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Impacts of Conservation Tillage and Biochar on Restoration of Soil Quality by Altering Rhizospheric Nutrient Cycling, Biocrust Formation and Crop Productivity: A Review

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ABSTRACT

Understanding soil–plant–microbe inter- and intra- interactions are is essential for ensuring proper soil health, quality, and soil-mediated ecosystem services (e.g., nutrient cycling) required for human–plant–animal life. Intensive and unsustainable farming practices can decrease soil microbial biodiversity, fertility, and quality leading to soil degradation, impaired nutrient cycling, and the incapability of soil to support plant growth. Under such a context, soil biological fertility can appear as a regenerative component that has the potential to harmonize and improve soil's physical, chemical, and biological parameters. The review study expresses the micro biome in the rhizosphere, microbial nutrient cycling, and biological soil crusts as the major components of soil biological fertility, and explores the answers to the questions: (i) how How does the rhizosphere promote plant growth, development, and nutrient cycling through soil microorganisms, (ii) How can soil microorganisms regulate macronutrient cycling and facilitate bio crust formation. Soil biological fertility is crucial for increasing crop resilience and productivity as well as sustainability in agriculture. Additionally, the reintroduction of plant growth promoting rhizo bacteria, a quantitative estimation of the root exudate's composition, identifying the spatiotemporal dynamics of potassium solubilizing bacteria, and establishing biological soil crusts in agricultural lands remain the major tasks for improving soil biological fertility and the transition towards regenerative agriculture. Despite the promising potential of conservation tillage and biochar, the study meets problems such as diversity in soil types, climatic circumstances, and the long-term stability of biochar effects, which limit the generalization of results. However, by combining the most recent research on how these approaches boost crop productivity, encourage the formation of biocrusts, and enhance rhizospheric nutrient cycling, this review makes a substantial contribution and provides insightful information for long-term soil restoration plans.

Keywords: *Biocrusts; Rhizosphere; Soil Micro biome; Soil Quality; Carbon Cycling and Bioavailability.*

Introduction

Degradation of soil resulting from extensive agricultural practices and changing climatic conditions poses serious threats to global food security (22). The exponentially increasing greenhouse gas (GHGs) emissions due to various anthropogenic activities are also detrimental to the environment and sustainable farming systems (55). Additionally, the increasing world population, which is expected to reach 9.8 billion by 2050, will also put the world's agricultural system under enormous pressure (48). Hence to feed the burgeoning population, meet the exacerbating food demand, and mitigation ofe climate change impacts need benign and cost-effective strategies which that can improve soil health, enhance crop yield, and ensure a sustainable farming system and environment (46). Endowed with unique attributes such as larger specific surface area (SSA), abundant surface functional groups, porous structure, better cation exchange capacity (CEC), embedded minerals, strong adsorption capacity, micronutrients, and high environmental stability, bio char has appeared as a promising material for soil management, soil fertility improvement, reduction in GHGs and environmental management (1). Biochar is a carbonaceous material generated from the decomposition of various feed stocks by the pyrolysis process (slow, intermediate, fast pyrolysis, and gasification) under oxygen-restricted conditions (43). A wide array of positive impacts is associated with bio char addition, such as increased soil microbial activities, enhanced soil nutrient uptake by plants (65), improved soil nutrient availability (14), and decreased nutrient leaching. Furthermore, it improves soil aeration, porosity, bulk density, infiltration rate, aggregate stability, water holding capacity, and hydraulic conductivity (18), stabilizes heavy metals, and limits their bioavailability to crops growing in hostile or poor-quality soils (19).

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Biochar also promotes microbial abundance (64) and alleviates heat, drought, and salinity stress effects on crops. It enhances crop growth and productivity (38), increases biological N fixation in legumes (39), and facilitates carbon sequestration. However, the outcomes mentioned above largely depend on biochar type, the temperature at which biochar is prepared, biochar dose, and soil type.

2. Conservation Tillage and Its Role in Soil Restoration

Conservation tillage refers to minimal soil disturbance practices such as no-tillage (NT), reduced tillage (RT), and strip-tillage (ST), which preserve soil structure, enhance organic matter retention, and promote beneficial microbial interactions.

2.1. Effects on Soil Physical Properties

- Conservation tillage improves soil aggregation and porosity, leading to better aeration and water infiltration (47).
- Reduced tillage prevents excessive breakdown of soil aggregates, maintaining soil structure and reducing erosion (29).
- The accumulation of organic residues on the soil surface enhances moisture retention and reduces temperature fluctuations (12).

2.2. Effects on Soil Chemical Properties

- Conservation tillage promotes the retention of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) by reducing leaching losses (23).
- Enhanced cation exchange capacity (CEC) and organic matter buildup contribute to better nutrient availability for plants (4).
- Decreased soil disturbance minimizes the oxidation of organic matter, preserving soil carbon stocks (41)

2.3. Effects on Soil Biological Properties

- Conservation tillage supports the proliferation of beneficial microbial communities, including mycorrhizal fungi and nitrogen-fixing bacteria (54).
- The presence of surface residues enhances microbial biomass and enzymatic activity, which are crucial for nutrient cycling (66).
- Reduced tillage fosters higher earthworm populations, leading to improved soil aeration and organic matter decomposition (10).

3. Biochar as a Soil Amendment

Biochar is a carbon-rich material produced through the pyrolysis of organic biomass, such as crop residues, wood, and manure. It has been widely recognized for its ability to enhance soil quality, sequester carbon, and improve crop productivity.

3.1. Effects on Soil Structure and Moisture Retention

- Biochar improves soil aggregation and reduces bulk density, promoting better root penetration and water retention (31).
- Its high porosity enhances water-holding capacity, mitigating drought stress in crops (5).

3.2. Effects on Soil Nutrient Dynamics

- Biochar increases the availability of macronutrients (N, P, K) and micronutrients (Zn, Fe, Mn) by reducing leaching losses and enhancing adsorption sites (20).
- It modifies soil pH, leading to improved nutrient solubility and availability (45).
- Biochar application stimulates microbial activity, accelerating organic matter decomposition and nutrient mineralization (63).

3.3. Effects on Soil Microbial Communities

- Biochar provides a stable habitat for beneficial microbes, including nitrifiers, denitrifiers, and mycorrhizal fungi (52).
- It promotes microbial diversity and metabolic efficiency, enhancing nutrient cycling processes (27).
- Biochar can reduce soil-borne pathogens by inducing systemic resistance in plants (17).

4. Synergistic Effects of Conservation Tillage and Biochar on Rhizospheric Nutrient Cycling:

The combination of conservation tillage and biochar application enhances nutrient cycling by modifying soil microbial interactions and nutrient availability.

4.1. Enhanced Microbial Activity and Enzyme Production

- Conservation tillage fosters microbial hotspots, while biochar provides a stable carbon source, enhancing microbial efficiency (15).
- Increased production of enzymes such as phosphatases, ureases, and dehydrogenases accelerates nutrient mineralization (33).

4.2. Improved Nitrogen Cycling

- Biochar improves nitrogen use efficiency by reducing ammonia volatilization and nitrate leaching (25).
- Conservation tillage supports biological nitrogen fixation by enhancing legume-rhizobia interactions (28).

4.3. Phosphorus and Potassium Availability

- Conservation tillage reduces phosphorus runoff, while biochar enhances phosphorus retention through adsorption mechanisms (60).
- Potassium availability is improved as biochar prevents leaching losses and enhances root uptake (36).

5. Biocrust Formation and Soil Stability

Biological soil crusts (biocrusts) play a crucial role in soil stabilization, organic matter accumulation, and microbial diversity.

5.1. Conservation Tillage and Biocrust Development

- Reduced soil disturbance allows biocrust communities to establish, protecting against erosion and improving water infiltration (7).
- Biocrusts enhance nitrogen fixation and carbon sequestration, contributing to soil fertility (44).

5.2. Role of Biochar in Biocrust Enhancement

- Biochar creates microhabitats for cyanobacteria and lichens, fostering biocrust development (58).
- It increases organic carbon inputs, supporting microbial colonization and stabilization of soil particles (13).

6. Impact on Crop Productivity

- Conservation tillage and biochar enhance root growth, leading to better nutrient uptake and drought resilience (62).
- Increased soil organic matter and microbial activity translate into higher yields in cereals, legumes, and vegetables (3).

- Improvements in soil aeration and nutrient availability contribute to better seed germination and plant vigor (49).

7. Biochar as a soil ameliorator

Biochar's physiochemical properties can directly and indirectly affect the soil attributes. After biochar's addition to soil, its contribution to soil's physical structure may be significant, as it influences the soil aeration, water holding capacity (WHC), bulk density (BD), and distribution of pore size, porosity, and surface area of soil. Furthermore, several biological and chemical properties of soil can be altered through biochar addition. Different kinds of biochar's, when added in a sufficient amount into different soils, substantially amend the various soil physical attributes. Soil bulk density (BD) is an important indicator of soil physical condition because it indicates the arrangement and packing of soil particles (46) (8). Low soil BD enhances soil composition, decreases soil compaction, and improves WHC and nutrient release (51). Biochar application decreases both the bulk and particle densities of soils (37). This decrease could be attributed to the lower BD (.6 g cm^{-3}) and particle density (1.5–2.0 g cm^{-3}) of biochar's as compared to the 1.25 g cm^{-3} BD and 2.4–2.8 g cm^{-3} particle density of soils (Yu *et al.,* 2019). Biochar BD varies depending upon the type of feedstock and preparation conditions. For instance, BD of wood biochar is 1.30 g cm^{-3}, woody forest residue biochar is .09 g cm^{-3}, straw biochar is 1.30 g cm^{-3}, maize cob biochar is .29–.36 g $cm^{-3,}$ and rice husk biochar is .37 g cm^{-3} (62).

The reduction in soil BD after biochar addition results in an overall increase in soil porosity (42). The increase in soil porosity is attributed to the biochar porosity (70%–90%) and is further contributed by increased soil aggregation, reduced bulk density, reduction of soil packing, and interaction with mineral soil particles (9). Biochar application elevates the total porosity especially the micropores because they help to form porous material (61). The micropores enhance the water retention, whereas macropores improve the drainage. The soil porosity was observed to increase in the range of 5–25 µm after biochar amendment. Increase An increase in soil porosity can enhance the movement of gases, water, and heat in the soils. The type of feedstock used for biochar production significantly influences the soil porosity pattern (61). Woody biochar's contains higher porosity compared to the biochar's prepared from crop residues, which causes differences in the biomass cell structure, composition, size, and shape (16). Soil WHC is also affected by the porous structure of the biochar (8). The high porosity and specific surface area (SSA) increase the WHC, reduce the soil water permeability resistance, and change the water flow direction and residence time in the soil (2). The improvement in soil WHC after the addition of biochar is attributed to the rise in pore space of the soil and biochar mixture. This mixing resulted in an increased number of waters holding sites due to a large number of pores which increased the WHC of soil amended with biochar (61).

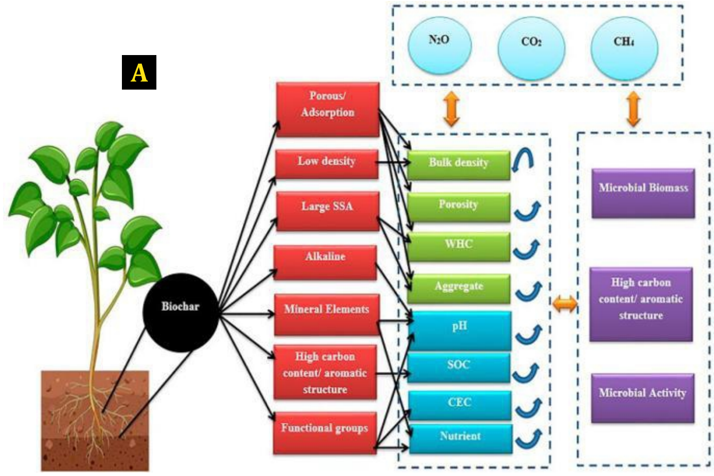


Figure 1: *Effect of biochar application on soil physicochemical and biological properties; Carbon dioxide (CO_2), Cation exchange capacity (CEC), Nitrous oxide (N_2O), Methane (CH_4), Soil organic carbon (SOC), Specific surface area (SSA), Water holding capacity (WHC)*

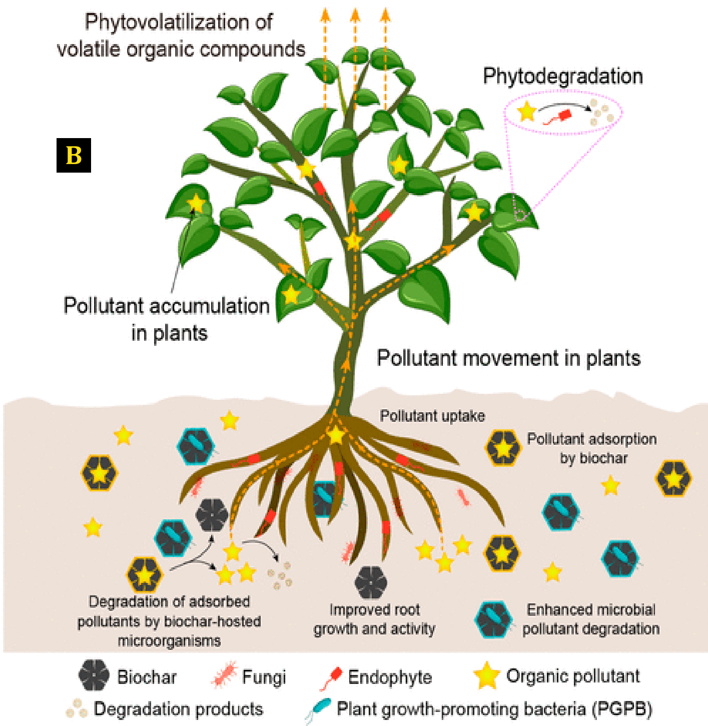


Figure 2: *Proposed mechanisms of synergistic contributions of biochar, PGPB, and plants for remediation of organic pollutants in soils [56].*

The use of biochar dramatically changes the biological and physicochemical characteristics of soil, improving soil health and mitigating the effects of climate change. Especially on sandy or damaged soils, its high specific surface area (SSA) and porous structure enhance soil aeration, aggregation, and water water-holding capacity (WHC) (30). Additionally, biochar improves cation exchange capacity (CEC), which lowers leaching losses of important elements like potassium and ammonium and improves nutrient retention (21).

Biochar increases soil organic carbon (SOC) levels by promoting humus-forming microbial activities and providing stable carbon forms (50). By modifying soil redox potential and nutrient cycling pathways, biochar promotes a more active and diversified microbial population that can reduce the release of greenhouse gases like methane (CH_4) and nitrous oxide (N_2O) (11). Additionally, by stabilizing organic matter and lowering microbial mineralization rates, biochar can lower carbon dioxide (CO_2) emissions. Because of these combined benefits, biochar is a useful technique for enhancing soil function and lessening agricultural systems' environmental impact (24).

For the remediation of organic contaminants in soils, the combination of biochar, plants, and plant growth-promoting bacteria (PGPB) is a viable integrated approach. (57) claim that biochar immobilizes organic pollutants such as pesticides and polycyclic aromatic hydrocarbons (PAHs) by acting as a microbial transporter and physical adsorbent. This lowers the toxicity and immediate bioavailability of these contaminants. By producing phytohormones, ACC deaminase, and antioxidant enzymes, PGPB simultaneously increases plant resistance to pollutants and aids in the biodegradation of pollutants through co-metabolism. Further encouraging the breakdown of contaminants, the biochar-enhanced rhizosphere offers the ideal milieu for microbial colonization and enzymatic activity. In addition to generating root exudates that promote microbial activity, plants also aid by absorbing and changing specific organic molecules. A biologically active and efficient mechanism for soil detoxification is produced by this triad: plants aid in the uptake and transformation of contaminants, PGPB breaks them down, and biochar stabilizes them (57; 35; 34).

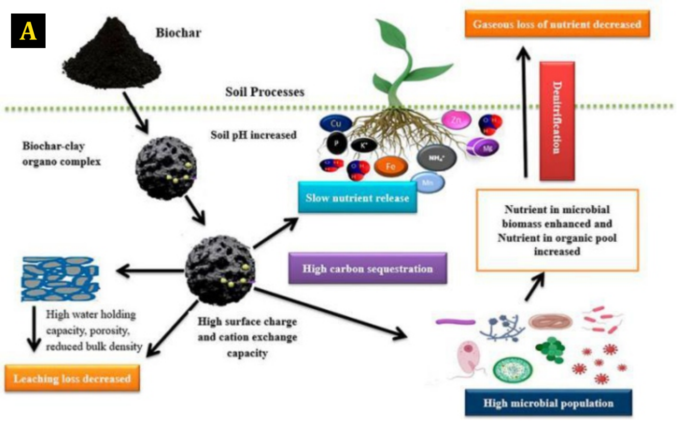


Figure 3a: Biochar induced modifications in soil properties and its impact on plant growth and development; Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Phosphorus (P), Potassium (K), Ammonium (NH_4), Zinc (Zn).

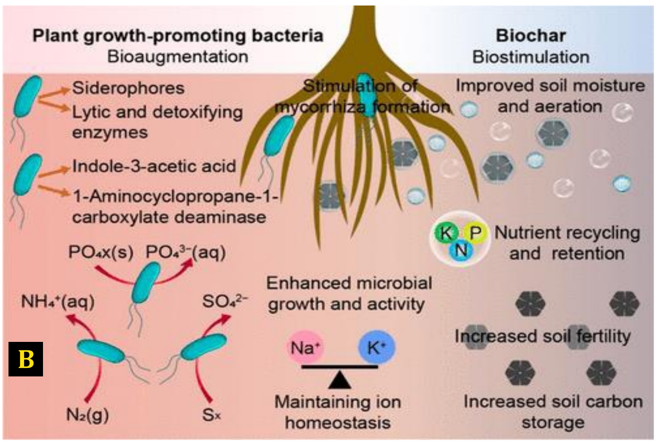


Figure 3b: Bioaugmentation by PGPB and bio-stimulation by biochar are the two main strategies to complement phytoremediation and improve soil qualities. PGPB can (1) fix nitrogen, solubilize phosphate and potassium, and oxidize sulfur (ruby arrows) [40]

Application of biochar alters important physicochemical characteristics of the soil, including pH, cation exchange capacity (CEC), and redox potential. These changes impact the availability of macro- and micronutrients that are vital for the growth and development of plants. Biochar can improve the availability of nutrients like phosphate (P) and magnesium (Mg) while decreasing the solubility of potentially harmful metals like Cu and Mn by raising the pH of the soil, especially in acidic soils. Over time, it becomes more accessible to plants due to its high surface area and porous structure, which enhance the retention and gradual release of potassium (K), ammonium (NH_4^+), and zinc (Zn). Furthermore, through root exudates and microbial siderophores, biochar's interaction with soil microbes can promote the mobilization of iron (Fe) and other micronutrients. These biochar-induced changes support better root architecture, nutrient uptake, and overall biomass accumulation, contributing to improved plant health and productivity (31) ; (6).

Two complementary techniques that greatly increase the effectiveness of phytoremediation and boost soil quality are bioaugmentation with plant growth-promoting bacteria (PGPB) and bio-stimulation with biochar. By carrying out essential biochemical processes like nitrogen fixation, phosphate and potassium solubilization, and sulphur sulfur oxidation—all of which are vital for nutrient-deficient and contaminated soils—PGPB improves plant resilience and growth. The rehabilitation of contaminated settings is accelerated by these microbial activities, which also improve plant biomass, promote root development, and boost nutrient availability and uptake. However, by giving PGPB a friendly environment and enhancing soil structure, water retention, and cation exchange capacity, biochar functions as a bio stimulant. Additionally, it adsorbs harmful substances, decreasing their toxicity and bioavailability to microorganisms and plants. Together, PGPB and biochar create a biologically enriched and chemically balanced rhizosphere that supports robust plant-microbe interactions for sustainable soil restoration (26); (53).

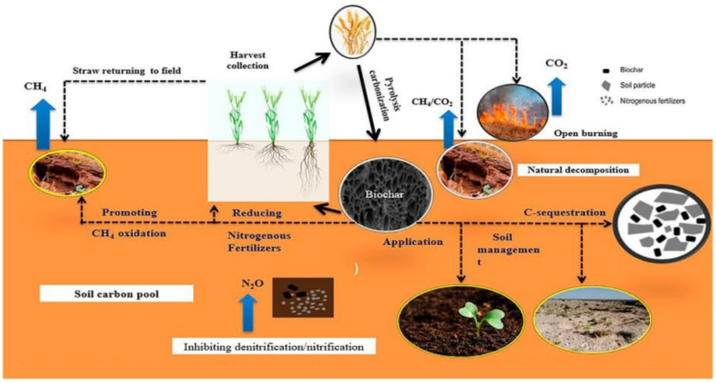
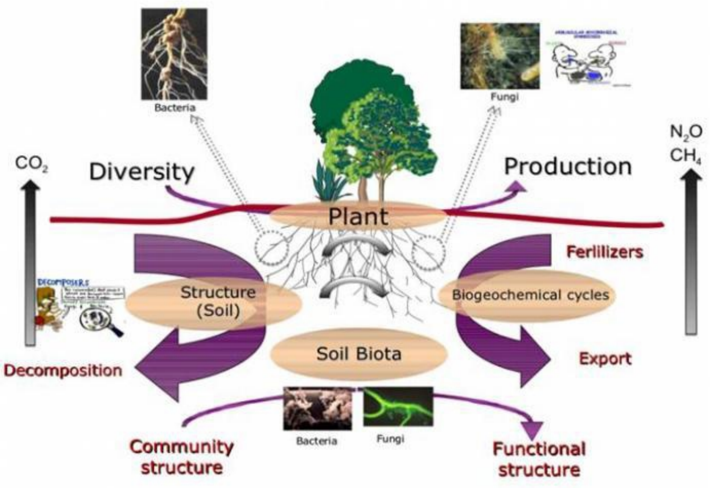


Figure 4: Mechanism of greenhouse gas (GHG) reduction and soil carbon (C) sequestration through biochar application; Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O).

Applying biochar to soil improves soil carbon sequestration while lowering emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which helps mitigate greenhouse gas emissions. When added to soil, biochar can function as a long-term carbon sink because of its extremely stable, aromatic carbon structure, which also renders it resistant to microbial breakdown. Additionally, biochar enhances the aeration and redox conditions of soil by inhibiting the anaerobic microbial activity that produces CH_4, especially in wet or waterlogged soils. By improving nitrogen retention, decreasing nitrification and denitrification rates, and encouraging microbial nitrogen immobilization, it also lowers N_2O emissions. The high surface area, porosity, and capacity of biochar to absorb nitrate and ammonium ions are responsible for these effects. Through these combined mechanisms, biochar offers a multifaceted approach to climate change mitigation and soil health restoration (32) (11).



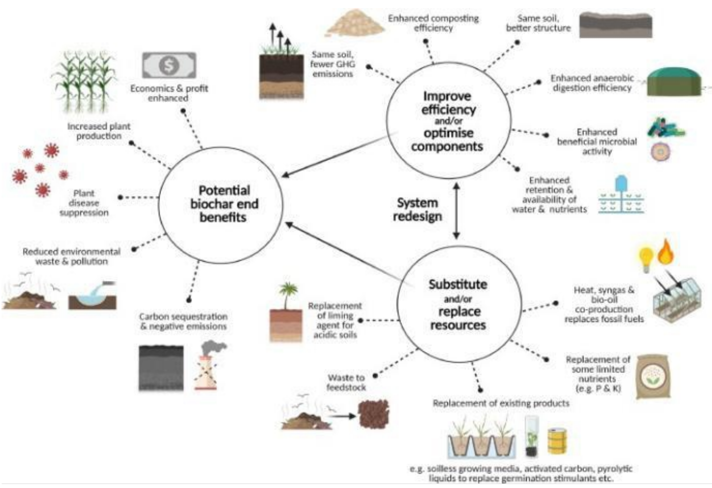
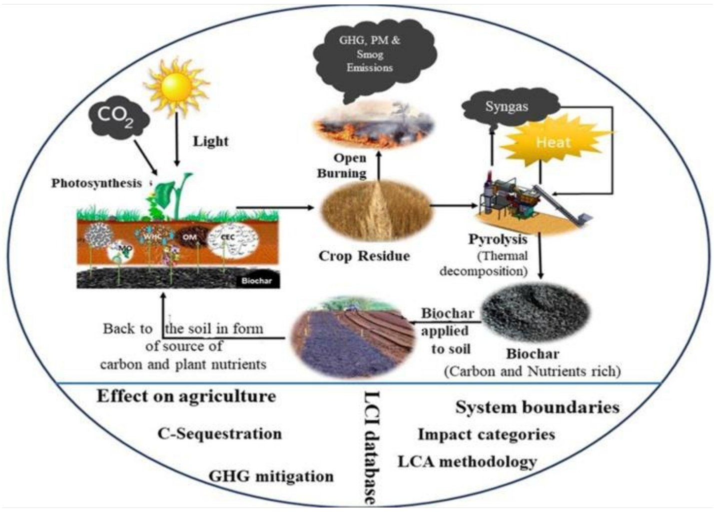


Figure 5: *The theoretical role of biochar in the intensification of plant-related industries, which involves system redesign via increased efficiency or substituting or replacing resources or combinations of each (31: 59).*

By enabling system redesign through increased resource efficiency, substitution, and integration of sustainable inputs, biochar theoretically has the ability to propel the intensification of plant-related businesses. Because it improves soil fertility, nutrient use efficiency, and water retention, it lessens the need for irrigation and artificial fertilizers, which lowers input costs and environmental impacts. Additionally, biochar can be used as a vehicle for agrochemicals or biofertilizers, enabling precision farming with less waste and more effective delivery. Additionally, by turning agricultural waste into valuable soil additives, it can support circular bio economies and replace artificial soil conditioners. These multipurpose advantages minimize ecological trade-offs while boosting productivity, which is in line with sustainable intensification aims. (31); (59). By redesigning agro-industrial systems around such eco-efficient inputs, biochar contributes not only to sustainable agriculture but also to bio-based industrial innovation.



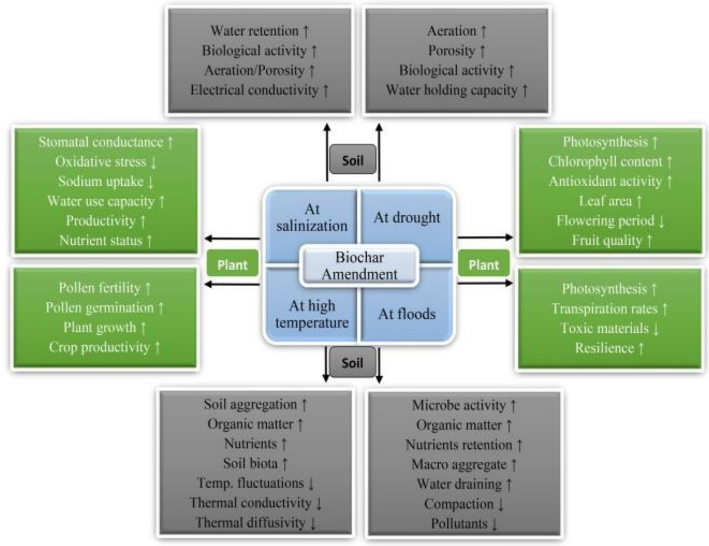


Figure 6: *Effects of biochar amendments on soil health*

By enhancing the physical, chemical, and biological characteristics of soil, biochar additives greatly improve soil health. Biochar improves plant-available water by physically increasing soil porosity and water-holding capacity, especially in sandy and damaged soils. Chemically, it improves cation exchange capacity (CEC), increases nutrient retention, lowers nitrogen and phosphorus leaching losses, and elevates soil pH in acidic soils. By offering a stable environment and adsorbing toxins that might otherwise prevent microbial growth, biochar promotes microbial variety and activity on a biological level. Together, these enhancements promote improved crop productivity, nutrient cycling, and root development (21); (30). Moreover, biochar's long-term stability contributes to sustained soil fertility and ecosystem resilience.

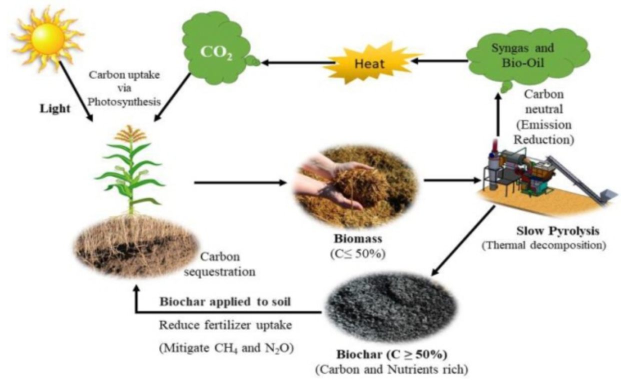
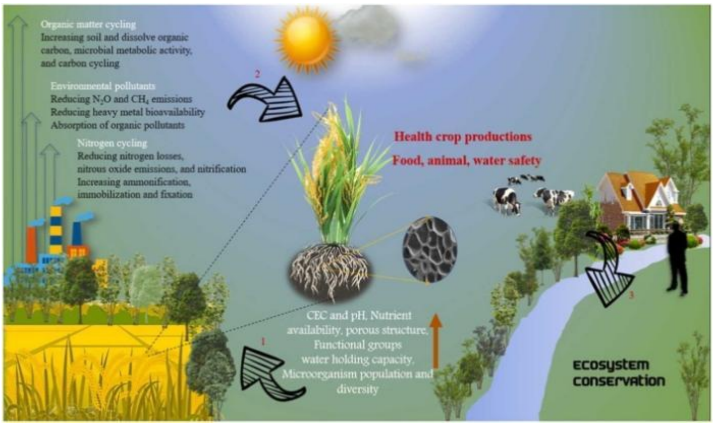
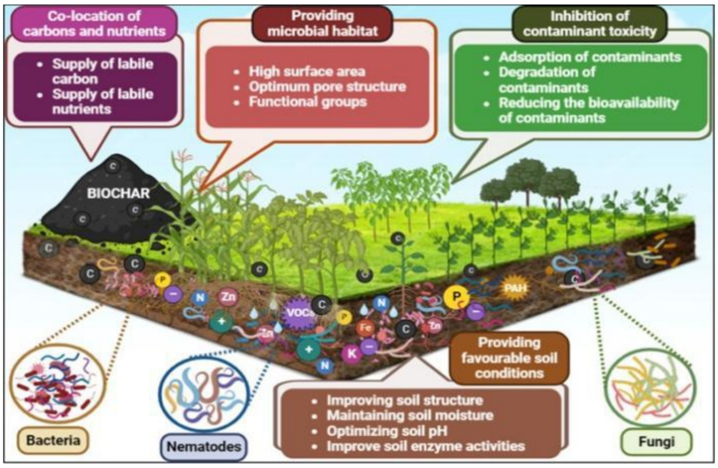


Figure 7: *C sequestration cycle of biochar in soil and crop plant system*

Because it stabilizes organic carbon in the soil for centuries to millennia, biochar is essential to the carbon sequestration cycle and lowers atmospheric CO_2 levels. Because of its refractory aromatic structure, biochar is resistant to microbial degradation when added to soil, enabling it to function as a long-term carbon sink. Additionally, it improves soil carbon dynamics by promoting root exudation and microbial activity, both of which can aid in the development of stable soil organic matter. Furthermore, soils treated with biochar frequently increase crop biomass output, which strengthens the carbon sequestration loop by increasing carbon inputs through root and shoot residues. Biochar is positioned as a crucial element in sustainable agroecosystems due to its dual function of directly stabilizing carbon and indirectly promoting plant-driven carbon inputs (32).





Conclusion

The use of biochar and conservation tillage have become popular methods for improving agricultural sustainability and repairing damaged soils. This review emphasizes how they work in concert to improve soil quality by stabilizing soil structure, promoting the growth of beneficial microbial communities, and increasing rhizospheric nutrient cycling. The establishment of soil biocrusts, which further aid in microbial variety and erosion prevention, is encouraged by conservation tillage, which also reduces soil disturbance and maintains organic matter. Biochar simultaneously increases nutrient retention, improves the physicochemical characteristics of the soil, and serves as a home for soil microbes, which increases nutrient turnover in the rhizosphere. By fostering a more robust and biologically active soil environment, the combination of these techniques increases crop productivity. However, the degree of these advantages may differ according on to crop species, environmental factors, soil type, and biochar characteristics.

To maximize their combined utilization and provide customized management plans, long-term field investigations, and region-specific research are crucial. All things considered, biochar and conservation tillage are complementing instruments in the fight for climate-resilient agriculture and sustainable land management. Reversing soil deterioration, improving food security, and advancing more general environmental objectives like carbon sequestration and biodiversity protection may all be greatly aided by their adoption.

Future Scope of the Study

To further understand the combined effects of conservation tillage and biochar under various soil and climatic circumstances, future research should concentrate on long-term, field-based studies across a variety of agro-ecological zones. Research into the molecular processes that control microbial dynamics and rhizospheric nutrient cycling, as well as the function of bio-crusts in boosting plant productivity and soil resilience, is essential. Furthermore, incorporating cutting-edge modeling techniques and monitoring technology can assist optimize these methods for wider implementation in sustainable agriculture.

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Author Contribution

VK[1] and SS: data collection, paper preparation, method-ology, and interpretation. MA and VK[2]: conceptualization, incorporation of recent research data, editing, and reviewing. AKT and LK: conceptualization, data modification, and reviewing. HT and RKN: resources, editing, reviewing, paper correction, and formatting. All authors agreed with the final draft.

Declarations

Conflict of Interest: The authors declare no competing interests.

Disclaimer: The views expressed in this work belong to the authors, and they do not necessarily reflect or represent those of their universities.

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