022-01643-y.
12. Gu Y, Liang X, Zhang H, Fu R, Li M, Chen C. Effect of biochar and bioorganic fertilizer on the microbial diversity in the rhizosphere soil of *Sesbania cannabina* in saline-alkaline soil. *Front Microbiol.* 2023;14. DOI:10.3389/fmicb.2023.1190716.
13. Hakim S, Naqqash T, Nawaz M, Laraib I, Siddique M, Zia R, *et al.* Rhizosphere engineering with plant growth-promoting microorganisms for agriculture and ecological sustainability. *Front Sustain Food Syst.* 2021;5. DOI:10.3389/fsufs.2021.617157.
14. He C, Harindintwali J, Cui H, Zheng W, Zhu Q, Chang SC, *et al.* Decoupled fungal and bacterial functional responses to biochar amendment drive rhizosphere priming effect on soil organic carbon mineralization. *Biochar.* 2024;6. DOI:10.1007/s42773-024-00376-5.
15. He M, Xu Z, Hou D, Gao B, Cao X, Ok YS, *et al.* Waste-derived biochar for water pollution control and sustainable development. *Nat Rev Earth Environ.* 2022;3:444-460. DOI:10.1038/s43017-022-00306-8. Hu, W., Zhang, Y., Rong, X., Zhou, X., Fei, J., Peng, J., & Luo, G. (2024). Biochar and organic fertilizer applications enhance soil functional microbial abundance and agroecosystem multifunctionality. *Biochar*, 6, 1-17. <https://DOI.org/10.1007/s42773-023-00296-w>
16. Ibrahim M, Tong C, Hu K, Zhou B, Xing S, Mao Y. Biochar-fertilizer interaction modifies N-sorption, enzyme activities and microbial functional abundance regulating nitrogen retention in rhizosphere soil. *Sci Total Environ.* 2020;739:140065. DOI:10.1016/j.scitotenv.2020.140065.
17. Idbella M, Baronti S, Giagnoni L, Renella G, Becagli M, Cardelli R, *et al.* Long-term effects of biochar on soil chemistry, biochemistry, and microbiota: results from a 10-year field vineyard experiment. *Appl Soil Ecol.* 2024. DOI:10.1016/j.apsoil.2023.105217.
18. Joseph S, Cowie A, Van Zwieten L, Bolan N, Budai A, Buss W, *et al.* How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy.* 2021;13:1731-1764. DOI:10.1111/gcbb.12885.
19. Kurniawan TA, Othman MH, Liang X, Goh HH, Gikas P, Chong KK, *et al.* Challenges and opportunities for biochar to promote circular economy and carbon neutrality. *J Environ Manage.* 2023;332:117429. DOI:10.1016/j.jenvman.2023.117429.
20. Li W, Hou Y, Long M, Wen X, Han J, Liao Y. Long-term effects of biochar application on rhizobacteria community and winter wheat growth on the Loess Plateau in China. *Geoderma.* 2023. DOI:10.1016/j.geoderma.2022.116250.
21. Li X, Yao S, Bian Y, Jiang X, Song Y. The combination of biochar and plant roots improves soil bacterial adaptation to PAH stress: insights from soil enzymes, microbiome, and metabolome. *J Hazard Mater.* 2020;400:123227. DOI:10.1016/j.jhazmat.2020.123227.
22. Li Z, Lin K, Wang Y, Zhai Y, Wang B, Ping M, *et al.* Synergistic superiority of AMF and biochar in enhancing rhizosphere microbiomes to support plant growth under Cd stress. *Biochar.* 2025;7. DOI:10.1007/s42773-025-00498-4.
23. Liao H, Li Y, Yao H. Biochar amendment stimulates utilization of plant-derived carbon by soil bacteria in an intercropping system. *Front Microbiol.* 2019;10. DOI:10.3389/fmicb.2019.01361.

24. Liu W, Xiao X, Li L, Shen X, Cao Y, Gao C, *et al.* Biochar-based metal tolerating plant growth-promoting bacterial inoculants enhanced the ability of ryegrass for phytostabilization. *Environ Res.* 2024;120389. DOI:10.1016/j.envres.2024.120389.
25. Marcińczyk M, Oleszczuk P. Biochar and engineered biochar as slow- and controlled-release fertilizers. *J Clean Prod.* 2022. DOI:10.1016/j.jclepro.2022.130685.
26. Murtaza G, Ahmed Z, Eldin S, Ali B, Bawazeer S, Usman M, *et al.* Biochar-soil-plant interactions: a cross talk for sustainable agriculture under changing climate. *Front Environ Sci.* 2023;11. DOI:10.3389/fenvs.2023.1059449.
27. Mustafa A, Saeed Q, Lu X, Farooqi Z, Arshad U, Holátko J, *et al.* Beyond one-size-fits-all: tailoring engineered biochar for purpose-specific rhizosphere engineering in crop production, protection, and soil remediation. *Biochar.* 2026;8. DOI:10.1007/s42773-025-00521-8.
28. Neogi S, Sharma V, Khan N, Chaurasia D, Ahmad A, Chauhan S, *et al.* Sustainable biochar: a facile strategy for soil and environmental restoration, energy generation, mitigation of global climate change and circular bioeconomy. *Chemosphere.* 2021;133474. DOI:10.1016/j.chemosphere.2021.133474.
29. Osman AI, Fawzy S, Farghali M, El-Azazy M, Elgarahy AM, Fahim RA, *et al.* Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. *Environ Chem Lett.* 2022;20:2385-2485. DOI:10.1007/s10311-022-01424-x.
30. Parastesh F, Lajayer BA, Dell B. Plant growth-promoting rhizobacteria and biochar as drought defense tools: a comprehensive review of mechanisms and future directions. *Curr Issues Mol Biol.* 2025;47. DOI:10.3390/cimb47121040.
- Pathak, H., Chauhan, P., Seth, C., Dubey, G., & Upadhyay, S. (2024). Mechanistic and future prospects in rhizospheric engineering for agricultural contaminants removal, soil health restoration, and management of climate change stress.. *The Science of the total environment*, 172116. <https://doi.org/10.1016/j.scitotenv.2024.172116>
31. Prochnow F, Cavali M, Dresch A, Belli I, Libardi N, De Castilhos A. Biochar: from laboratory to industry scale—an overview of scientific and industrial advances, opportunities in the Brazilian context, and contributions to sustainable development. *Processes.* 2024;12(5). DOI:10.3390/pr12051006.
32. Ramesh K, Raghavan V. Agricultural waste-derived biochar-based nitrogenous fertilizer for slow-release applications. *ACS Omega.* 2024;9:4377-4385. DOI:10.1021/acsomega.3c06687.
33. Sarfraz R, Hussain A, Sabir A, Fekih I, Ditta A, Xing S. Role of biochar and plant growth-promoting rhizobacteria to enhance soil carbon sequestration—a review. *Environ Monit Assess.* 2019;191:251. DOI:10.1007/s10661-019-7400-9.
34. Sarma H, Shyam S, Zhang M, Guerriero G. Nano-biochar interactions within the rhizosphere and their implications for plant-soil dynamics. *Soil Environ Health.* 2024. DOI:10.1016/j.seh.2024.100095.
35. Shi A, Hu Y, Zhang X, Zhou D, Xu J, Rensing C, *et al.* Biochar loaded with bacteria enhanced Cd/Zn phytoextraction by facilitating plant growth and shaping rhizospheric microbial community. *Environ Pollut.* 2023;121559. DOI:10.1016/j.envpol.2023.121559.
36. Shoudho K, Khan T, Ara U, Khan M, Shawon Z, Hoque M. Biochar in global carbon cycle: towards sustainable development goals. *Curr Res Green Sustain Chem.* 2024. DOI:10.1016/j.crgsc.2024.100409.
37. Singh E, Mishra R, Kumar A, Shukla S, Lo SL, Kumar S. Circular economy-based environmental management using biochar: driving towards sustainability. *Process Saf Environ Prot.* 2022. DOI:10.1016/j.psep.2022.05.056.
38. Wang C, Luo D, Zhang X, Huang R, Cao Y, Liu G, *et al.* Biochar-based slow-release fertilizers for sustainable agriculture: a mini review. *Environ Sci Ecotechnol.* 2022;10:100167. DOI:10.1016/j.ese.2022.100167.
39. Wang K, Hou J, Zhang S, Hu W, Yi G, Chen W, *et al.* Preparation of a new biochar-based microbial fertilizer: nutrient release patterns and synergistic mechanisms to improve soil fertility. *Sci Total Environ.* 2022;160478. DOI:10.1016/j.scitotenv.2022.160478.
40. Wen Y, Wu R, Qi D, Xu T, Chang W, Li K, *et al.* The effect of AMF combined with biochar on plant growth and soil quality under saline-alkali stress: insights from microbial community analysis. *Ecotoxicol Environ Saf.* 2024;281:116592. DOI:10.1016/j.ecoenv.2024.116592.
41. Wu X, Yang F, Zhang J, Gao F, Hu Y, Yang K, *et al.* Biochar's role in improving pakchoi quality and microbial community structure in rhizosphere soil. *PeerJ.* 2024;12:e16733. DOI:10.7717/peerj.16733.
42. Yan H, Cong M, Hu Y, Qiu C, Yang Z, Tang G, *et al.* Biochar-mediated changes in the microbial communities of rhizosphere soil alter the architecture of maize roots. *Front Microbiol.* 2022;13. DOI:10.3389/fmicb.2022.1023444.
43. Yang H, Kerner P, Liang X, Struhs E, Mirkouei A, You Y. Biochar amendment modulates root metabolome and rhizosphere microbiome of wheat. *Biochar.* 2025;7. DOI:10.1007/s42773-025-00434-6.
44. Yang L, Shen P, Liang H, Wu Q. Biochar relieves the toxic effects of microplastics on the root-rhizosphere soil system by altering root expression profiles and microbial diversity and functions. *Ecotoxicol Environ Saf.* 2024;271:115935. DOI:10.1016/j.ecoenv.2024.115935.
45. Yrjälä K, Ramakrishnan M, Salo E. Agricultural waste streams as resource in circular economy for biochar production towards carbon neutrality. *Curr Opin Environ Sci Health.* 2022. DOI:10.1016/j.coesh.2022.100339.
46. Yuan X, Cao Y, Li J, Patel A, Dong C, Jin X, *et al.* Recent advancements and challenges in emerging applications of biochar-based catalysts. *Biotechnol Adv.* 2023;108181. DOI:10.1016/j.biotechadv.2023.108181.