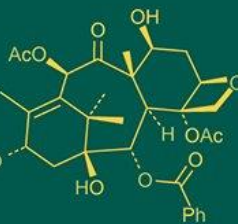
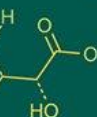
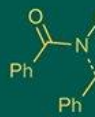


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Eco-friendly biochar applications in crop production, pest management, and disease control

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Abstract

Biochar that is eco-friendly has come up as a solution to sustainable amendment that has a multifaceted application in crop production, pest management, and control of diseases. The result of pyrolysis of the organic biomass under low oxygen levels is biochar, which improves the physicochemical properties of the soils, such as enhanced soil structure, better water retention, cation exchange capacities, and nutrient availability. It is porous, thus offering a good environment to soil microorganisms that enhance the growth and adaptation of plants. Application of biochar in crop production systems has also been reported to enhance seed germination, root growth, and yield, especially during stress (drought and nutrient deficiency) conditions. Also, biochar has been shown to be useful in the suppression of pests and diseases in that it induces systemic resistance in the plants, adsorbs toxins, and inhibits the growth of pathogens within the rhizosphere. It also leads to integrating pest management because it affects the diversity of soil microbes and disturbs the life cycle of pests. In addition, biochar helps in the sequestration of carbon and in the curtailment of greenhouse gas emissions, which contributes towards climate-savvy agriculture. Although it has a number of benefits, variability in the feedstock, production, and application rates could affect its efficacy, so a set of guidelines in the application of this system to the field needs standardization. All in all, biochar addition to the current agricultural practice presents a potential, environmentally friendly approach to improve its productivity, sustainability, and resilience in the protection of crops and the management of soil.

Keywords: Biochar, Sustainable agriculture, Soil health, Pest management, Disease suppression, Carbon sequestration

1. Introduction

Biochar can be defined as a stable carbon-rich material created via thermoconversion of organic biomass in the absence of, or with limited, oxygen (pyrolysis). It is usually fine-grained and highly porous, with a high carbon content, and is distinguished from charcoal because it is meant to be used in soil systems and the environment. Recent studies highlight biochar as a versatile soil amendment offering enhanced soil fertility, nutrient retention, and long-term carbon storage, thus bridging agricultural and climate change mitigation efforts (Bera, 2024; Kocsis *et al.*, 2022) [3, 21].

Biochar is not a new concept; its use dates back to ancient civilisations, as evident in the creation of Terra Preta ("black earth") soils in the Amazon region. These human-made soils, formed more than 2,000 years ago by indigenous people, were constructed by adding charred biomass and organic wastes (e.g., bones, manure) to the soil. The Terra Preta soils are much more fertile than the adjacent soils with greater nutrient status, better structure, and increased microbial diversity. The longevity and fertility of these soils have laid the groundwork for biochar research today, showcasing the recalcitrance of carbon and its positive impact on soil systems (Allohverdi *et al.*, 2021; Liu *et al.*, 2025) [2, 28].

A variety of feedstocks can be used to produce biochar, such as crop residues (straw, husks), wood products (wood chips, bark), manure, and even human and food waste. The feedstock used affects the chemical properties and agronomic performance of biochar. The pyrolysis process, including temperature (typically 350-750°C), heating rate, and residence time, also influences the physical and chemical characteristics of biochar. For example, biochar produced at higher pyrolysis temperatures is more stable (i.e., has a higher aromatic carbon

content), has a higher pH, and a higher surface area, while biochar produced at lower temperatures contains more volatile compounds and nutrients (Liu *et al.*, 2025; Bera, 2024) [3, 28].

Biochar's physicochemical characteristics play a crucial role in its agricultural uses. These include a porous structure, high specific surface area, high cation exchange capacity (CEC), and the presence of functional groups on the surface. These attributes improve water-holding capacity, nutrient retention, and provide a habitat for microorganisms. Biochar can also affect soil pH, typically raising it in acidic soils, thus enhancing nutrient availability and alleviating toxicity caused by elements like aluminum. Furthermore, the recalcitrant carbon structure allows biochar to remain in the soil for a long time, which is beneficial for carbon sequestration and climate change mitigation (Kocsis *et al.*, 2022; Bera, 2024) [3, 21].

The other key feature is the diversity of biochar characteristics based on the feedstock. For instance, biochars produced from wood feedstocks generally have a greater surface area and stability, whereas biochars from manure feedstocks contain more nutrients (such as nitrogen and phosphorus). This makes it possible to use biochar to tailor properties of agricultural soils, such as improving soil fertility, soil structure, or water-holding capacity (Liu *et al.*, 2025) [28].

2. Biochar and Soil Health Improvement

Biochar is an effective approach to enhance soil health due to its distinct properties, such as high porosity, surface area, and stable carbon content. The application of biochar to soil greatly improves soil structure through the formation of aggregates and improved pore interconnectivity. The porosity of biochar helps to form macro- and micro-aggregates, which in turn improve soil aeration, lower soil bulk density, and promote root growth. Research has demonstrated that biochar-treated soils have enhanced soil structure and aggregation, essential components for maintaining soil fertility (Elkhlifi *et al.*, 2023; Enebe *et al.*, 2025) [8, 9].

Water holding capacity (WHC) is one of the most well-known and studied properties enhanced by biochar. Biochar's high specific surface area and large pore volume enable it to hold a significant amount of water that can be gradually released to plants. Biochar particles interact with soil to form larger aggregates, with increased porosity, which retains water and prevents water losses via leaching. Studies have shown that biochar can enhance soil WHC by 10-30% (depending on soil and biochar type and application rate), which is particularly beneficial in arid and sandy soils (Zhang *et al.*, 2024) [52].

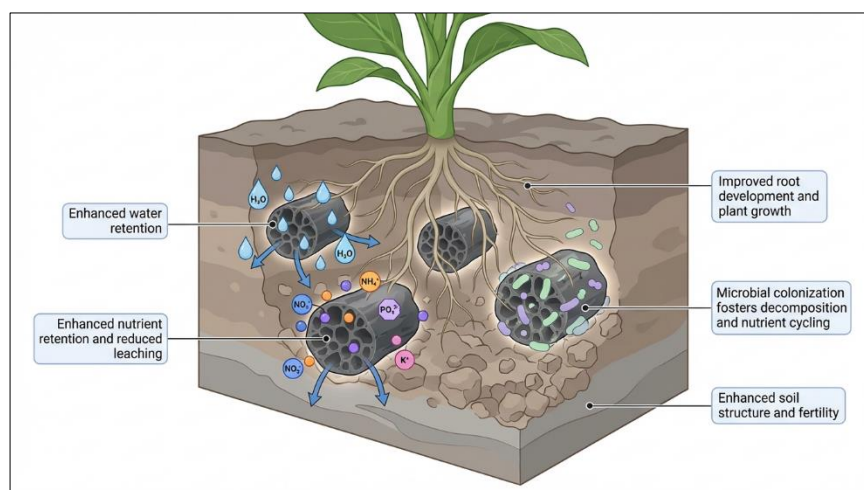


Fig 1: This diagram shows the ways biochar benefits the soil by improving water and nutrient retention, encouraging microbial life, and promoting healthy plant growth that results in better root development and soil structure.

Another important function of biochar is its role in soil chemical properties, such as soil pH and cation exchange capacity (CEC). Biochars are generally alkaline and can increase the pH of acidic soils, increasing nutrient availability and alleviating the toxic effects of elements like aluminum. Moreover, biochar increases soil CEC because of its high number of negatively charged functional groups and high specific surface area, allowing it to bind and retain important nutrients such as calcium, magnesium, potassium, and ammonium ions. Higher CEC helps retain nutrients and prevent their loss, leading to higher fertility and productivity (Elkhlifi *et al.*, 2023; Singh *et al.*, 2024) [8, 42].

Another key benefit of biochar is its carbon sequestration potential and impact on climate change. Biochar is rich in aromatic carbon structures that are resistant to microbial breakdown, making it very stable and long-lived in soils (hundreds to thousands of years). This property allows biochar to serve as a sink for carbon dioxide in the

atmosphere, contributing to its sequestration. Additionally, biochar has a positive effect on greenhouse gas emissions (e.g., nitrous oxide, methane) through changes in soil microbial activity and nutrient efficiency. It can therefore be used as a climate-smart agriculture and land management practice (Werner *et al.*, 2022; Liu *et al.*, 2023) [27].

Biochar has a significant impact on soil organic matter (SOM) and nutrient cycling. It may stimulate microbial activity by creating space in its pores, which in turn drives microbial processes of nutrient transformation. It can affect the mineralisation and stabilisation of organic matter, which can lead to greater nutrient availability and/or reduced nutrient losses. It can also sorb organic compounds and nutrients, leading to a slow-release source of nutrients for plants. Biochar-SOM interactions can also result in priming effects, stimulating decomposition of the existing organic matter, and improving carbon storage in the soil (Elkhlifi *et al.*, 2023; Zhang *et al.*, 2024) [8, 52].

Table 1: Effects of Biochar on Soil Health Parameters

Soil Property	Mechanism of Biochar Action	Observed Effects	Key Outcomes
Soil structure & porosity	Formation of aggregates, increased pore connectivity	Improved aeration, reduced bulk density	Better root growth and soil stability
Water holding capacity	High surface area and pore volume retain water	10-30% increase in WHC	Enhanced drought tolerance
Soil pH	Alkaline nature of biochar	Neutralization of acidic soils	Increased nutrient availability
Cation exchange capacity (CEC)	Presence of functional groups and adsorption sites	Increased nutrient retention	Reduced leaching losses
Carbon sequestration	Stable aromatic carbon structure	Long-term carbon storage	Climate change mitigation
Soil organic matter & nutrient cycling	Microbial habitat and adsorption of nutrients	Enhanced microbial activity and nutrient availability	Improved soil fertility

3. Biochar in Crop Productivity

3.1 Effect on Seed Germination and Early Plant Growth

This is often reported to increase seed germination and early growth as a result of alteration of the micro-environment of the root zone and soil. The structure of biochar helps in water retention and provides a home for microorganisms, which together promote faster seed germination and establishment. Laboratory and field experiments have shown that biochar increases the germination rate, root length, and seedling growth and development, particularly in poor-quality soils (Karim *et al.*, 2025; Hoque *et al.*, 2025). Furthermore, biochar can adsorb allelochemicals and reduce the soil toxicity, which enhances the seedling growth and assures uniform crop establishment.

3.2 Nutrient Retention and Slow-Release Behavior

Nutrient retention and slow release of biochar are key properties for enhancing crop production. Biochar's high surface area and cation exchange capacity allow it to retain nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which reduces nutrient leaching and prolongs their release. The nutrient retention and sustained release enhance nutrient supply during crop growth, enhancing nutrient-use efficiency. Studies have shown biochar-amended soils to have enhanced nutrient retention and fertiliser-use efficiency, increasing crop yields (Jalal *et al.*, 2023; Hoque *et al.*, 2025).

3.3 Influence on Root Development and Plant Physiology

Biochar has an impact on root development and plant physiology. Improved soil aeration and reduced soil compaction enable deeper rooting and an increase in root surface area, providing more water and nutrient absorption. Biochar also enhances microbial and symbiotic (mycorrhizae) activity, enhancing nutrient uptake. Physiologically, plants raised with biochar have higher chlorophyll content, photosynthesis, and water-use efficiency. These all contribute to enhanced plant growth and vigour (Hoque *et al.*, 2025).

3.4 Yield Improvement in Cereals, Pulses, and Horticultural Crops

There have been numerous field and meta-analysis studies that have reported yield improvement with biochar application in a wide range of crops: cereals (rice, wheat, maize), pulses (soybean, lentil), and horticultural crops. Generally, biochar increases the yields by 10-20%, with

higher yields in acidic or low-fertility soils. For example, meta-analysis indicates yield increases of around 14% in staple crops (maize, wheat, and rice) grown with low fertiliser inputs (Zhang *et al.*, 2024)^[52]. Similarly, studies on rice and wheat production demonstrate increased yield and biomass with the use of biochar (Farooqi *et al.*, 2024; Dai *et al.*, 2024)^[6]. Similarly, biochar increases fruit quality, yield, and nutrient content in fruit trees due to improved soil moisture and fertility.

3.5 Synergistic Effects with Fertilizers and Organic Amendments

Biochar can be used in combination with fertilizers and organic amendments (compost and manure). When applied together with fertilizers, biochar enhances nutrient efficiency by reducing nutrient loss and enhancing the availability of nutrients, thereby allowing the application of fertilizers to be reduced without losing yield. Studies have demonstrated that the application of biochar with organic manure increases crop productivity, nutrient efficiency, and water-use efficiency compared to the single use of biochar and manure (Sharma *et al.*, 2024; Khairoa *et al.*, 2025). Further, biochar assists in organic matter stabilisation, thus improving soil fertility and productivity. This integrated approach is consistent with sustainable agriculture systems that need higher production with lower environmental impact.

4. Biochar in Nutrient Management

4.1 Reduction of Nutrient Leaching (N, P, K)

Biochar plays a critical role in preventing nutrient loss from agricultural lands, including nitrogen (N), phosphorus (P), and potassium (K). The porous structure and large specific surface area of biochar facilitate nutrient adsorption and retention, reducing nutrient mobility and therefore, leaching into groundwater. Recent studies demonstrate that biochar is crucial in reducing nitrate leaching through the increase in soil adsorption and shift in the nitrogen transformation process (Luo *et al.*, 2025; Sun *et al.*, 2024). Likewise, phosphorus leaching is minimised by biochar's ability to retain phosphate ions and increase phosphorus availability to crops (Sun *et al.*, 2024). Retention of K is also improved by an increase in the cation exchange capacity (CEC), which reduces the losses in sandy soils (Rodrigues *et al.*, 2023). So, biochar acts as a source of nutrients, releasing nutrients into the environment in a sustainable manner.

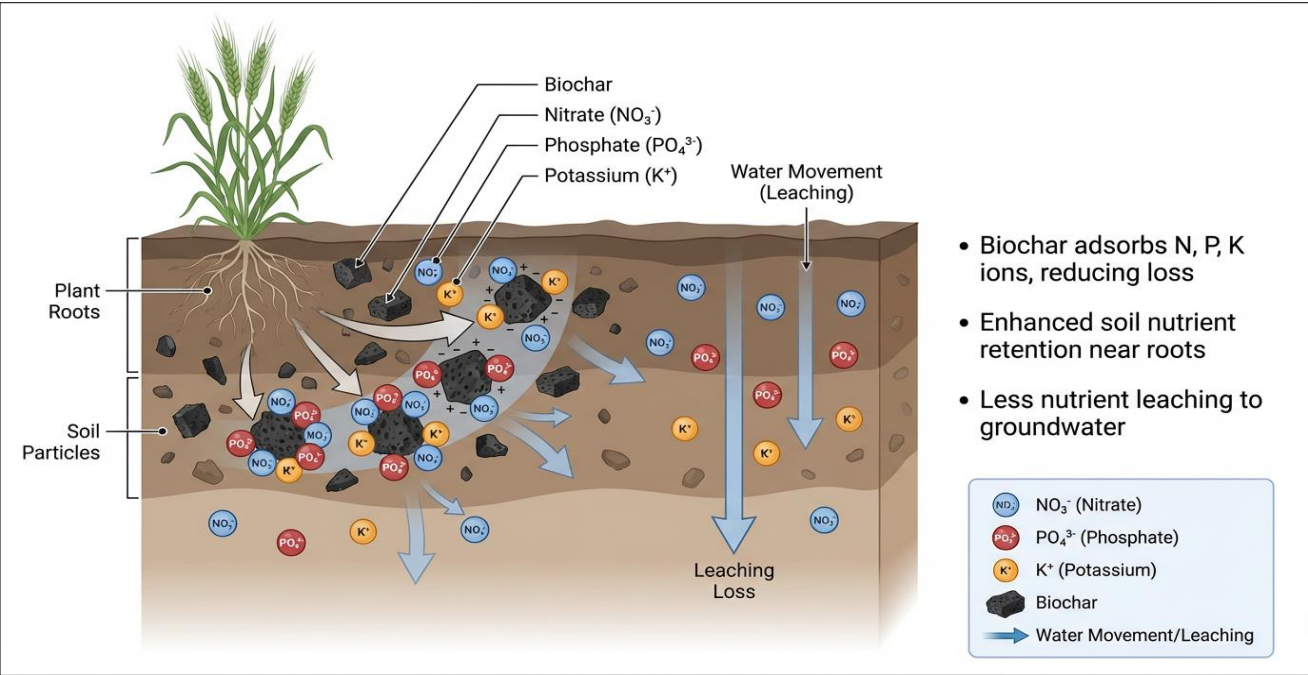


Fig 2: This diagram shows how biochar sorbs key nutrients (nitrate, phosphate, and potassium) in soil and prevents leaching. This helps retain nutrients around plant roots, increasing nutrient availability and preventing groundwater pollution.

4.2 Enhancement of Fertilizer Use Efficiency

Fertilizer use efficiency (FUE) is enhanced in the presence of biochar due to increased nutrient retention, decreased nutrient volatilization, and nutrient release matched with crop requirements. Biochar's interaction with fertilizers reduces nutrient release, thus reducing losses and improving nutrient availability. Research shows that biochar application enhances the use efficiency of inorganic fertilizers for nitrogen and phosphorus, which increases crop yield and decreases the amount of fertilizers (Gupta *et al.*, 2024; Thakur *et al.*, 2023). Further, biochar enhances microbial and enzymatic activities in soils, resulting in improved soil fertility. This integrated nutrient management not only helps in saving the cost of inputs but also in reducing the environmental impact of fertilizers.

4.3 Role in Immobilization of Heavy Metals

Biochar is well known to immobilize heavy metals in soil, such as cadmium (Cd), lead (Pb), and arsenic (As). This can be attributed to its high surface area, functional groups, and pH, which promote precipitation and complexation. Functionalized biochars, such as iron-impregnated biochar, are even more effective in decreasing the solubility and bioavailability of heavy metals in soils, while retaining

nutrients (Ray *et al.*, 2025). This helps to immobilise contaminants and prevents their uptake by plants and subsequent transfer into the food chain, making biochar an effective tool in improving soil health and ensuring food safety. Such a nutrient retention and contaminant immobilization effect makes biochar a promising approach for sustainable soil management and remediation.

4.4 Biochar as a Carrier for Beneficial Microbes and Biofertilizers

Biochar is a good carrier for beneficial soil microorganisms and biofertilizers due to its pores and carbon skeleton. The pores provide a haven for the microbes to colonise, shielding them from adverse environments and enhancing their survival in the soil. This stimulates the action of plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and other beneficial microbes to release and recycle nutrients. Research shows that the use of biochar in soil enhances microbial diversity and activity, resulting in increased nitrogen fixation, phosphorus solubilisation, and decomposition of organic matter (Hu *et al.*, 2023; Luo *et al.*, 2023). This, in turn, increases nutrient availability and plant growth, and decreases the use of chemical fertilizers.

Table 2: Role of Biochar in Nutrient Management

Aspect	Mechanism of Biochar Action	Key Nutrients/Elements Affected	Outcomes in Soil-Plant System
Nutrient leaching reduction	Adsorption, increased CEC, pore entrapment	N (nitrate, ammonium), P (phosphate), K	Reduced leaching losses, improved nutrient retention
Fertilizer use efficiency	Slow-release behavior, reduced volatilization	N, P, K	Enhanced nutrient uptake, reduced fertilizer requirement
Heavy metal immobilization	Surface adsorption, precipitation, complexation	Cd, Pb, As, Zn	Reduced toxicity, improved crop safety
Microbial carrier function	Habitat for microbes, improved microbial activity	N-fixing bacteria, P-solubilizing microbes	Enhanced nutrient cycling and soil fertility
Nutrient cycling enhancement	Enzyme activation, microbial stimulation	N, P, organic carbon	Improved nutrient availability and soil health
Soil buffering capacity	pH regulation and ion exchange	Acidic soils (Al, H ⁺ ions)	Balanced nutrient availability and reduced toxicity

5. Biochar in Pest Management

5.1 Mechanisms of Pest Suppression (Physical Barrier, Adsorption of Toxins)

Biochar helps to control pests directly and indirectly. Biochar can act as a physical barrier to insect movement and feeding (particularly soft-bodied pests) in the soil, as a result of its abrasive and porous nature. Biochar is also very adsorbent, which enables it to bind (adsorb) allelochemicals, toxins, and even pesticides. This immobilises toxic compounds to pests and detoxifies the soil. New research showcases biochar as a pesticide adsorbent (such as insecticides), which influences their persistence and may have non-target impacts (Singh *et al.*, 2024) ^[42]. As well, recent research shows new approaches such as pest biochar, which can efficiently adsorb insecticides, suggesting it could be used as a multifunctional material to control pests and pesticides (Zang *et al.*, 2025) ^[51].

5.2 Impact on Insect Behavior and Population Dynamics

Biochar amendments impact the behaviour and population dynamics of insects. Changes in soil physical and chemical characteristics, such as increased air and water content and nutrients, influence the environment of insects. Studies suggest that biochar affects insects' food selection, preferred oviposition sites, and increases insect mortality, causing reduced pest pressure in some crops. Further, biochar-induced changes in plant physiology (e.g., enhanced nutrition and plant resistance) make plants more resistant to pests. Studies have demonstrated that biochar can induce systemic resistance in plants, such as induced systemic resistance (ISR) and systemic acquired resistance (SAR), to induce plant mechanisms against pests and pathogens (Bhatt *et al.*, 2024; Lakshmi, 2023) ^[4, 23].

5.3 Biochar as a Carrier for Biopesticides and Entomopathogens

Biochar's surface area, porosity, and stability make it an excellent support for biopesticides and entomopathogens. It provides a refuge for beneficial microbes, like *Beauveria* and *Metarhizium*, which are used as biocontrol agents. Formulations containing biochar enhance the survival, establishment, and efficacy of these agents by reducing the effects of environmental factors such as UV light and desiccation. It can also prolong the release of microbial inoculums to improve their effectiveness and persistence. The use of biochar in combination with microbial biopesticides is part of sustainable pest control strategies, as it reduces the need for chemical pesticides and promotes safe and sustainable pest control (Vermelho *et al.*, 2024; Jalloh *et al.*, 2025) ^[46, 17].

5.4 Influence on Soil-Dwelling Pests

The use of biochar affects soil pests such as nematodes, larvae, and root feeders. Its use changes the characteristics of the habitat, which in turn affects pest populations, either reducing or redistributing them. For example, enhanced soil and microbial diversity may increase natural enemy populations, such as predatory nematodes and beneficial insects, leading to lower pest numbers. However, biochar can also directly impact soil insects by changing soil pH, moisture content, and thermal conditions, thus creating an unfavorable habitat for pests. Studies have shown that biochar application can affect insect populations and

infestation by altering life cycles and habitat, thus decreasing infestation.

6. Biochar in Disease Suppression

6.1 Suppression of Soil-Borne Pathogens (Fungi, Bacteria, Nematodes)

Biochar is an important component of controlling various soil-borne pathogens, such as fungi (*Fusarium*, *Rhizoctonia*), bacteria (*Ralstonia*), and nematodes. Suppression is primarily indirect, with biochar not always being toxic, but changing soil physical-chemical properties and microbial communities. This results in improved nutrient availability, absorption of phytotoxins, and changes in root exudates, making it difficult for pathogens to thrive (Bhatt *et al.*, 2024; Shree *et al.*, 2024) ^[4, 40]. Laboratory and greenhouse experiments have shown biochar treatments (1-2%) effectively suppress plant diseases, like tomato *Fusarium* wilt, by lowering pathogen population and enhancing the plant's health (Jin *et al.*, 2023) ^[18]. Biochar has also been shown to inhibit nematodes due to changes in soil microbiota and nematicidal compounds (Shree *et al.*, 2024) ^[40].

6.2 Induced Systemic Resistance (ISR) in Plants

Biochar has been shown to induce systemic resistance (ISR) in plants by activating their natural defenses against pathogens. It induces the activation of important immunity-related pathways, including salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) (Bhatt *et al.*, 2024) ^[4]. Additionally, biochar enhances the activity of antioxidant enzymes and induces the expression of defense genes, allowing plants to cope with pathogen attacks. This results in a quicker and more efficient response to pathogens. Research also indicates that biochar-induced ISR is strengthened by using beneficial microbial inoculants, which result in disease alleviation (Liu *et al.*, 2023) ^[27].

6.3 Changes in Rhizosphere Microbial Communities

Perhaps the most important way biochar suppresses disease is through changes in rhizosphere microbial populations. Biochar creates a porous structure and a carbon source promoting beneficial microorganisms like *Pseudomonas*, *Bacillus*, and mycorrhizal fungi (Science of the Total Environment, 2024). These microbes outcompete pathogens for resources, secrete antifungal compounds, and promote plant growth. In one study, biochar increased the number of bacteria and decreased pathogenic fungi to enhance soil suppressiveness (Jin *et al.*, 2023) ^[18]. Additionally, biochar changes the microbial diversity and composition, resulting in improved pathogen biological control. It can also enhance the establishment of introduced beneficial microorganisms, further contributing to disease suppression (Liu *et al.*, 2023) ^[27].

6.4 Role in Reducing Disease Incidence and Severity

Overall suppression of pathogens, induction of ISR, and changes in the soil microbiome result in disease reduction and mitigation. The beneficial effects of biochar on plant health, nutrition, and root growth render plants resistant to pathogens (Bhatt *et al.*, 2024) ^[4]. Numerous field and lab reports show reduced disease severity in different crops, such as suppression of groundnut stem rot and vegetable wilt diseases (Manasa *et al.*, 2024; Jin *et al.*, 2023) ^[34, 18].

7. Biochar and Soil Microbiology

Biochar is a vital soil amendment, and it is also an essential component of soil microbiology via enhancing the microbial abundance, diversity, and activity. Biochar's porous structure, high surface area, and high carbon content are a habitat for beneficial microorganisms (e.g., bacteria, fungi, and actinomycetes). For example, application of biochar increases the abundance of plant growth-promoting microorganisms (e.g., *Bacillus*, *Pseudomonas*, and other beneficial microorganisms) and increases soil fertility and yield (Guan *et al.*, 2023; Zou *et al.*, 2024) ^[12, 56]. The increased populations are attributed to the higher nutrient retention, buffering effect, and reduced environmental stress of biochar-treated soil.

Biochar's porous structure is important in providing niches for microbes. Biochar's porous structure provides microhabitats that are sheltered from predators and other environmental stresses, like desiccation and temperature extremes. The microhabitats also enhance the adsorption of organic matter and nutrients that can serve as a resource for the microbes. This makes biochar beneficial for microbial colonisation and stabilises the microbial community. Structural improvement helps in the survival and performance of microbes, particularly in poor and degraded soils, and improves continuous soil biological fertility (Bhattacharyya & Furtak, 2022) ^[5].

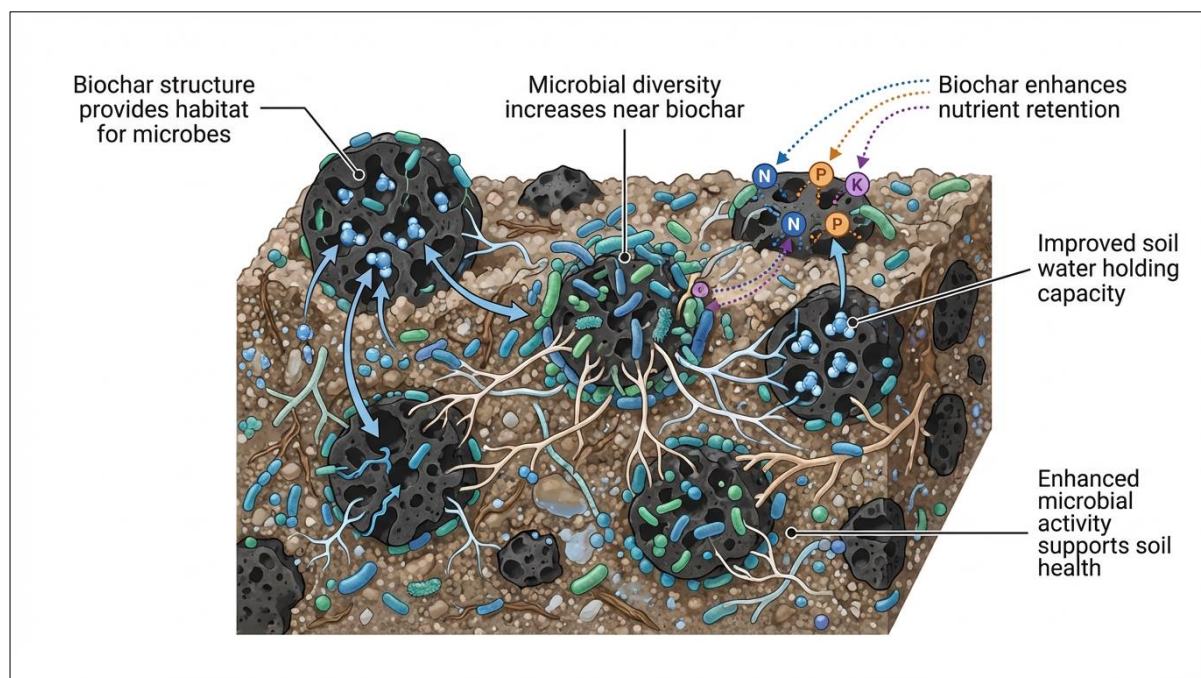


Fig 3: This infographic shows that biochar benefits soil ecosystems by creating niches for microorganisms, increasing nutrient retention, and increasing water storage capacity, which improves soil and plant health and productivity.

Biochar also synergises with mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR), which are important for plant growth. PGPR make nutrients available to the plants by nitrogen fixation, phosphate solubilisation, and the production of phytohormones, while arbuscular mycorrhizal fungi (AMF) improve nutrient and water uptake by expanding the root surface. Biochar acts as a carrier to immobilise and protect these microorganisms, improving their survival in the rhizosphere. For instance, PGPR immobilized in biochar has increased their survival, establishment, and efficacy, which has subsequently led to improved soil and plant growth (Guan *et al.*, 2023; Fasusi *et al.*, 2023) ^[12]. Additionally, co-application of biochar and PGPR has been found to have a greater effect on plant growth and soil health, particularly in stressed environments (such as salty soils) (Malik *et al.*, 2024) ^[33].

Another aspect of biochar-microbe interaction is on soil enzyme activities, as measures of soil biological activity. Biochar has been reported to enhance the activities of enzymes like dehydrogenase, urease, phosphatase, and β -glucosidase, which are important in nutrient cycling, such as carbon, nitrogen, and phosphorus. This is due to biomass growth and the preservation of extracellular enzymes by biochar. Biochar can also adsorb the enzyme inhibitors and

contaminants, promoting the enzyme activity and biochemical reactions in the soil. Increased enzyme activity leads to more nutrient release and soil fertility, leading to sustainable crop production (Zou *et al.*, 2024; Bhattacharyya & Furtak, 2022) ^[56, 5].

8. Environmental and Ecological Benefits

8.1 Reduction in Greenhouse Gas Emissions (CH_4 , N_2O)

The use of biochar is well-known for its ability to reduce greenhouse gas (GHG) emissions (such as methane (CH_4) and nitrous oxide (N_2O)) from croplands. The application of biochar enhances soil aeration, modifies microbial activities, and increases carbon storage in soils, which suppresses methanogenesis and stimulates methane oxidation. Recent research has shown large mitigation effects on CH_4 emissions in rice fields when biochar is applied, particularly in combination with improved irrigation management (López-Piñeiro *et al.*, 2025; Dai *et al.*, 2024) ^[29, 6]. Likewise, biochar helps in curbing N_2O emissions via effects on nitrogen transformation processes like nitrification and denitrification. It improves the retention and retention of nitrogen and hence reduces the N_2O emissions in fertilized soils (Zhong *et al.*, 2025) ^[54]. But the efficiency of mitigation depends on the amount of N input, soil and

biochar characteristics, and some studies have reported varying effects with high fertilizer application (Li *et al.*, 2024)^[24].

8.2 Waste Biomass Utilization and Circular Economy

Biochar is generated via the pyrolysis of agricultural biomass, forest biomass, and other biomass, transforming waste products into fertilisers. This is in line with the circular economy principle as the biomass waste is utilised instead of being burnt or discarded as waste, avoiding pollution. Bio-oil and syngas are also produced with biochar, and these can be used as renewable energy sources, thus increasing resource efficiency (Zhu *et al.*, 2025)^[55]. Biochar converts waste into stable carbon and helps in sequestering carbon in the soil for the long term, thus reducing carbon emissions from biomass decomposition or incineration. This approach not only helps in waste reduction but also in creating employment in the rural and agricultural sectors, promoting sustainable development, in accordance with global goals (Waheed *et al.*, 2024)^[48].

8.3 Remediation of Contaminated Soils

Its surface area and adsorption characteristics make biochar useful to clean up contaminated soils. It has the ability to immobilise heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As), reducing their phytotoxicity and ecotoxicity. It also adsorbs organic pollutants (pesticides and hydrocarbons) and prevents their leaching and migration. Biochar also improves soil properties (pH, cation exchange capacity (CEC), and organic matter) that facilitate microbial breakdown of contaminants. As such, biochar is a cost-effective and environmentally friendly soil additive to enhance soil properties, particularly in polluted and abandoned agricultural lands (Zhang *et al.*, 2024)^[52].

8.4 Reduction in Agrochemical Dependency

Biochar helps to lower the use of chemical fertilizers and pesticides by enhancing soil fertility, nutrient availability, and plant growth. The increased nutrient use efficiency with biochar reduces the dependency on fertilizers and thus reduces costs and risks with nutrient runoff and leaching. Moreover, biochar enhances the population of beneficial microorganisms that inhibit plant pathogens, thus reducing the need for pesticides (Liu *et al.*, 2023)^[27].

9. Limitations and Challenges

Although using biochar has several agronomic and environmental benefits, there are some challenges and limitations. The first is the biochar properties that vary depending on the feedstock source and production method (mainly temperature and time of pyrolysis). This greatly influences biochar's physicochemical characteristics (pH, surface area, porosity, and nutrient content) in turn influencing soil properties and crop performance (Wu *et al.*, 2023; Mahmood *et al.*, 2024)^[49, 32]. This might limit biochar's applicability to a wide range of agroecosystems and its predictability in field conditions.

A key factor is the toxicity of high application rates of biochar. Excessive biochar application can have adverse effects on soil fertility (nutrient imbalance, increased soil pH, and formation of toxic compounds like polycyclic aromatic hydrocarbons (PAHs), which may affect soil microbes, animals, and plant performance) (Mahmood *et al.*, 2024)^[32]. Other studies show high application rates (e.g.,

greater than 20 t ha⁻¹) may not be agronomically and environmentally beneficial, implying that a biochar dose is needed (Patel and Panwar, 2024)^[35].

The lack of clear guidelines for biochar production and application also limits its use. Currently, there is no uniformity in the standards, certifications, and their application rates, which may lead to inconsistent field results. What's more, there are inconsistencies in the production practices among many biochar producers, which could pose problems in biochar quality and safety (Senadheera *et al.*, 2024)^[38]. This also presents a challenge for scientists and policymakers in making recommendations to farmers.

There are challenges with the economic and scale-up aspects. Biochar production is energy-intensive and costly, in terms of capital investment, for example, in feedstock harvesting and transport, and pyrolysis equipment. Researchers have shown that the cost of production and the payback period (up to a few years) are high, making it less attractive to farmers and small-scale farmers (Patel and Panwar, 2024; Senadheera *et al.*, 2024)^[34, 38]. In addition, logistical aspects of scale-up (production, supply, and delivery), and market development also pose challenges to commercialisation (Waheed *et al.*, 2024)^[48].

10. Future Prospects and Research Needs

The research focus on biochar is now for enhancing its effectiveness, scalability, and use in sustainable agriculture. A promising field is that of modified biochar with superior properties. Recent studies have demonstrated that engineered biochar (modified biochar, prepared by chemical activation, doping, or surface modification) has improved properties for nutrient retention, contaminant removal, and interactions with microorganisms, compared to conventional biochar (Liang & Chen, 2025; Singh *et al.*, 2026)^[25, 41]. Such modified forms of biochar with superior reactivity and efficiency, such as nano-biochar and biochar composites, have great potential for cleaning up the environment as well as precision nutrient release.

An integration of biochar with nanotechnology and precision agriculture is also on the rise. The use of biochar combined with nanosensors, smart nutrient delivery, and precision farming enables precise regulation of soil nutrients, water, and carbon. This helps in the transition from traditional soil amendments to smart soil applications, leading to better resource use efficiency and sustainability (Kong *et al.*, 2025)^[22]. Nano-biochar, due to its large surface area and high adsorption capacity, can also selectively eliminate contaminants and boost soil-plant interactions (Frontiers, 2023)^[12].

There are many advances being made, but there is a need for long-term field studies in different agro-climatic regions. Existing research is short-term lab and greenhouse experiments, which may not indicate the outcomes from field trials. There is a need for long-term studies to determine biochar's persistence, the stability of the carbon sequestered, and its long-term effects on soil fertility, productivity, and greenhouse gas emissions. In addition, interactions of biochar with the soil, cropping systems, and climate are also poorly understood (Abbey *et al.*, 2025)^[1]. These will give localised recommendations and enhance the predictability of biochar.

The other key consideration is to develop policies to encourage farmers' uptake. Although biochar has been

demonstrated to have multiple environmental and agricultural benefits, it is still not widely used due to a lack of awareness, financial and regulatory barriers. What should be the next steps should be to establish quality standards, certification, and incentives (carbon credits and subsidies) for biochar use. In addition, adopting biochar in national policies for climate-smart agriculture and circular economy will facilitate the commercialisation and upscaling of biochar (Upadhyay *et al.*, 2024; Liang & Chen, 2025)^[45, 25]. Overall, the future of biochar will be technology development, interdisciplinary research, and policies. Developing engineered biochar, using nanotechnology and precision farming to use biochar, conducting long-term field trials, and providing institutional support will be essential to ensure the use of biochar for sustainable agricultural and environmental methods.

11. Conclusion

Biochar is an environmentally friendly and multifunctional amendment with tremendous potential for crop production, pest control, and disease prevention. Biochar use enhances soil fertility and water holding capacity, and provides a stable source of nutrients, which promote plant growth and improve yield. Biochar also helps with plant protection by inhibiting soil-borne diseases, pest populations, and stimulating beneficial soil microbes in the plant's root zone. This, overall, leads to healthier plants and decreased reliance on chemical fertilisers and pesticides. In the realm of sustainable and climate-smart agriculture, biochar is a key to carbon sequestration, reduction of greenhouse gas emissions, and recycling of agricultural wastes, and contributes to environmental sustainability. However, to be more widely used, biochar needs to deal with issues of quality, optimal application rates, and farmer education. In the future, biochar, when used in conjunction with organic amendments, biofertilizers, and precision farming, can be more effective. Improving policy settings, encouraging on-farm research, and cost-effective biochar production technologies will be key to scaling up its application in integrated and sustainable agriculture.

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