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REVIEW

Soil and Biochar: Attributes and Actions of Biochar for Reclamation of Soil and Mitigation of Soil Borne Plant Pathogens

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Abstract
Applying biochar appears to be the most promising emerging tool for managing plant diseases. Biochar induces plant resistance, sorbs allelopathic and fungitoxic compounds and supports an increase in beneficial microorganisms altering soil properties that improve health and nutrient availability. We got the notion that using biochar would result in spectacular outcomes. We examine studies on the use and application of biochar to help researchers and readers broaden their understanding of the potential use of biochar in treating plant diseases with improved soil physics and chemistry.

Keywords Black carbon · Biological control · Biodegradation · Bioremediation · Soil Health · Plant growth

1 Introduction

Biochar, also known as "black carbon" (Singh and Kumar 2020), is a solid byproduct of biomass pyrolysis that is created when carbon-rich materials are heated to high temperatures in an oxygen-deficient atmosphere. Numerous soil properties, including pH, microbial diversity and community structure, GHG emission, nutrient retention, and soil physical structure, may be changed when biochar is applied to the soil, according to extensive research on the subject over the past few years (Singh and Kumar 2020). Biochar can be used for a number of processes, including wastewater treatment (Shaheen et al. 2019), crop disease management (Ahmed et al. 2022), immobilization of contaminants (Shen et al. 2019), enhancement of soil fertility (Arif et al. 2020) since it does have a well-developed porous structure (Leng et al. 2021), a large number of inorganic nutrients (Dai et al. 2020), a large number of functional groups and excellent stability of carbon (Wang et al. 2020b).

Global population growth is a challenge to food supply, which is made worse by climate change, ongoing pest and disease outbreaks, and poor crop productivity due to the hurdles in identifying diseases in plants, particularly those are caused by the soil borne pathogens (Ghorbanpour et al. 2018). Some of these plant pathogens found in soil include fungi, oomycetes, bacteria, viruses, and nematodes, with fungi being the most common category to infect and harm roots (Montiel-Rozas et al. 2019). Since soil-borne diseases share some traits in common and affect both abiotic and biotic components, therefore, the management of such infections seems challenging (Liu et al. 2020).

Synthetic pesticides have become the first and foremost strategies for preventing outbreaks of pests and diseases in agriculture, but their careless use has exacerbated environmental issues and impacted the environment and at last human health negatively. Biological control has been around for a while, recorded for certain good management of soil borne diseases but could not attract as much attention as chemicals. Species of many fungi and bacteria for example *Trichoderma, Beauveria, Metarhizium, Pseudomonas, Bacillus* etc. has recently gained increase in application against soil borne diseases as they have shown antagonistic potential, making it one of the alternative methods for disease eradication (Zin and Badaluddin 2020).

In the past few years, a new low cost alternative of chemicals “Biochar” has emerged and gained a lot of attention for reclamation of soil and management of soil borne diseases (Silva et al. 2021). Lima et al. (2018) and Medeiros et al. (2020) researched using biochar and stated that biochar enhances the physical, chemical, and biological characteristics of the soil in addition to improving water and nutrient

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retention, promoting carbon sequestration, enhancing beneficial soil microbes and controlling soil-borne plant pathogens. The objective of this review is to emphasize the application of biochar in soil, particularly focusing on managing soil-borne plant pathogens. This involves biochar's primary action of enhancing soil health and its secondary action of exhibiting antimicrobial activities against plant pathogens (Lehmann and Joseph 2015; Joseph et al. 2019).

1.1 Composition and Making of Biochar

Biomass is being converted to biochar as a result of growing interest in using it for various applications. Thermochemical conversion is a typical method for making biochar. The methods of thermochemical conversion include torrefaction, gasification, hydrothermal carbonization, and pyrolysis. Biochar generates energy from crop waste, greenhouse waste, wood chips, and a variety of other wastes at temperatures ranging from 400 to 500°C in the absence of oxygen. In varying amounts; it is made up of CHO (carbon, hydrogen & oxygen), nitrogen (N), and ash (Elkhlifi et al. 2023).

Pyrolysis between 250-900°C decomposes organic molecules in an environment devoid of oxygen called ‘Thermal Decomposition’ (Zakaria et al. 2023). This method is an alternative method for turning waste biomass into products with added value like biochar, syngas, and bio-oil (Shi et al. 2022). The lignocellulosic ingredients, such as lignin, hemicellulose and cellulose, go through reaction processes 1. depolymerization, 2. fragmentation, and 3. cross-linking at a given temperature during the process, producing a variety of products in the form of solid, liquid, and gas (Pandit et al. 2023), (Fig. 1).

The methods used to characterize biochar are based on elemental analysis, surface functional groups, and structural analysis. The structural and elemental analysis of biochar facilitates predicting its environmental effects. These characteristics indicate that biochar is a top-rated absorbent that helps remove abiotic and biotic pollutants in bulk from soil (Wood et al. 2023). Understanding the impact of biochar pH on soil pH as well as other soil characteristics and processes is crucial. In the literature, biochar pH ranges from 3.1 to 12.0 (Lehmann 2007; Mukherjee et al. 2011).

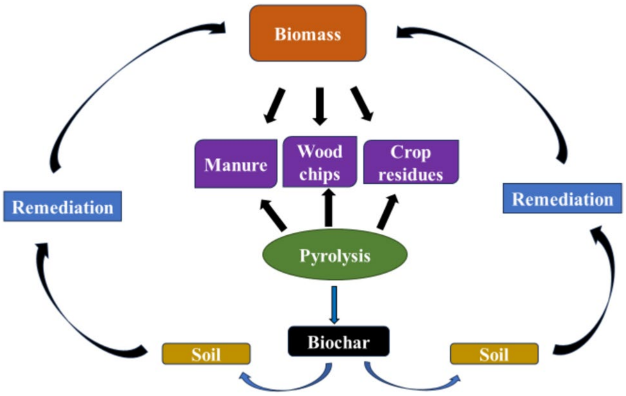

Fig. 1 Biochar of different biomass for soil remediation. Biochar from different biomasses after pyrolysis at different temperatures ranging from 400 to 700°C helps remediating soils

1.2 Biochar Impact on Soil Physical Attributes

Addition of biochar encourages changes in the physical properties of the soil. As a result of enhanced soil physical structure and consequently better growing conditions for plants, biochar helps reduce bulk density (Blanco-Canqui 2017). The use of biochar encourages soil aeration, water infiltration, and soil compaction reduction, all of which boost soil's ability to hold water (Fig. 2). The use of biochar encourages soil aeration, water infiltration, and soil compaction reduction, all of which boost soil's ability to store water. (Razzaghi et al. 2020). Decreased bulk density of soil always improves soil’s physico-chemistry; increases field capacity, soil porosity, available water content and permanent wilting point (Edeh et al. 2020). Zhang and colleagues (2017) used rice straw biochar in managing *Ralstonia solanacearum* causing bacterial wilt in tobacco under field conditions. They used 3 ton ha^{-1} biochar which resulted in a reduction of 76.64% in the disease incidence (Tables 1, 2, 3).

1.3 Biochar Impact on Soil Chemistry

Neutralizing acidity and increasing cation exchange capacity (CEC) are useful features with the purpose of improving the soil chemistry and biochar gained significant interest as an amendment to serve this purpose (Brassard et al. 2016). Oxides, hydroxides and carbonates of calcium, magnesium and Potassium from biochar contribute to high pH whereas, functional groups COOH, OH, and alcoholic OH which are abundant on the surface interact with basic soil cations to boost acidic soils to buffer pH (Han et al. 2020).

The alkalinity of the biochar depends on the temperature during pyrolysis and the ingredients of the source. The capacity of biochar to absorb the cations Ca2+ and NH4+, which are vital to plants, is directly connected to its CEC. After eight years of research on the application of biochar to soil, Luo and colleagues (2020) reported an increase in soil organic carbon and total nitrogen. Zhou and colleagues (2017) discovered that biochar accelerates the levels of sodium nitrate ($NaNO_3$), ammonium nitrate (NH_4NO_3), ammonium sulphate ($[NH_4]_2SO_4$), and ammonium tartrate ($C_4H_{12}N_2O_6$), all of which are critical for nitrogen signaling and MAPK (Mitogen-Activated Protein Kinase) pathogenicity (Table 3).

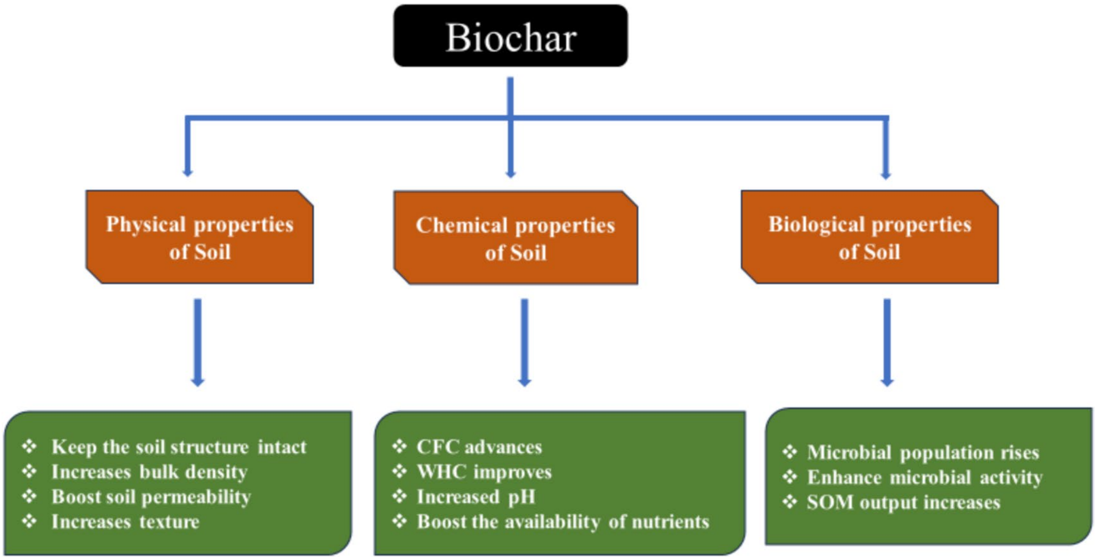

Fig. 2 Effect of biochar on the physical, chemical and biological properties of soil. Biochar enhances soil density, texture, porosity, permeability, pH, WHC & CFC values, nutrient availability and microbial population in the soil. Abbreviations used: CFC (Chlorofluorocarbon), WHC (Water Holding Capacity), pH (Potential of Hydrogen), SOM (Soil organic matter)

Table 1 Biochar application improves biological properties of soil

Sr. No	Crop	Soil type	Biochar	Root biomass	Above ground biomass	Shoot-to-root ratio	References
1	Maize (*Zea mays*)	-	*Acacia* bark	+88 to +92	+28 to +48	+23 to +49	Cong et al. 2023
2	Common bean rice (*Vigna umbellata*)	Oxisol	*Eucalyptus* bark	-9.9 to +9.3	+3.5 to +77.4	+29 to +37	Sanni et al. 2022
3	Rice (*Oryza sativa*)	Inceptisol and Oxisol	*Eucalyptus* bark	+1 to +10	+1 to +152	+2 to +200	Thavanesan and Seran 2018
4	Wheat (*Triticum*)	Sandy clay loam	*Eucalyptus* bark	-5 to +110	-25 to +13	-33 to +58	Abbas et al. 2017

Table 2 Biochar application improves physical properties of soil

Sr. no	Biochar	Soil type	EC	Bulk density (Density in mass)	Porosity	Temperature	References
1	Rice husk biochar (RHB 0.5%)	Sandy soil	0.44	1.48	44.02	-	Gamage et al. 2016
2	Rice husk Biochar (RHB 0.5%)	Loam soil	0.029	1.27	55.20	6.4	Gamage et al. 2016
3	Rice husk Biochar (RHB 1%)	Sandy soil	0.031	1.41	47.79	-	Gamage et al. 2016
4	Rice husk Biochar (RHB1%)	Loam soil	0.025	1.24	53.08	-	Gamage et al. 2016
5	Wheat Straw	Silt loam	-	1.29	23.3	8.8	Yan et al. (2019a, b)
6	Grain husk	Luvisol	0.02	-	15.5	17.3	Horák et al. (2019
7	Poultry manure	Alfisol	-	1.44	51	5	Are et al. (2017)

RHB Rice Husk Biochar, *EC* Emulsifiable Concentrate

1.4 Biochar Impact on Soil Water, pH and Nutrient Retention

One of the key areas of interest about biochar is its impact on soil water dynamics. Many researchers investigated that biochar reclaimed soil and improved water retention and availability, highlighting its ability to improve water holding capacity and reduce water loss through evaporation. Zhang et al. (2021) examined the impact of biochar on soil water retention in sandy soils and found that the addition of

Table 3 Biochar application improves chemical properties of soil

Sr No	Biochar	Soil type	pH	CFC	OM	References
1	Rice husk	Typic Hapludult	4.76	6.87	2.03	Ghorbani et al. (2019)
2	Winter grass	Entisol	7.80	18.2	1.21	Yadav et al. (2018)
3	Hardwood	Loam	4.80	-	1.25	Tarin et al. (2019)
4	Bamboo	-	4.90	21.1	1.13	Tarin et al. (2019)
5	Wheat straw	Soil	4.70	-	1	Tarin et al. (2019)

pH potential of Hydrogen, *CFC* Chlorofluorocarbons, *OM* Organic matter

biochar significantly increased the water holding capacity of the soil by enhancing its ability to retain water. Biochar pores create microhabitats, retain moisture and provide a favorable environment for root growth and water uptake by plants. Liu and teammates (2022) investigated how biochar affected soil and water availability in clay soils. Their findings indicated that biochar amendment improved soil structure and increased water infiltration rates, resulting in enhanced water availability for plant uptake. The researchers observed that biochar facilitated the formation of stable aggregates, reducing soil compaction and increasing capacity in soil to hold and release water over time. A study by Wang et al. (2020a) explored that biochar affects soil evaporation; reduces evaporation rates by enhancing soil water retention. Hydrophobic properties of biochar which act as physical barriers, reduces water loss from the soil surface (Fig. 3).

The potential of biochar as a sustainable soil management strategy for improving water and nutrient retention, which could have significant implications for enhancing agricultural productivity and mitigating environmental impacts are discussed by Li et al. (2021). They stated that biochar amendment improved the cation exchange capacity of soil, leading to increased nutrient retention and reduced nutrient leaching. Findings concluded by Guo et al. (2020) highlighted biochar, a sustainable and eco-friendly solution for water and pH regulation in agricultural and environmental systems (Fig. 4). They confirmed that biochar enhanced pH buffering capacity in acidic soils, mitigating the negative effects of soil acidification and maintaining optimal pH conditions for plant growth (Guo et al. 2020).

1.5 Biochar Impact on Greenhouse Gas Emissions and Carbon Sequestration

Being a carbon rich compound, biochar enhances carbon sequestration in soil and slows down climate change (Lehmann et al. 2006). In the biosphere, it has the ability to sequester carbon, as opposed to just storing it. Given the right economic and governmental tools, sequestration using presently accessible feedstock might occur at the gigatonnes (Gt) scale. Bioenergy co-products from pyrolysis have the potential to be more powerful than the carbon gain from burning. Therefore, using biochar seems the best possible alternative towards sustainable agriculture and environment includes direct inclusion of biomass, which causes quick and fast mineralization and CO_2 release (Nolan et al. 2021) (Fig. 5).

Soil becomes the second largest carbon reservoir on the earth with a capacity of over 2500 Gt C (Lal 2010). Because of this, even little changes in soil carbon storage have a significant effect on the amount of C in the

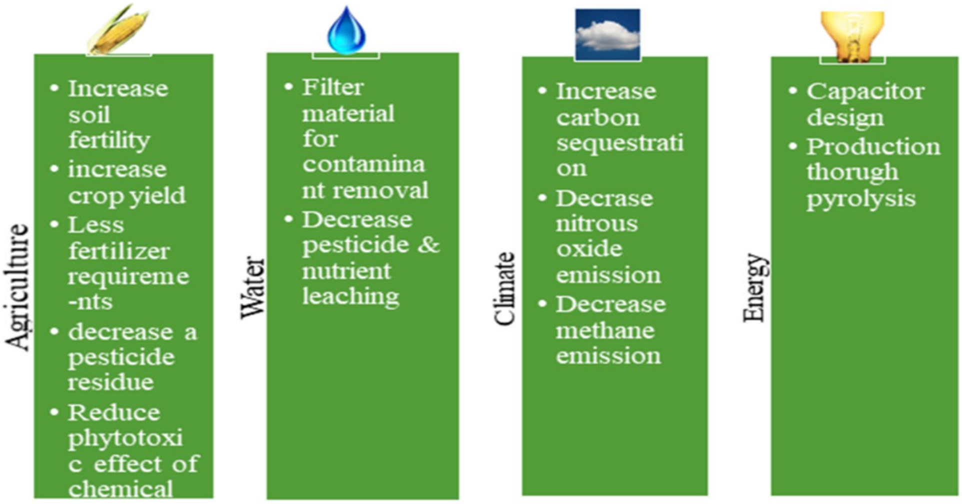

Fig. 3 General functional principles of biochar. Biochar used in different fields like Agricultures, Water, Climate & Energy for different purposes enhances soil fertility, carbon sequestration and decreases leaching of pesticides and nutrients, emission of methan and nitrous oxide

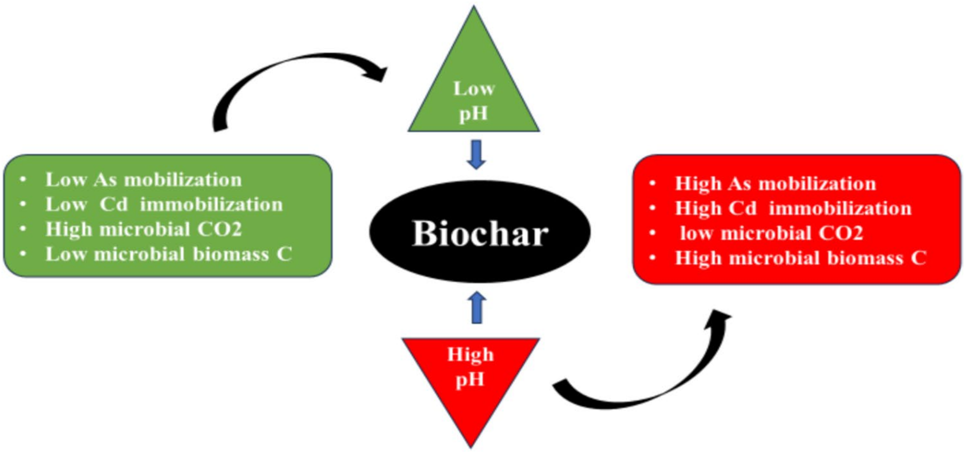

Fig. 4 Effect of biochar on soil pH. Biochar regulated pH in agricultural and environmental system. In low pH soil, biochar decreases the microbial biomass helps managing plant diseases by fungi and in high pH soil, biochar increases the microbial biomass of antagonistic microbes helps keep pathogenic microbes at their lower populations. Abbreviations used: As (Arsenic), Cd (Cadmium), CO2 (Carbon dioxide), C (Carbon), pH (Potential of Hydrogen)

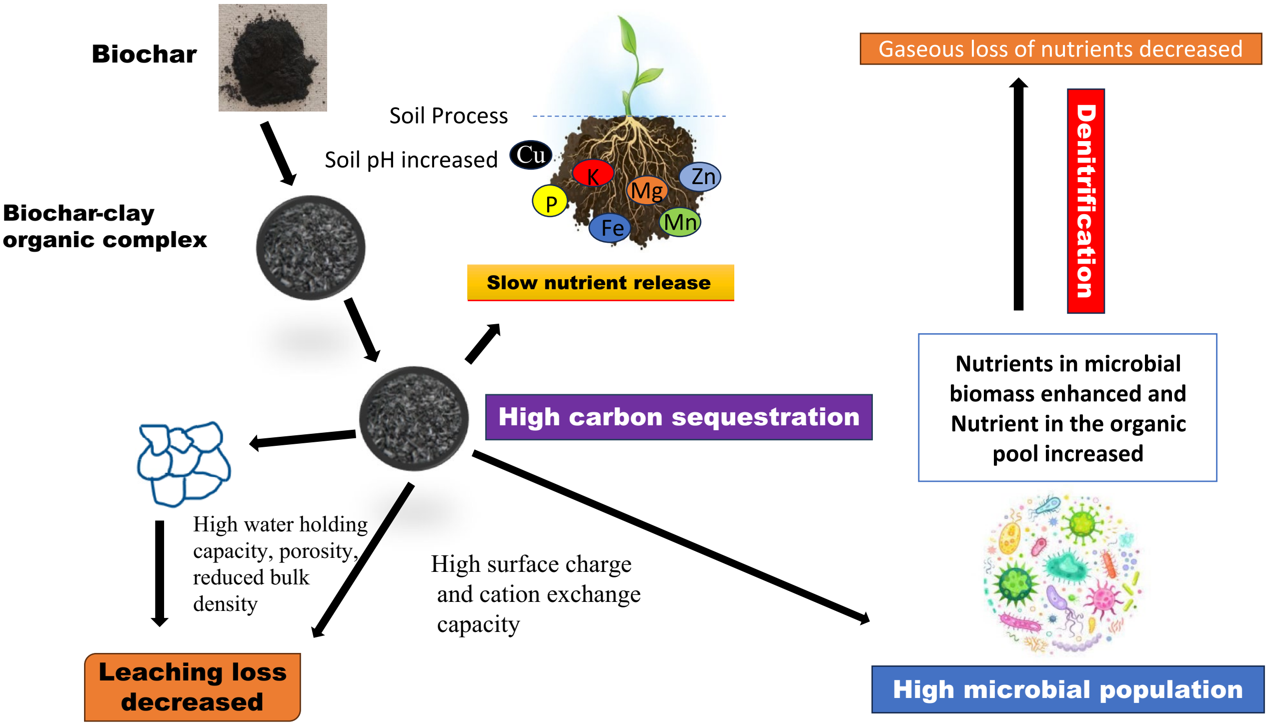

Fig. 5 Biochar effect on the carbon sequestration in soil. In plant ecosystem carbon emission caused after physiological activities of plants and microbial activities of soil microbes show negative effects on the plant shoots and roots and get released in the free environment. Biochar added in soil enhances carbon sequestration, releases different nutrients and makes available to the plants and increases soil fertility. Abbreviations used: Cu (Copper), P (Phosphorus), K (Potassium), Mg (Magnesium), Mn (Manganese), Fe (Iron), Zn (Zinc), pH (Potential of Hydrogen)

atmosphere and the rate of global warming (Smith 2012). According to UNFCCC, 2021 "4 per 1000" effort (4p1000) add an annual increase of 0.4% in soil carbon store help balancing annual rise in greenhouse gas emissions to improve environment and food security (Stockmann et al. 2013; Paustian et al. 2016, 2019; Zomer et al. 2017).

1.6 Biochar Impact on Carbon Neutrality

Biochar aids in achieving carbon neutrality due to its carbon-negative composition, CO_2 sorption, and harmful priming effects (Wang et al. 2023). According to Denevan and colleagues, since long Indians were using biological wastes to produce black amazonian soils of high fertility; the idea was to turn the biological waste into highly fertile soils. As a green immobilization agent, it also showed the capacity to immobilize organic and heavy metal pollutants (Hou et al. 2022; Wang et al. 2022; Wang et al. 2021). In addition to its conventional use as a soil supplement to increase soil fertility and immobilize pollutants, biochar has also recently been used in non-soil applications that have shown to have great promise for reducing climate change (Bartoli et al. 2020; Bolan et al. 2021).

1.7 Biochar Impact on Soil Microbial Attributes

Position, composition and population of microbes are brought by the amount of the biochar present in the soil. Porosity and high specific surface area of biochar helps produce a healthy environment for high reproduction in microbes and plant growth (Wang et al. 2016a, b). Palansooriya et al. (2019a, b) studied that micropores, mesopores and macropores of biochar particles help creating a convenient environment for the growth of bacteria, mycorrhizal fungi, ectomycorrhizal fungi and, arbuscular mycorrhizal fungi. Increased population of antagonists place a great defense against pathogens (Han et al. 2020) and many other bacteria like Proteobacteria play a key role in carbon and sulfur cycling (Zhu et al. 2019a, b) and nitrogen fixation (Semida et al. 2019).

The area near the root zone called 'rhizosphere' is the home of soil microorganisms. Since plants root exudate some compounds, become food for microorganisms henceforth, enhances microbial populations multifold than that of bulk soil (without vegetation) (Haldar and Sengupta 2016). There has been several mechanisms behind the modification of rhizospheric chemistry by plant roots include (I) absorption and secretion of organic compounds (II) gaseous exchange linked to the root and rhizosphere microbial respiration and, (III) uptake or release of water and nutrients linked to the changes to the redox potential and uptake or extrusion of protons (Dotaniya and Meena 2015). Neuman and Römheld 2012 have said, biochar does have the potential to change physical characteristics like number and size of micropores, aggregate stability, and hydrophobicity into rhizospheric soil.

Numerous studies have found that the type of soil in which biochar has been used can affect the number and

Table 4 Effect of Biochar on soil microbiota

Type of biochar/methodology	Effect on soil microbiota	Type of soil	References
Bichar made of swine manure and willow wood	Enhances microbial population	Loamy sand	Ameloot et al. (2013)
Slow pyrolysis (350–400 °C)	Dehydrogenase enzyme activity enhanced	Loamy sand	Ameloot et al. (2013)
Slow pyrolysis (350–400 °C)	Dehydrogenase enzyme activity declined	Sandy loam	Ameloot et al. 2013
Biochars: poultry litter (PL) and pine chips (P) at 400–500 °C	Increased SOM and microbial biomass, higher N mineralization in (PL)	Silt loam	Ameloot et al. 2013
Biochar composite hardwood trunk and branches	Increases soil respiration, growth rate of fungi and bacteria	Eutric cambisol (Silti-Chromic Cambisol)	Jones et al. (2012)
Biochar from fast pyrolysis wood	Increased microbial abundance	Soil mixed with sand/clay/clay clay Gram-negative bacteria-domination	Gomez et al. 2014
Wheat straw pyrolysis between 350 °C and 550 °C	increased bacterial 16S rRNA gene transcription -decreased fungal 18S rRNA gene transcription	Paddy soil	Chen et al. (2013)
Wood biochar + compost	Enhanced root invasion by arbuscular mycorrhizal fungi in the Fol + treatment compared with the Fol-	Sterilized soil-sand-clay mixture inoculated or not with *F. oxysporum* f.sp. *lycopersici* (Fol + or Fol-)	Akhter et al. 2015
Green waste biochar + compost	Reduced root invasion by arbuscular mycorrhizal fungi in the Fol + treatment compared to the Fol- treatment	Sterilized soil-sand-clay mixture inoculated or not with *F. oxysporum* f.sp. *lycopersici* (Fol + or Fol-)	Akhter et al. 2015
Empetrum nigrum L. twigs charcoal (EmpCh) forest humus charcoal (HuCh), both prepared at 450 °C for 30 min	Increased microbial biomass carbon and number of cells in both biochar treatments in comparison to control	Forest humus	Pietikäinen et al. 2000

P Pine chips, *PL* Poultry litter, *rRNA* ribosomal Ribonucleic Acid, *Fol Fusarium oxysporum* f.sp. *lycopersici*, *SOM* Soil organic matter biomass of soil microorganisms as well as the usefulness of these organisms in plant root colonization (Table 4). Li and teammates 2018 noted that charcoal increased the number of microbes in soil as determined by their respiration activity. On the other hand, Chintala et al., (2014) discovered a detrimental effect of soil added biochar on microbial activity.

1.8 Biochar Impact on Plant Growth Regulation

In 2011, Jeffery and his team conducted a thorough investigation and discovered that adding biochar to the soil has had beneficial effects; addition of biochar to soil has a considerable impact on plant development and the colonization of roots by microorganisms, such as nematodes and mycorrhizal fungi (Table 5). They observed a 10 percent increase in agricultural productivity after biochar was added. Prendergast-Miller and colleagues (2014) added biochar to soil found biomass of the roots is enhanced in maize and barley. Biochar accelerates secondary growth in plant roots and root hairs grow more in number and length to intake more nutrients and water from soil, resulting in increased growth and yield (Lehmann et al. 2011; Jeffery et al. 2017). Agegnehu and teammates in 2016 and Shen and teammates in 2018 applied biochar and found that biochar favorably affects stem and leaf growth; probably due to increased translocation of water and nutrients and photosynthesis. The higher crop production brought about by the faster growth seen in soils modified with biochar makes it a viable sustainable option for agricultural productivity (Verwaaijen et al. 2017; Glaser and Lehr 2019).

1.9 Application of Biochar in Plant Disease Management

Studies support that biochar contributes in managing diseases in plants especially which were caused by the soil borne pathogens (Medeiros et al. 2021). Biochar performs directly and or indirectly which suppress plant diseases via a number of mechanisms like (i) improving soil attributes help promote plant health by enhanced nutrient availability (ii) increase in the population of beneficial microorganisms that bring down the population of harmful microorganisms via competition, parasitism and antibiosis (iii) sorption of compounds by plants that are toxic to the plants pathogens (iv) induction of plant resistance by activating secondary metabolites after the resistance genes get activated and, (v) changes of abiotic conditions, pH, EC, CEC, temperature, moisture etc. provide different management mechanisms for disease suppression (Fig. 6).

Table 5 Effect of biochar in the rhizosphere of plants

Plant	Type of biochar	Effect on plants and soil	Reference
Malus domestica	Wood remnants	Improve microbial activity in soil, enhance the root growth	Ventura et al. (2014)
Malus domestica	Rice husk biochar (450 °C)	Increase root mass and photosynthetic parameters	Wang et al. (2016a, b)
Prunus persica	Pinewood	Higher biomass and improved phytonutrient content	Atucha and Litus (2015)
Fragaria x ananassa	Biochar made from citrus wood or greenhouse waste	Eliminate diseases caused by fungus	Meller Harel et al. (2012)
Solanum lycopersicum	WB (Wood chip biochar) mixed with compost	Wood chip biochar reduces the dry weight of roots and shoots and reduces the invasion of AMF	Akhter et al. 2015
Solanum lycopersicum	Green waste biochar (GWB)	Extend plant and reduce AMF invasion	Akhter et al. 2015
Solanum lycopersicum	Charcoal	Improve growth and yield of plant	Yilangai et al. (2014)
Solanum lycopersicum	Rice husk and shell of cotton seed at 400 °C	Improves water efficiency in reduced irrigation and yields similar to full irrigation	Akhtar et al. 2014
Daucus carota	Spelt husk biochar and wood residues biochar	The biomass of taproots and slender roots of plants treated with nematode Pratylenchus penetrans was higher than that of the control	George et al. 2016
Lactuca sativa	Sewage sludge, slow pyrolysis char gasification	Stimulating the growth of plant	Marks et al. (2014)
Lactuca sativa	Wood biochar	Strong inhibition of plant growth	Marks et al. (2014)
Lactuca sativa	Rice husk biochar	Improve final biomass, root biomass, plant height and number of leaves	Carter et al. 2013

GWB Green waste biochar, *WB* Wood chip biochar, *AMF* Arbuscular Mycorrhizal Fungi

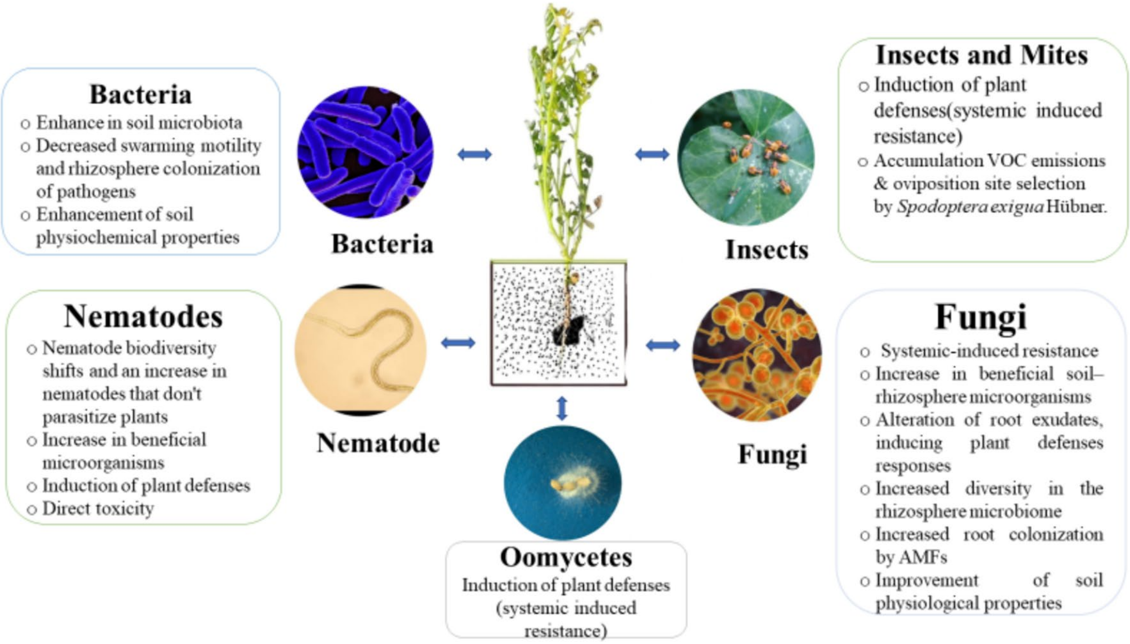

Fig. 6 Effect of Biochar on microbial population density. Biochar enhances root colonization, and accumulates VOCs affects physical, chemical and biological properties of soil and plant as well helps increase the population of beneficial microbes and decrease the population of phytopathogenic microbes. Abbreviations used: VOC (Volatile Organic Compounds), AMF (Arbuscular Mycorrhizal Fungi)

1.10 Biochar Effect on Phytopathogenic Bacteria

The use of biochar has shown promise in the management of bacterial infections in plants. Porous composition and large surface area of biochar absorbs and holds a variety of substances, including pathogens and their metabolites. Biochar naturally has antibacterial characteristics, Rodriguez-Ramos et al. (2022), proved that addition of biochar effectively reduced the population of bacteria resulting in decreased incidence of disease in tomato crops. Other way, it has also been demonstrated that the presence of biochar in the soil has a positive impact on the makeup of the microbial community, encouraging the prevalence of good microorganisms that compete with harmful bacteria. Bacterial wilt by *Ralstonia solanacearum* is a devastating disease that affects a variety of plant species, including tomato, brinjal, potato, peanut and banana which seems most significant in retarding yield to the global production of these crops (Mansfield et al. 2012). Bacterium enters the plant through the roots and colonizes the xylem, causing the plants to completely wilt and die (Genin and Denny 2012). Bacterium can spread through water, rhizospheric contact, etc. and persists in the soil for a very long time in the absence of crops that are vulnerable to it, making its control exceedingly difficult (Van Stan et al. 2020). Biochar dramatically reduced bacterial wilt through altering the microbial composition and soil's chemical characteristics (Chaudhari et al. 2021). Disease severity and incidence considerably reduced as compared to the control (Chen et al. 2011) (Tables 6 and 7).

According to Hu et al. (2023), using biochar increased the relative number of helpful bacteria, which helped to naturally decrease bacterial wilt (*Erwinia tracheiphila*) in cucumbers. *Bacillus, Telmatobacter Chlorochromatium, Chthoniobacter, Bradyrhizobium Geobacillus, Leptospirillum, Microvirga,*

Table 6 Effect of Biochar in the management of bacterial diseases

Sr. no	Source of biochar	Name of crop	Causal agents	Name of disease	Percentage of disease reduction	References
1	Biochar	Tobacco	*Ralstonia solanacearum*	Bacterial wilt	15–35%	Li et al. 2022
2	Biochar	Tomato	*Ralstonia solanacearum*	Bacterial wilt	10% to 80%	Chen et al. 2020
3	Biochar	Potato	*Ralstonia solanacearum*	Bacterial wilt	10 to 100%	Chen et al. 2020
4	Biochar	Peanut	*Ralstonia solanacearum*	Bacterial wilt	10 to 50%	Chen et al. 2020

*Aeromicrobium, Marisediminicola, Pseudoxanthomonas, Corynebacterium,*and *Burkholderia,*were among the beneficial bacteria that the biochar treatments greatly enhanced in soil (Chen et al. 2020). Rice hull biochar proved useful in preventing the bacterial wilt disease. Through altering soil chemical characteristics and microbial abundances, biochar additions dramatically reduced tobacco bacterial wilt in the field trial (Chen et al. 2020).

Biochar applied at a rate of 2 to 3% (wt/wt), demonstrated their efficacy in decreasing bacterial wilt in tobacco and tomato plants. Improved soil physicochemical characteristics and an increase in bacteria and actinomycetes in the rhizosphere after biochar application lowers *R. solanacearum* swarming motility and root colonization capability (Poveda et al. 2021; Samal et al. 2024). Amendment of biochar decreased incidence of disease incidence up to 78%, and this positive effect of biochar could be associated with enhanced activity of soil antagonists and altered composition of amino acids as well as rhizosphere organic acids. Amendment of biochar increased citric acid and lysine and reduced salicylic acid help improve microbial activity that rendered rhizospheric conditions unsuitable for the development of *R. solanacearum* (Tian et al. 2021).

1.11 Biochar Effect on Phytopathogenic Fungi

By incorporating biochar into the soil, plant diseases by fungi may become less severe due to its managerial effects on the soil-plant-rhizosphere-pathogen system; both plant growth and disease progression may be impacted by the direct and indirect effects of biochar on the soil environment, host plant, pathogen, and rhizosphere microbiome. Numerous responses of biochar, including water adsorption capacity & holding capacity, redox activity, pH neutralization, and induced systemic plant resistance to fungal infections in some circumstances help managing with soil borne infections by pathogenic fungi (Graber et al. 2014). Soil enriched with biochar greatly reduced Fusarium wilt and chlamydospore production (Akhter et al. 2015). In tomato and pepper, biochar from citrus wood$^{1\text{-}5\%}$ controlled *B. cinerea* and *Leveillula taurica* respectively. The utilization of biochar-treated pots resulted in a remarkable improvement in the growth of pepper plants compared to the unamended controls. This enhancement was evident in various plant parameters, including increased leaf area, canopy dry weight, number of nodes, as well as improved yields of buds, flowers, and fruits (Graber et al. 2010). "Numerous organic compounds from various chemical classes, such as n-alkanoic acids, hydroxy and acetoxy acids, benzoic acids, diols, triols, and phenols, have been detected in organic solvent extracts of the biochar. This has shown potential for enhancing plant performance through two distinct mechanisms. Firstly, the biochar appears to promote shifts in microbial populations towards beneficial plant growth-promoting rhizobacteria or fungi, possibly due to its chemical or physical properties. Secondly, when used in low concentrations, the biochar chemicals, many of which can be phytotoxic or biocidal at higher concentrations, exhibit stimulatory effects on plant growth, a phenomenon known as hormesis". According to Meller Harel et al. 2012 pepper biochar controlled effectively *Colletotrichum acutatum* and *Podosphaera aphanis.* Necrotrophic fungus *Rhizoctonia solani* was also controlled by application of biochar (Verwaaijen et al. 2017). A reduced infection in a plant most

Table 7 Effect of Biochar in the management of fungal diseases

Sr. no	Source of biochar	Name of crop	Causal agents	Name of disease	Percentage of disease reduction	References
1	Greenhouse waste (GWH) biochar	Cucumber	*Rhizoctonia solani*	Damping off	37%	Jaiswal et al. 2019
2	Sewage biochar	Pea	*Sclerotinia sclerotium*	White mold	25%	de Araujo et al. 2021
3	Biochar	Tomato	*Fusarium oxysporum* f. sp. *lycopersici*	Wilt	28.24%	Jin et al. 2022
4	Sewage Sludge Biochar	Soybean	*Macrophomina phaseolina*	Charcoal rot on soybean	40%	de Araujo et al. 2021
5	Sewage Sludge Biochar	Soybean	*Sclerotium rolfsii*	Southern blight of soybean	26%	de Araujo et al. 2021
6	Biochar green waste	Chickpea	*Fusarium oxysporum*	Wlit	15%	Jahan et al. 2020
7	Biochar	Cucumber	*Pythium aphanidermatum*	Damping off	76%	Jaiswal et al. 2019
8	Biochar	Common bean	*Pythium*	Root rot	18.50%	Were et al. 2021
9	Biochar green waste	Chickpea	*Phytophthora medicaginis*	Root rot	5%	Jahan et al. 2020
10	Biochar	Tobacco	*Phytophthora nicotianae*	Black shank disease	50–60%	Li et al. 2022

likely is due to the development of systemic inducers of resistance (Elad et al. 2010) that work as a signaling cascade.

Fusarium oxysporum f. sp. *asparagi* and *F. proliferatum* are the causes of crown and root rot diseases that affect *asparagus*; allelopathic poisons released into the soil aggravate the disease. Application of hardwood biochar increases antagonists' population helps promote systemic resistance against above mentioned *Fusarium* spp. (Elmer 2016). Biochar exerts beneficial effects of soil through altering soil properties, nutrients availability, as well as stimulating populations of antagonistic bacteria such as *Pseudomonas* and Arbuscular mycorrhizal fungi (AMFs) (Poveda et al. 2021).

Oomycetes fungi are the pathogens of numerous plant species including many food and cash crops (Hargreaves and van West 2019). Tree infecting species of oomycetes fungi i.e., *Phytophthora* spp., *Pythium* spp. have been treated with biochar. Zwart and Kim in 2012 experimented using 5% biochar W/V used against *P. cinnamomi* and *P. cactorum* and proved that biochar slows down disease and physiological pressure. Nevertheless, several studies have reported that the application of biochar increased the colonization of oomycetes group fungi *P. ultimum* in lettuce, sweet pepper, and basil, without any observable adverse impacts on the root system or plant growth (Gravel et al. 2013).

1.12 Biochar Effect on Phytopathogenic Nematodes

Plant-parasitic nematodes (PPN) are among the major obstacle responsible for biotic stress in plants as they are capable altering physiology and histology affect metabolic activities in vegetative as well as reproductive parts of plant resulting in considerable yield losses (Khan et al. 2022). Biochar application has shown to suppress population of plant pathogenic nematodes, hence been promoted as an eco-friendly management approach and an alternative to synthetic pesticides (Eche and Okafor 2020). In a greenhouse trial by Rahayu and Sari (2017) application of biochar resulted in increase of growth and biomass of coffee seedlings and suppressing the population of parasitic nematode in coffee seedlings. Using 0-4% concentration of biochar caused mortality of 37.5% (0.5%)-74.5% (4.0%) in coffee nematode, *Pratylenchus coffeae*.

Biochar derived from hard wood proved successful in lowering the population of *P. coffeae*, a migratory endoparasitic and significant damaging root lesion nematode of banana. Adding of biochar generated out of poultry litter dramatically decreased population of *Meloidogyne javanica*, *Pratylenchus* spp., *Tylenchulus semipenetrans*, *Criconemoid* spp. and *Helicotylenchus* spp. in grapevine (Rahman et al. 2014). Biochar incorporation reduced the abundance of the stubby-root nematode *Trichodorus* sp. in maize crops and the migratory endoparasites nematode *P. penetrans* in carrot crops. Five-year monitoring of the impact of biochar and manure added to low fertile yellow cinnamon soil showed significant decreasing of PPNs levels. The addition of biochar to rice potting soils reduced the crop's susceptibility to the root-knot nematode *M. graminicola* (Stefanovska et al. 2022). Ikram and colleagues (2024) investigated effect of biochar alone and in combination with oil cakes of mustard, castor, linseed, coconut, and sesame against *M. incognita*. They reported increase in plant growth, fresh weight, total chlorophyll, dry weight, nitrate reductase activity, carotenoid levels, and decrease in nematode population, egg masses per root, and number of galls per root.

Biochar effects contribute to the prevention of root or foliar plant pathogens by modifying root exudates, soil characteristics, and nutrient availability, thereby impacting the growth of antagonistic microorganisms (Medeiros et al. 2021). The introduction of biochar in the roots trigger systemic plant defenses, leading to activated stress-hormone responses, changes in active oxygen species, and other internal plant alterations, which ultimately reduce foliar pathogenic fungus too (Poveda et al. 2021).

1.13 Comparison of Biochar with Chemicals Over Long Term Effects on Plants and Surrounding Ecosystems

Biochar and pesticides are two agricultural practices that have been extensively studied for their impact on plant growth, soil health, and overall ecosystem dynamics. Both methods aim to improve crop productivity and protect plants from pests and diseases, but they differ significantly in their mechanisms and long-term effects. This discussion explores the effects of biochar and pesticides on plants, soil, and ecosystems, with a focus on their long-term implications. Biochar has gained attention due to its potential benefits for plant productivity and soil health. When applied to soils, biochar improves soil fertility, water retention, and nutrient availability over the long term (Lehmann and Joseph 2015). The high surface area and porous structure of biochar enhance microbial activity and nutrient cycling, leading to increased plant growth and yield (Jeffery et al. 2011). Biochar does influence beneficial soil microbial communities that suppress plant pathogens in the rhizosphere (Inyang et al. 2016). As a result, biochar applications have shown a reduction in disease incidence and severity in various plant species (Azeem et al. 2023). Furthermore, the slow decomposition rate of biochar helps to sequester carbon in the soil for extended periods, contributing to climate change mitigation (Smith et al. 2008). In contrast, pesticides are chemical substances specifically designed to control pests and diseases in agricultural systems. Although pesticides can effectively suppress pests and protect crops, their usage

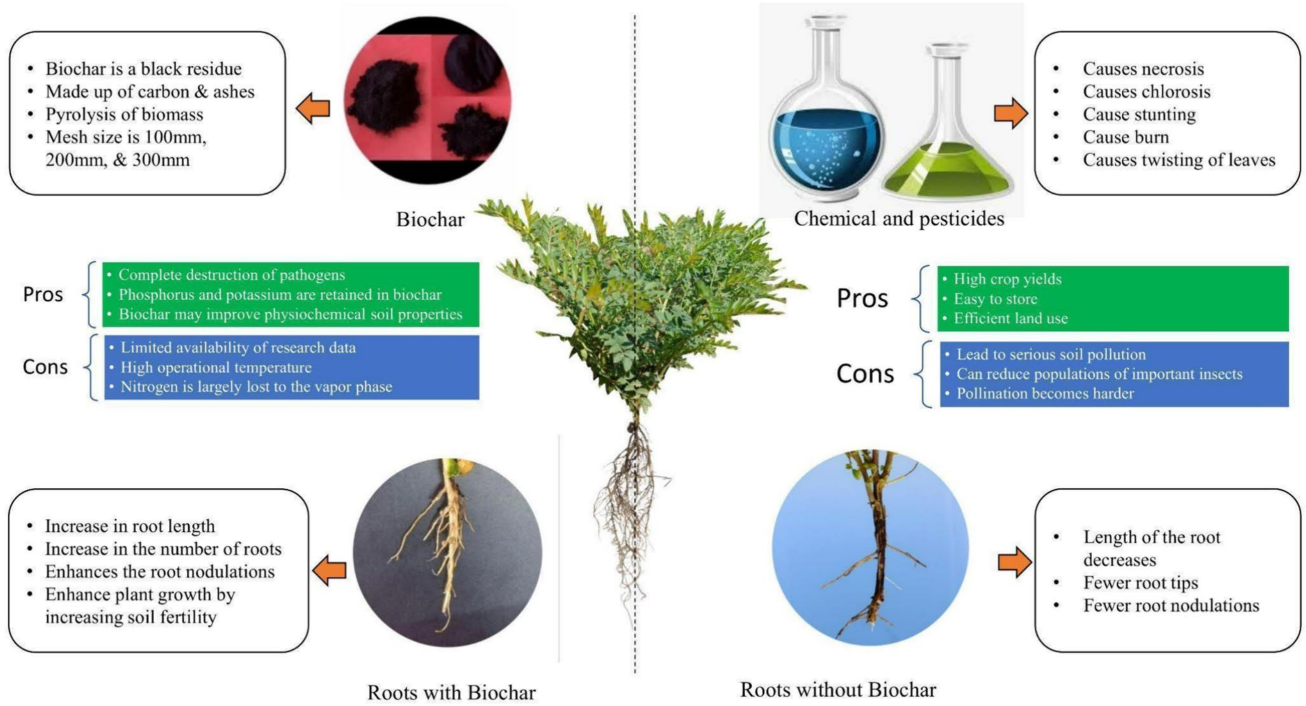

Fig. 7 Long-term effects of biochar in comparison with chemicals. Biochar addition in the soil helps decrease in the leaching of pesticides and reduce residual load on plant system, contamination of soil & ground water and killing of beneficial micro-flora

raises concerns about environmental contamination, potential harm to non-target organisms, and the development of pesticide resistance (Bass and Basu 2011; Grube et al. 2011) (Fig. 7). The accumulation of pesticide residues in the soil can persist for years and may have detrimental effects on soil health and biodiversity (Kohler and Triebskorn 2013).

2 Conclusion

After amendment of biochar in the soil, physico-chemistry of the soil is improved to support plant's growth, sustainable production and food security. Various mechanisms of biochar make it an effective alternative tool for soil reclamation and rejuvenation. Use of biochar from different alternative organic sources have been proved as an alternative to improve soil fertility, nutrient absorption, water retention, microbial activity restores degraded land. Biochar acts as a carbon sink and contributes to long-term carbon sequestration to mitigate climate change impacts and emissions of greenhouse gases.

As a part of plant disease and pest management, biochar-based amendment is a promising method that is compatible with a circular economy focused on zero waste. Biochar manages plant diseases caused by soil-borne and other pathogens through a variety of deteriorating mechanisms such as antibacterial, fungitoxic, and nematotoxic effects, as well as the sorption of phytotoxic and allelopathic compounds that disease plants. Through various supporting mechanisms, such as inducing plant resistance, increasing the activities and abundance of beneficial microorganisms, and altering soil biotic and abiotic conditions biochar helps plant to grow and produce well.

As a result, introducing biochar into agricultural systems might provide a more ecologically sound and environmentally responsible means of enhancing crop productivity and long-term plant protection. Future studies should concentrate on investigating extremely productive strains, perfecting conditions, and evaluating a wide range of waste sources for biochar formation as well as their effectiveness in field tests.

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Declarations

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References

Abbas T, Rizwan M, Ali S, Zia-ur-Rehman M, Qayyum MF, Abbas F, Hannan F, Rinklebe J, Ok YS (2017) Effect of biochar on cadmium bioavailability and uptake in wheat (*Triticum aestivum* L.) grown in a soil with aged contamination. Ecotoxicol 140:37–47. https://doi.org/10.1016/j.ecoenv.2017.02.028

Agegnehu G, Bass AM, Nelson PN, Bird MI (2016) Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Sci Total Env 543:295–306. https://doi.org/10.1016/j.scitotenv.2015.11.054

Ahmed S, Sharma S, Kumar A, Sharma A, Rana T (2022) The perspectives of induced resistance in Brinjal against *Phomopsis vexans* causing phomopsis blight: a review. Biopestic Int 18:9–21. https://connectjournals.com/02196.2022.18.9

Akhtar SS, Li G, Andersen MN, Liu F (2014) Biochar enhances yield and quality of tomato under reduced irrigation. Agric Water Manag 138:37–44. https://doi.org/10.1016/j.agwat.2014.02.016

Akhter A, Hage-Ahmed K, Soja G, Steinkellner S (2015) Compost and biochar alter mycorrhization, tomato root exudation, and development of *Fusarium oxysporum* f.sp. *lycopersici*. Front Plant Sci 138:37–44. https://doi.org/10.3389/fpls.2015.00529

Ameloot N, Graber ER, Verheijen FG, De Neve S (2013) Interactions between biochar stability and soil organisms: review and research needs. Eur J Soil Sci 64(4):379–390. https://doi.org/10.1111/ejss.12064

Araujo AS, Blum LE, Andrade DV, Silva Júnior PB, Figueiredo CC (2021) Sewage sludge biochar effects on phytopathogenic fungi and beneficial microorganisms. Braz Arch Biol Technol 64:1–15. https://doi.org/10.1590/1678-4324-2021210266

Are KS, Adelana AO, Fademi IO, Aina OA (2017) Improving physical properties of degraded soil: potential of poultry manure and biochar. Agri Nat Res 51:454–462. https://doi.org/10.1016/j.anres.2018.03.009

Arif M, Jan T, Riaz M, Fahad S, Adnan M, Ali K, Mian IA, Khan B, Rasul F (2020) Biochar; a remedy for climate change. In: Environment, climate, plant and vegetation growth, Springer Cham, pp 151–171. https://doi.org/10.1007/978-3-030-49732-3_8

Atucha A, Litus G (2015) Effect of biochar amendments on peach replant disease. Hortscience 50:863–868. https://doi.org/10.21273/HORTSCI.50.6.863

Azeem M, Sun TR, Jeyasundar PG, Han RX, Li H, Abdelrahman H, Shaheen SM, Zhu YG, Li G (2023) Biochar-derived dissolved organic matter (BDOM) and its influence on soil microbial community composition, function, and activity: a review. Crit Rev Environ Sci Technol 53:1–23. https://doi.org/10.1080/10643389.2023.2190333

Bai W, Kong F, Lin Y, Zhang C (2016) Extract of *Syringa oblata*: a new biocontrol agent against tobacco bacterial wilt caused by *Ralstonia solanacearum*. Pestic Biochem Physiol 134:79–83. https://doi.org/10.1016/j.pestbp.2016.04.002

Bartoli M, Giorcelli M, Jagdale P, Rovere M, Tagliaferro A (2020) A review of non-soil biochar applications. Materials 13:261. https://doi.org/10.3390/ma13020261

Bass C, Basu P (2011) Gene amplification and insecticide resistance. Pest Manag Sci 67:886–890. https://doi.org/10.1002/ps.2189

Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am J 81:687–711. https://doi.org/10.2136/sssaj2017.01.0017

Bolan N, Hoang SA, Beiyuan J, Gupta S, Hou D, Karakoti A, Joseph S, Jung S, Kim KH, Kirkham MB, Kua HW (2021) Multifunctional applications of biochar beyond carbon storage. Int Mater 67:1–51. https://doi.org/10.1080/09506608.2021.1922047

Brassard P, Godbout S, Raghavan V (2016) Soil biochar amendment as a climate change mitigation tool: key parameters and mechanisms involved. J Environ Manage 181:484–497. https://doi.org/10.1016/j.jenvman.2016.06.063

Carter S, Shackley S, Sohi S, Suy TB, Haefele S (2013) The impact of biochar application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*). Agronomy 3:404–418. https://doi.org/10.3390/agronomy3020404

Casey FX, Hakk H, DeSutter TM (2020) Free and conjugated estrogens detections in drainage tiles and wells beneath fields receiving swine manure slurry. Environ Pollu 256:113384. https://doi.org/10.1016/j.envpol.2019.113384

Chaudhari S, Upadhyay A, Kulshreshtha S (2021) Influence of organic amendments on soil properties, microflora and plant growth. In: Sustainable agriculture reviews, vol 52. Springer, Cham, pp 147–191. https://doi.org/10.1007/978-3-030-73245-5_5

Chen Y, Huang B, Huang M, Cai B (2011) On the preparation and characterization of activated carbon from mangosteen shell. J Taiwan Ins Chem Eng 42:837–842. https://doi.org/10.1016/j.jtice.2011.01.007

Chen J, Liu X, Zheng J, Zhang B, Lu H, Chi Z, Pan G, Li L, Zheng J, Zhang X, Wang J (2013) Biochar soil amendment increased bacterial but decreased fungal gene abundance with shifts in community structure in a slightly acid rice paddy from Southwest China. Appl Soil Ecol 71:33–44. https://doi.org/10.1016/j.apsoil.2013.05.003

Chen S, Qi G, Ma G, Zhao X (2020) Biochar amendment controlled bacterial wilt through changing soil chemical properties and microbial community. Microbiol Res 231:126373. https://doi.org/10.1016/j.micres.2019.126373

Chintala R, Mollinedo J, Schumacher TE, Malo DD, Julson JL (2014) Effect of biochar on chemical properties of acidic soil. Arch Agron Soil Sci 60:393–404. https://doi.org/10.1080/03650340.2013.789870

Choudhary B, Paul D (2018) Isotherms, kinetics and thermodynamics of hexavalent chromium removal using biochar. J Environ Chem Eng 6:2335–2343. https://doi.org/10.1016/j.jece.2018.03.028

Cong M, Hu Y, Sun X, Yan H, Yu G, Tang G, Chen S, Xu W, Jia H (2023) Long-term effects of biochar application on the growth and physiological characteristics of maize. Front Plant Sci 14:1172425. https://doi.org/10.3389/fpls.2023.1172425

Dai L, Li L, Zhu W, Ma H, Huang H, Lu Q, Yang M, Ran Y (2020) Post-engineering of biochar via thermal air treatment for highly efficient promotion of uranium (VI) adsorption. Bioresour Technol 298:122576. https://doi.org/10.1016/j.biortech.2019.122576

de Medeiros EV, da Silva LF, da Silva JS, da Costa DP, de Souza CA, Berger LR, de Souza Lima JR, Hammecker C (2021) Biochar and Trichoderma spp. in management of plant diseases caused by soilborne fungal pathogens: a review and perspective. Res Soc Dev 10:e296101522465. https://doi.org/10.33448/rsd-v10i15.22465

de Sousa Lima JR, de Moraes SW, de Medeiros EV, Duda GP, Corrêa MM, Martins Filho AP, Clermont-Dauphin C, Antonino AC, Hammecker C (2018) Effect of biochar on physicochemical properties of a sandy soil and maize growth in a greenhouse experiment. Geoderma 319:14–23. https://doi.org/10.1016/j.geoderma.2017.12.033

del Mar Montel-Rosas, Hurtado-Navarro M, Díez-Rojo MÁ, Pascual JA, Ros M (2019) Sustainable alternatives to 1, 3-dichloropropene for controlling root-knot nematodes and fungal pathogens in melon crops in Mediterranean soils: efficacy and effects on soil quality. Environ Pollut 247:1046–1054. https://doi.org/10.1016/j.envpol.2019.01.042

Dotaniya ML, Meena VD (2015) Rhizosphere effect on nutrient availability in soil and its uptake by plants: a Review. Proc Natl Acad Sci India B - Biol Sci 85:1–12. https://doi.org/10.1007/s40011-013-0297-0

Eche CO, Okafor OE (2020) Control potential of some indigenous biochars against *Meloidogyne incognita* [(Kofoid and White) Chitwood] in tomato (*Solanum lycopersicum* L.). J Entomol 12:32–38. https://doi.org/10.5897/JEN2020.0251

Edeh IG, Mašek O, Buss W (2020) A meta-analysis on biochar's effects on soil water properties–New insights and future research challenges. Sci Total Env 714:136857. https://doi.org/10.1016/j.scitotenv.2020.136857

Elad Y, David DR, Harel YM, Borenshtein M, Kalifa HB, Silber A, Graber ER (2010) Induction of systemic resistance in plants by biochar, a soil-applied carbon sequestering agent. Phytopathol 100:913–921. https://doi.org/10.1094/PHYTO-100-9-0913

Elkhlifi Z, Iftikhar J, Sarraf M, Ali B, Saleem MH, Ibranshahib I, Bispo MD, Meili L, Ercisli S, Torun Kayabasi E, Alemzadeh Ansari N (2023) Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: a review. Sustainability 15:2527. https://doi.org/10.3390/su15032527

Elmer WH (2016) Effect of leaf mold mulch, biochar, and earthworms on mycorrhizal colonization and yield of asparagus affected by Fusarium crown and root rot. Plant Dis 100(12):2507–2512. https://doi.org/10.1094/PDIS-10-15-1196-RE

Gamage DV, Mapa RB, Dharmakeerthi RS, Biswas A (2016) Effect of rice-husk biochar on selected soil properties in tropical Alfisols. Soil Res 54:302–310. https://doi.org/10.1071/SR15102

Genin S, Denny TP (2012) Pathogenomics of the *Ralstonia solanacearum* species complex. Annu Rev Phytopathol 50:67–89. https://doi.org/10.1146/annurev-phyto-081211-173000

George C, Kohler J, Rillig MC (2016) Biochars reduce infection rates of the root-lesion nematode *Pratylenchus penetrans* and associated biomass loss in carrot. Soil Biol Biochem 95:11–18. https://doi.org/10.1016/j.soilbio.2015.12.003

Ghorbani M, Asadi H, Abrishamkesh S (2019) Effects of rice husk biochar on selected soil properties and nitrate leaching in loamy sand and clay soil. Int Soil Water Conserv Res 7:258–265. https://doi.org/10.1016/j.iswcr.2019.05.005

Ghorbanpour M, Omidvari M, Abbaszadeh-Dahaji P, Omidvar R, Kariman K (2018) Mechanisms underlying the protective effects of beneficial fungi against plant diseases. Biol Control 117:147–157. https://doi.org/10.1016/j.biocontrol.2017.11.006

Glaser B, Lehr VI (2019) Biochar effects on phosphorus availability in agricultural soils: a meta-analysis. Sci Rep 9:9338. https://doi.org/10.1038/s41598-019-45693-z

Gomez JD, Denef K, Stewart CE, Zheng J, Cotrufo MF (2014) Biochar addition rate influences soil microbial abundance and activity in temperate soils. Eur J Soil Sci 65:28–39. https://doi.org/10.1111/ejss.12097

Goulson D (2013) An overview of the environmental risks posed by neonicotinoid insecticides. J Appl Ecol 50:977–987. https://doi.org/10.1111/1365-2664.12111

Graber ER, Meller Harel Y, Kolton M, Cytryn E, Silber A, Rav David D, Tsechansky L, Borenshtein M, Elad Y (2010) Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. Plant Soil 337:481–496. https://doi.org/10.1007/s11104-010-0544-6

Graber ER, Frenkel O, Jaiswal AK, Elad Y (2014) How may biochar influence severity of diseases caused by soilborne pathogens? Carbon Manag 5:169–183. https://doi.org/10.1080/17583004.2014.913360

Gravel V, Dorais M, Ménard C (2013) Organic potted plants amended with biochar: its effect on growth and *Pythium* colonization. Can J Plant Sci 93:1217–1227. https://doi.org/10.4141/cjps2013-315

Grube A, Donaldson D, Kiely T, Wu L, Pesticide R (2011) Exposure and toxicity—the impacts of pesticide use on people's health. Environ Health Perspect 120:576–582

Guo M, Song W, Tian J (2020) Biochar-facilitated soil remediation: mechanisms and efficacy variations. Front Environ Sci 8:512512. https://doi.org/10.3389/fenvs.2020.521512

Haldar S, Sengupta S (2016) Microbial ecology at rhizosphere: bioengineering and future prospective. In: Choudhary D, Varma A, Tuteja N (eds) Plant-microbe interaction: an approach to sustainable agriculture. Springer, Singapore pp63–69. https://doi.org/10.1007/978-981-10-2854-0_4

Han LF, Sun K, Yang Y, Xia XX, Li FB, Yang ZF, Xing BS (2020) Biochar's stability and effect on the content, composition and turnover of soil organic carbon. Geoderma 364:114184. https://doi.org/10.1016/j.geoderma.2020.114184

Hargreaves J, van West P (2019) Oomycete-root interactions. Methods Rhizosphere Biol Res 83–103. https://doi.org/10.1007/978-981-13-5767-1_6

Horák J, Šimanský V, Igaz D (2019) Biochar and biochar with N fertilizer impact on soil physical properties in a silty loam Haplic Luvisol. J Ecol Eng 20:31–38. https://doi.org/10.12911/22998993/109857

Hou R, Wang L, O'Connor D, Rinklebe J, Hou D (2022) Natural field freeze-thaw process leads to different performances of soil amendments towards Cd immobilization and enrichment. Sci Total Environ 831:154880. https://doi.org/10.1016/j.scitotenv.2022.154880

Hu J, Shen Y, Zhu N (2023) Optimizing adsorption performance of sludge-derived biochar via inherent moisture-regulated physicochemical properties. Waste Manag 169:70–81. https://doi.org/10.1016/j.wasman.2023.06.033

Ikram M, Singh S, Bano N, Alahmadi TA, Shariq M, Siddiqui MA, Islam J (2024) Biochar and oil cakes act as antagonists towards *Meloidogyne incognita* in tomato: a sustainable approach. Plant Stress 11:100320. https://doi.org/10.1016/j.stress.2023.100320

Inyang MI, Gao B, Yao Y, Xue Y, Zimmerman A, Mosa A, Pullammanappallil P, Ok YS, Cao X (2016) A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. Crit Rev Environ Sci Technol 46:406–433. https://doi.org/10.1080/10643389.2015.1096880

Jahan M, Shazad U, Naqvi S, Tahir I, Abbas T, Iqbal M (2020) Effects of Mesorhizobium ciceri and biochar on the growth, nodulation and antifungal activity against root pathogenic fungi in chickpea (*Cicer arietinum* L.). J Plant Pathol Microbiol 11:1–7. https://doi.org/10.35248/2157-7471.20.00.520

Jaiswal AK, Graber ER, Elad Y, Frenkel O (2019) Biochar as a management tool for soilborne diseases affecting early-stage nursery seedling production. Crop Prot 120:34–42. https://doi.org/10.1016/j.cropro.2019.02.014

Jeffery S, Verheijen FG, van der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ 144:175–187. https://doi.org/10.1016/j.agee.2011.08.015

Jeffery S, Abalos D, Prodana M, Bastos AC, Van Groenigen JW, Hungate BA, Verheijen F (2017) Biochar boosts tropical but not temperate crop yields. Environ Res Lett 12:053001. https://doi.org/10.1088/1748-9326/aa67bd

Jin X, Bai Y, Khashi u Rahman M, Kang X, Pan K, Wu F, Pommier T, Zhou X, Wei Z (2022) Biochar stimulates tomato roots to recruit a bacterial assemblage contributing to disease resistance against Fusarium wilt. iMeta 1:e37. https://doi.org/10.1002/imt2.37

Jones DL, Rousk J, Edwards-Jones G, DeLuca TH, Murphy DV (2012) Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biol Biochem 45:113–124. https://doi.org/10.1016/j.soilbio.2011.10.012

Joseph S, Camps-Arbestain M, Lin Y, Munroe P, Chia C, Hook J, Van Zwieten L, Kimber S, Cowie A, Singh BP, Lehmann J (2019) An investigation into the reactions of biochar in soil. In: Lehmann J, Joseph S (eds) Biochar for Environmental Management: Science. Routledge, Technology and Implementation, pp 271–309

Khan F, Shariq M, Asif M, Ansari T, Fatima S, Khan A, Siddiqui MA (2022) Organic nematicides: a green technique and its overview for nematode pest management. In: Sustainable management of nematodes in agriculture, vol. 1: organic management (pp 39–66). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-09943-4_2

Köhler HR, Triebskorn R (2013) Wildlife ecotoxicology of pesticides: can we track effects to the population level and beyond. Science 341:759–765. https://doi.org/10.1126/science.1237591

Lal R (2010) Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Biosci 60:708–721. https://doi.org/10.1525/bio.2010.60.9.8

Lehmann J (2007) Bio-energy in the black. Front Ecol Environ 5:381–387. https://doi.org/10.1890/1540-9295(2007)5[381:BITB]2.0.CO;2

Lehmann J, Joseph S (2015) Biochar for environmental management: an introduction. In: Biochar for environmental management. Routledge, London, pp 1–13. https://doi.org/10.4324/9780203762264

Lehmann J, Gaunt J, Rondon M (2006) Biochar sequestration in terrestrial ecosystems–a review. Mitig Adapt Strateg Glob Chang 11:403–427. https://doi.org/10.1007/s11027-005-9006-5

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota–a review. Soil Biol Biochem 43:1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Leng L, Xiong Q, Yang L, Li H, Zhou Y, Zhang W, Jiang S, Li H, Huang H (2021) An overview on engineering the surface area and porosity of biochar. Sci Total Environ 763:144204. https://doi.org/10.1016/j.scitotenv.2020.144204

Li Y, Li Y, Chang SX, Yang Y, Fu S, Jiang P, Zhou J (2018) Biochar reduces soil heterotrophic respiration in a subtropical plantation through increasing soil organic carbon recalcitrancy and decreasing carbon-degrading microbial activity. Soil Biol Biochem 122:173–185. https://doi.org/10.1016/j.soilbio.2018.04.019

Li X, Zhu J, Tan X, Zhao Q, Wu J, Xu X (2021) Biochar amendment increases soil nutrient retention and reduces nutrient leaching in a subtropical region of China. Environ Sci Pollut Res 28:5621–5631. https://doi.org/10.1016/j.scitotenv.2021.146441

Li C, Ahmed W, Li D, Yu L, Xu L, Xu T, Zhao Z (2022) Biochar suppresses bacterial wilt disease of flue-cured tobacco by improving soil health and functional diversity of rhizosphere microorganisms. Appl Soil Ecol 171:104314. https://doi.org/10.1016/j.apsoil.2021.104314

Liu J, Ding Y, Ji Y, Gao G, Wang Y (2020) Effect of maize straw biochar on bacterial communities in agricultural soil. Bull Environ Contam Toxicol 104:333–338. https://doi.org/10.1007/s00128-020-02793-1

Liu Y, Wu J, Zhang H, Yan C, Wang G (2022) Effects of biochar amendment on soil water availability and water retention in clayey soil. J Soils Sediments 22:325–335. https://doi.org/10.1016/j.scitotenv.2021.151791

Luo C, Yang J, Chen W, Han F (2020) Effect of biochar on soil properties on the Loess Plateau: results from field experiments. Geoderma 369:114323. https://doi.org/10.1016/j.geoderma.2020.114323

Mansfield J, Genin S, Magori S, Citovsky V, Sriariyanum M, Ronald P, Dow MA, Verdier V, Beer SV, Machado MA, Toth IA (2012) Top 10 plant pathogenic bacteria in molecular plant pathology. Mol Plant Pathol 13:614–629. https://doi.org/10.1111/j.1364-3703.2012.00804.x

Marks EA, Mattana S, Alcañiz JM, Domene X (2014) Biochars provoke diverse soil mesofauna reproductive responses in laboratory bioassays. Eur J Soil Biol 60:104–111. https://doi.org/10.1016/j.ejsobi.2013.12.002

Medeiros EV, Moraes MC, Costa DP, Silva JS, Oliveira JB, José RS, Menezes RS, Hammecker C (2020) Biochar and Trichoderma aureoviride applied to the sandy soil: effect on soil quality and watermelon growth. Not Bot Horti Agrobot Cluj Napoca 48:735–751. https://doi.org/10.15835/nbha48211851

Meller Harel Y, Elad Y, Rav-David D, Borenstein M, Shulchani R, Lew B, Graber ER (2012) Biochar mediates systemic response of strawberry to foliar fungal pathogens. Plant Soil 357:245–257. https://doi.org/10.1007/s11104-012-1129-3

Mukherjee A, Zimmerman AR, Harris W (2011) Surface chemistry variations among a series of laboratory-produced biochars. Geoderma 163:247–255. https://doi.org/10.1016/j.geoderma.2011.04.021

Neumann G, Römheld V (2012) Rhizosphere chemistry in relation to plant nutrition. In: Marschner's mineral nutrition of higher plants, Academic Press, pp347–368. https://doi.org/10.1016/B978-0-12-384905-2.00014-5

Noguera D, Rondón M, Laossi KR, Hoyos V, Lavelle P, de Carvalho MH, Barot S (2010) Contrasted effect of biochar and earthworms on rice growth and resource allocation in different soils. Soil Biol Biochem 42:1017–1027. https://doi.org/10.1016/j.soilbio.2010.03.001

Nolan CJ, Field CB, Mach KJ (2021) Constraints and enablers for increasing carbon storage in the terrestrial biosphere. Nat Rev Earth Environ 2:436–446. https://doi.org/10.1038/s43017-021-00166-8

Palansooriya KN, Ok YS, Awad YM, Lee SS, Sung JK, Koutsospyros A, Moon DH (2019a) Impacts of biochar application on upland agriculture: a review. J Environ Manag 234:52–64. https://doi.org/10.1016/j.jenvman.2018.12.085

Palansooriya KN, Wong JT, Hashimoto Y, Huang L, Rinklebe J, Chang SX, Bolan N, Wang H, Ok YS (2019b) Response of microbial communities to biochar-amended soils: a critical review. Biochar 1:3–22. https://doi.org/10.1007/s42773-019-00009-2

Pandit C, Pandit S, Pant M, Ghosh D, Agarwal D, Lahiri D, Nag M, Ray RR (2023) A concise review on the synthesis, and characterization of the pyrolytic lignocellulosic biomass for oil, char and gas production: recent advances and its environmental application. Chem Afr 6:2237–2226. https://doi.org/10.1007/s42250-022-00512-3

Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P (2016) Climate-smart soils. Nature 532:49–57. https://doi.org/10.1038/nature17174

Paustian K, Collier S, Baldock J, Burgess R, Creque J, DeLonge M, Dungait J, Ellert B, Frank S, Goddard T, Govaerts B (2019) Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. Carbon Manag 10:567–587. https://doi.org/10.1080/17583004.2019.1633231

Pietikäinen J, Kiikkilä O, Fritze H (2000) Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. Oikos 89:231–242. https://doi.org/10.1034/j.1600-0706.2000.890203.x

Pimentel D (2005) Environmental and economic costs of the application of pesticides primarily in the United States. Environ Dev Sustain 7:229–252. https://doi.org/10.1007/s10668-005-7314-2

Poveda J, Martínez-Gómez Á, Fenoll C, Escobar C (2021) The use of biochar for plant pathogen control. Phytopathol 111:1490–1499. https://doi.org/10.1094/PHYTO-06-20-0248-RVW

Prendergast-Miller MT, Duvall M, Sohi SP (2014) Biochar–root interactions are mediated by biochar nutrient content and impacts on soil nutrient availability. Eur J Soil Sci 65:173–185. https://doi.org/10.1111/ejss.12079

Rahayu DS, Sari NP (2017) Development of *Pratylenchus coffeae* in biochar applied soil, coffee roots and its effect on plant growth. Pelita Perkeb 33:24–32

Rahman L, Whitelaw-Weckert MA, Orchard B (2014) Impact of organic soil amendments, including poultry-litter biochar, on nematodes in a Riverina, New South Wales, vineyard. Soil Res 52:604–619. https://doi.org/10.1071/SR14041

Razzaghi F, Obour PB, Arthur E (2020) Does biochar improve soil water retention? System Rev Meta-Anal Geoderma 361:114055. https://doi.org/10.1016/j.geoderma.2019.114055

Rodriguez-Ramos JC, Turini T, Wang D, Hale L (2022) Impacts of deficit irrigation and organic amendments on soil microbial populations and yield of processing tomatoes. App Soil Ecol 180:104625. https://doi.org/10.1016/j.apsoil.2022.104625

Rondon M, Ramirez JA, Lehmann J. Greenhouse gas emissions decrease with charcoal additions to tropical soils. In: Proceedings of the 3rd USDA symposium on greenhouse gases and carbon sequestration, Baltimore, USA (vol 208)

Samal I, Mahanta DK, Bhoi TK, Komal J, Jatav HS, Jatav SS, Sathyanarayana E (2024) Sustainable use of biochar. In: Dr. Hanuman Singh Jatav, Dr. Satish Singh and Dr. Bijay Singh (ed) Approaches of biochar in ecosystem management: current scenario and future perspectives. IntechOpen limited, London. https://doi.org/10.5772/intechopen.1004288

Sanni KO, Dayo-Olagbende GO, Godonu KG, Dada BF, Ewulo BS, Ojeniyi SO, Oduntan OO, Bello AA (2022) Effect of rice husk biochar on soil physicochemical properties and performance of cowpea (*Vigna ungiuculata*). Rev Contemp Sci Acad Stud 2:1–7. https://doi.org/10.55454/rcsas.2.10.2022.002

Semida WM, Beheiry HR, Sétamou M, Simpson CR, Abd El-Mageed TA, Rady MM, Nelson SD (2019) Biochar implications for sustainable agriculture and environment: a review. S Afr J Bot 127:333–347. https://doi.org/10.1016/j.sajb.2019.11.015

Shaheen SM, Niazi NK, Hassan NE, Bibi I, Wang H, Tsang DC, Ok YS, Bolan N, Rinklebe J (2019) Wood-based biochar for the removal of potentially toxic elements in water and wastewater: a critical review. Int Mater 64:216–247. https://doi.org/10.1080/09506608.2018.1473096

Shen Z, Zhang J, Hou D, Tsang DC, Ok YS, Alessi DS (2019) Synthesis of MgO-coated corncob biochar and its application in lead stabilization in a soil washing residue. Environ Int 122:357–362. https://doi.org/10.1016/j.envint.2018.11.045

Shi X, Li P, Wang X, Song J, Fang S, Chang C, Pang S (2022) Enhancement of the production of aromatics and bio-syngas from microwave ex-situ pyrolysis based on Zn/Zr modified biochar and multi-catalysts. Energy 261:125307. https://doi.org/10.1016/j.energy.2022.125307

Silva CC, Medeiros EV, Fracetto GG, Fracetto FJ, Martins Filho AP, Lima JR, Duda GP, Costa DP, Lira Junior MA, Hammecker C (2021) Coffee waste as an eco-friendly and low-cost alternative for biochar production impacts on sandy soil chemical attributes and microbial gene abundance. Bragantia 80:e2121. https://doi.org/10.1590/1678-4499.20200459

Singh N, Kumar A (2020) Plant disease management through bio-char: a review. Int J Curr Microbiol Appl Sci 11:3499–3510. http://www.ijcmas.com

Smith P (2012) Soils and climate change. Curr Opin Environ Sustain 4:539–544. https://doi.org/10.1016/j.cosust.2012.06.005

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B (2008) Greenhouse gas mitigation in agriculture. Philos Trans R Soc B Biol Sci 363:789–813. https://doi.org/10.1098/rstb.2007.2184

Solaiman ZM, Blackwell P, Abbott LK, Storer P (2010) Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. Soil Res 48:546–554. https://doi.org/10.1071/SR10002

Stefanovska T, Skwiercz A, Pidlisnyuk V, Zhukov O, Kozacki D, Mamirova A, Newton RA, Ust'ak S, (2022) The short-term effects of amendments on nematode communities and diversity patterns under the cultivation of *Miscanthus* × *giganteus* on marginal land. Agronomy 12:2063. https://doi.org/10.3390/agronomy12092063

Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, Minasny B, McBratney AB, De Courcelles VD, Singh K, Wheeler I (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric Ecosyst Environ 164:80–99. https://doi.org/10.1016/j.agee.2012.10.001

Tarin MW, Fan LL, Shen L, Lai JL, Tayyab M, Sarfraz R, Chen LY, Ye J, He TY, Rong JD, Chen LG (2019) Effects of different biochars ammendments on physiochemical properties of soil and root morphological attributes of *Fokenia hodginsii* (Fujian Cypress). Appl Ecol Environ Res 17:1–14. https://doi.org/10.15666/aeer/1705_1110711120

Thavanesan S, Seran TH (2018) Effect of rice straw and husk biochar on vegetative growth and yield attributes of *Oryza sativa* L. Int J Crop Sci Technol 4:49–56. https://doi.org/10.26558/ijcst.427516

Tian JH, Shuang RA, Yang GA, Yang LU, Cai KZ (2021) Wheat straw biochar amendment suppresses tomato bacterial wilt caused by *Ralstonia solanacearum*: Potential effects of rhizosphere organic acids and amino acids. J Integr Agric 20:2450–2462. https://doi.org/10.1016/S2095-3119(20)63455-4

Tikoria R, Kumar D, Sharma R, Parkirti P, Jasrotia S, Chowdhary AB, Ohri P (2023) Insights into the role of biochar as potential agent in the management of disease caused by phytopathogens: a review. J Soil Sci Plant Nutr 23:4856–4885. https://doi.org/10.1007/s42729-023-01489-9

Van Elsas JD, Kastelein P, van Bekkum P, van der Wolf JM, de Vries PM, van Overbeek LS (2000) Survival of *Ralstonia solanacearum* biovar 2, the causative agent of potato brown rot, in field and microcosm soils in temperate climates. Phytopathol 90:1358–1366. https://doi.org/10.1094/PHYTO.2000.90.12.1358

Van Stan JT II, Morris CE, Aung K, Kuzyakov Y, Magyar D, Rebollar EA, Remus-Emsermann M, Uroz S, Vandenkoornhuyse P (2020) Precipitation partitioning—hydrologic highways between microbial communities of the plant microbiome. In: Precipitation partitioning by vegetation: a global synthesis. Springer, Cham, pp 229–252. https://doi.org/10.1007/978-3-030-29702-2

Ventura M, Zhang C, Baldi E, Fornasier F, Sorrenti G, Panzacchi P, Tonon G (2014) Effect of biochar addition on soil respiration partitioning and root dynamics in an apple orchard. Eur J Soil Sci 65:186–195. https://doi.org/10.1111/ejss.12095

Verwaaijen B, Wibberg D, Kröber M, Winkler A, Zrenner R, Bednarz H, Niehaus K, Grosch R, Pühler A, Schlüter A (2017) The *Rhizoctonia solani* AG1-IB (isolate 7/3/14) transcriptome during interaction with the host plant lettuce (*Lactuca sativa* L.). PloS One 12:e0177278. https://doi.org/10.1371/journal.pone.0177278

Wang Q, Fang W, Yan D, Han D, Li Y, Ouyang C, Guo M, Cao A (2016a) The effects of biochar amendment on dimethyl disulfide emission and efficacy against soil-borne pests. Water Air Soil Pollut 227:1–9. https://doi.org/10.1007/s11270-016-2796-0

Wang Z, Shen D, Shen F, Li T (2016b) Phosphate adsorption on lanthanum loaded biochar. Chemosphere 150:1–7. https://doi.org/10.1016/j.chemosphere.2016.02.004

Wang L, Chen L, Tsang DC, Guo B, Yang J, Shen Z, Hou D, Ok YS, Poon CS (2020a) Biochar as green additives in cement-based composites with carbon dioxide curing. J Clean Prod 258:120678. https://doi.org/10.1016/j.jclepro.2020.120678

Wang L, O'Connor D, Rinklebe J, Ok YS, Tsang DC, Shen Z, Hou D (2020b) Biochar aging: mechanisms, physicochemical changes, assessment, and implications for field applications. Environ Sci Tech 54:14797–14814. https://doi.org/10.1021/acs.est.0c04033

Wang L, Chen L, Poon CS, Wang CH, Ok YS, Mechtcherine V, Tsang DC (2021) Roles of biochar and CO2 curing in sustainable magnesia cement-based composites. ACS Sustain Chem Eng 9(25):8603–8610. https://doi.org/10.1021/acssuschemeng.1c02008

Wang L, Guo J, Wang H, Luo J, Hou D (2022) Stimulated leaching of metalloids along 3D-printed fractured rock vadose zone. Water Res 226:119224. https://doi.org/10.1016/j.watres.2022.119224

Wang L, Deng J, Yang X (2023) Role of biochar toward carbon neutrality. Carbon Res 2:2. https://doi.org/10.1007/s44246-023-00035-7

Were SA, Narla R, Mutitu EW, Muthomi JW, Munyua LM, Roobroeck D, Valauwe B (2021) Biochar and vermicompost soil amendments reduce root rot disease of common bean (*Phaseolous Vulgaris* L.). Afr J Biol Sci 3:176–196. https://doi.org/10.33472/AFJBS.3.1.2021.176-196

Wood R, Masek O, Erastova V (2023) Biochars at the molecular level. Part 1--Insights into the molecular structures within biochars. arXiv preprint arXiv:2303.09661. https://doi.org/10.48550/arXiv.2303.09661

Yadav V, Khare P, Deshmukh Y, Shanker K, Nigam N, Karak T (2018) Performance of biochar derived from *Cymbopogon winterianus* waste at two temperatures on soil properties and growth of *Bacopa monneri*. Commun Soil Sci Pl Analy 49:2741–2764. https://doi.org/10.1080/00103624.2018.1538371

Yamato M, Okimori Y, Wibowo IF, Anshori S, Ogawa M (2006) Effects of the application of charred bark of *Acacia mangium* on the yield of maize [*Zea mays*], cowpea [*Vigna unguiculata*] and peanut [*Arachis hypogaea*], and soil chemical properties in South Sumatra, Indonesia. Soil Sci Plant Nut 52:489–495. https://doi.org/10.1111/j.1747-0765.2006.00065.x

Yan G, Xing Y, Lü XT, Xu L, Zhang J, Dai G, Luo W, Liu G, Dong X, Wang Q (2019a) Effects of artificial nitrogen addition and reduction in precipitation on soil CO2 and CH4 effluxes and composition of the microbial biomass in a temperate forest. Eur J Soil Sci 70:1197–1211. https://doi.org/10.1111/ejss.12812

Yan S, Niu Z, Zhang A, Yan H, Zhang H, He K, Liu G (2019b) Biochar application on paddy and purple soils in southern China: soil carbon and biotic activity. R Soc Open Sci 6:181499. https://doi.org/10.1098/rsos.181499

Yilangai RM, Manu SA, Pineau W, Mailumo SS, Okeke-Agulu KI (2014) The effect of biochar and crop veil on growth and yield of Tomato (*Lycopersicum esculentus* Mill) in Jos, North central Nigeria. Curr Agric Res J 2:37–42. http://hdl.handle.net/123456789/2651

Zakaria MR, Farid MA, Andou Y, Ramli I, Hassan MA (2023) Production of biochar and activated carbon from oil palm biomass: current status, prospects, and challenges. Ind Crops Prod 199:116767. https://doi.org/10.1016/j.indcrop.2023.116767

Zhang X, Gao B, Zheng Y, Hu X, Creamer AE, Annable MD, Li Y (2017) Biochar for volatile organic compound (VOC) removal: sorption performance and governing mechanisms. Biores Technol 245:606–614. https://doi.org/10.1016/j.biortech.2017.09.025

Zhang Q, Liu S, Zhao B, Li Y, Sun X (2021) Effects of biochar on soil water retention and maize yield in sandy soil. Arch Agron Soil Sci 67:558–571. https://doi.org/10.1007/s13399-021-02081-w

Zhou Y, Liu X, Xiang Y, Wang P, Zhang J, Zhang F, Wei J, Luo L, Lei M, Tang L (2017) Modification of biochar derived from sawdust and its application in removal of tetracycline and copper from aqueous solution: adsorption mechanism and modelling. Bioresour Technol 245:266–273. https://doi.org/10.1016/j.biortech.2017.08.178

Zhu K, Wang X, Chen D, Ren W, Lin H, Zhang H (2019a) Wood-based biochar as an excellent activator of peroxydisulfate for acid orange 7 decolorization. Chemosphere 231:32–40. https://doi.org/10.1016/j.chemosphere.2019.05.087

Zhu L, Yang H, Zhao Y, Kang K, Liu Y, He P, Wu Z, Wei Z (2019b) Biochar combined with montmorillonite amendments increase bioavailable organic nitrogen and reduce nitrogen loss during composting. Biores Technol 294:122224. https://doi.org/10.1016/j.biortech.2019.122224

Zin NA, Badaluddin NA (2020) Biological functions of *Trichoderma* spp. for agriculture applications. Ann Agric Sci 65:168–178. https://doi.org/10.1016/j.aoas.2020.09.003

Zomer RJ, Bossio DA, Sommer R, Verchot LV (2017) Global sequestration potential of increased organic carbon in cropland soils. Sci Rep 7:15554. https://doi.org/10.1038/s41598-017-15794-8

Zwart DC, Kim SH (2012) Biochar amendment increases resistance to stem lesions caused by *Phytophthora* spp. in tree seedlings. Hort Sci 47:1736–1740. https://doi.org/10.21273/HORTSCI.47.12.1736