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REVIEW

Biochar as Soil Amendment in Climate-Smart Agriculture: Opportunities, Future Prospects, and Challenges

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Abstract

There appears to be an increasing demand for quality food and fodder to ensure environmental safety. Although chemical fertilizers and pesticides are widely used to increase crop yield and plant protection, the unauthorized and injudicious use of chemicals negatively affects native flora and fauna and depletes natural soil fertility, culminating in quality loss, climate crisis, and global warming. Recently, there has been a lot of focus on using biochar to improve soil health, mitigate soil degradation, and control soil and water pollution because biochar restores ecosystems and enhances soil quality. Biochar is a solid, carbon-rich material with a high surface area and improved nutrient content that exhibits slow nutrient release properties obtained through the pyrolysis of various biochar-based environmental materials. Sustainable biochar release in the soil can improve plant growth through nutrient use efficiencies, enhancing beneficial plant–microbe interactions, and plant protection. The current review summarizes the properties and cost-effective production technologies of quality biochar, sustainable application, action mechanisms for improving soil properties, and prominent plant–microbe interactions for enhanced plant growth and survival under climate-smart agriculture. Biochar's agronomic potential in the soil is affected by physical and chemical properties, such as surface area, particle density, and pore size distribution, as well as pH, electrical conductivity, total and plant-available concentrations of carbon, nitrogen, potassium, and phosphorus, cation exchange capacity, and certain minor nutrients. Additionally, the essential requirements of healthy soil and associated attributes of good agricultural practices are addressed, along with the key benefits, limitations, and opportunities of biochar application for enhancing sustainability in agriculture.

Keywords Agriculture sustainability · Biochar · Climate-smart agriculture · Good agricultural practices · Plant–microbe interaction · Pyrolysis

1 Introduction

Agriculture, in the present scenario, is more harrowing due to numerous environmental and health concerns (Bhattacharyya et al. 2023a). The widespread administration of agrochemicals in farming has been identified as one of the greatest challenges that humanity must overcome in the twenty-first century. This is due to the fact that the chemical inputs trigger the accumulation of toxic pollutants and heavy metals, such as arsenic (As), cadmium (Cd), chromium (Cr), fluorine (F), lead (Pb), and mercury (Hg) in agricultural soils, and the freshwater resources that reside nearby. Toxic chemicals and fertilizers cause numerous challenges in agriculture leading to disrupting the natural health of soil, water, and environment (Mahanta et al. 2023). In relatively small quantities, macronutrients like nitrogen, phosphorus, and potassium as chemical fertilizers are not toxic to the soil and environment, but the rapid and illegitimate application of the chemical elements as nutrients is always hazardous and disrupts the native soil and environment through persistence, bioaccumulation, and biomagnification. Persistent usage of chemical fertilizers has been linked to issues such as gradual land degradation and compaction, soil erosion, and inefficient nutrient uptake capacities by plants (Hossain et al. 2022). Bhattacharyya and Sarmah (2018) have

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investigated the negative consequences of pesticides used in intense conventional agricultural practices to manage pests, pathogens, and nutrient deficiencies. The widespread application of agrochemicals in agriculture, including their uses in the management of perennial crops like tea, has resulted in decreased soil quality, air and groundwater pollution, the creation of undesirable residues like maximum residue limits (MRLs), rising costs, the recurrence of diverse plant pests and pathogens, changes in the susceptibility of pests and resistance development (Bhattacharyya et al. 2023b). Roy et al. (2020) contend that pesticides pose significant threats to human health, other non-target organisms, soil, water and the entire environment. The inorganic pesticides, insecticides, and other agrochemicals are posing serious threats to sustainable crop production, both in terms of quality and quantity. This is because these chemical supplements are known to impair soil health and fertility and contribute toxicity to air, groundwater, and foods, causing extensive contamination; in addition, they impede the native microbial populations in soil (Bhattacharyya and Jha 2012). Increasing risks in creating major ecological problems, such as soil and ecosystem degradation, soil compaction, and loss of fertility, are often due to pesticides that rarely make it to their intended target because of chemical leaching, volatilization, and aerosolization activities (Singh et al. 2022a). Highly eroded, deteriorated topsoil looks to be less capable of retaining soil moisture, which is necessary for maintaining healthy plant–microbe interactions as well as to preserve the soil's ability to retain sufficient water and nutrients. The toxic effects generated due to chemical contamination in soil, air, water, and associated environment are depicted in Supplementary Fig. 1.

Several chemical fertilizers have been observed to completely permeate the soil before being assimilated by plants, leading to cause negative effects on native soil, water, and environment. As, beryllium (Be), Cd, Cr, copper (Cu), Pb, Hg, nickel (Ni), selenium (Se), silver (Ag), titanium (Ti), and zinc (Zn) were identified as major environmental pollutants (Nunes et al. 2020), while Cd, Cr, Cu, manganese (Mn), Ni, and Zn are categorized as major indigenous pollutants in soils and sediment. According to Bhattacharyya et al. (2022), the rising levels of emerging pollutants in soil and aquatic habitats are due to anthropogenic activities such as the use of hazardous chemicals, fertilizers, and pesticides in soil and agriculture that jeopardize human health and ecosystem. As one of agriculture's major operating expenses, inorganic fertilizer appears to contribute significantly to greenhouse gas (GHG) emissions, climate crisis, and global warming (Walling and Vaneeckhaute 2020).

In light of the foregoing, substantial efforts have been made to supplement the nutritional needs of crops in order to reduce the use of toxic pesticides and fertilizers in agricultural soils. Hemathilake and Gunathilake (2022) emphasized the necessity of sustainable approaches to enhance crop productivity and associated agricultural products of superior quality to satisfy the rising global demand of quality food and safety. The incorporation of alternative, non-chemical and sustainable agricultural techniques, such as the use of biological agents like beneficial microorganisms and soil amendments including the biochar has proven to be an effective strategy in enhancing the crop yield and biomass production. Additionally, these methods strengthen the vitality of plants and increase their resistance to devastating pests and pathogens for an extended period of time. Similarly, soil enrichment techniques such as the use of green manure, animal manure, compost, and biofertilizers have recently gained momentum as a means to promote agricultural sustainability. Nagpal et al. (2021) addressed the significance of incorporating biochar with quality microbial bio-formulations as essential components of modern agriculture. Biochar is an eco-friendly, carbon-rich organic product generated through the pyrolysis of organic biomasses, including biochar-based material derived from renewable resources, under oxygen-free conditions (Tomczyk et al. 2020). It is a stable byproduct of carbonizing plants, animals, and industrial wastes (Lehmann et al. 2021) that improves soil physicochemical and biological properties. Biochar has been suggested to boost a number of key soil properties like permeability, water holding capacity, pore size, water resistance, and biogeochemical activity. Recognizing its all-around beneficial actions, biochar production from diverse organic products and biochar-based materials and byproducts of agricultural and industrial origin has emerged as an intriguing area of research under climate-smart agriculture for enhanced sustainability (Lehmann et al. 2021). Agriculture residue, woody and aquatic biomass, animal waste including the litters of cattle's and poultry, grass cuttings, and green manure are considered as major feedstock materials that may be used in biochar production. These feedstock materials may be subjected to optimum biological, physical, and chemical activation processes in order to produce active biochar as a finished product.

The current review highlights the importance of implementing non-chemical and sustainable programs for effective soil management through improved use efficiency of biochar as an active soil amendment either directly or as carriers of diverse microbial formulations such as microbial biofertilizers and biopesticides that are of prominent significance to agriculture. Biochar application in agricultural soil and their compatibility with other agrochemical substances and supplements are addressed to elucidate the scope of biochar research under the climate-smart agriculture. Additionally, the certification and ethical standards of biochar application in agriculture are discussed to highlight the perspectives of worldwide recognition of biochar as an indispensable component of sustainable agriculture.

2 Biochar in Sustainable Agriculture

Enhanced nutrient use efficacy in plants is a prerequisite for their long-term survival and sustainability. The indiscriminate use of toxic substances in agriculture escalates the risk of toxicity generation in processed food and commercialization (Bhattacharyya and Sarmah 2018; Bhattacharyya et al. 2023a). Singh et al. (2020c) asserted that the ecological balance that is disrupted through the rapid application of agrochemicals in soils can be restored by adopting sustainable agricultural practices that utilize biological and industrial wastes to promote plant growth, biomass yield, and beneficial plant–microbe interactions. Among a variety of biological soil conservation practices, biochar has the potential to be an indispensable and accessible input for sustainable agriculture, as it may efficiently sequester immense quantities of carbon in soil over time, boosting soil fertility, and crop yield, and mitigating global warming (Semida et al. 2019). The majority of biochar research has focused on the impact of biochar and its application potential in tropical soils, using char obtained from local earthen kilns with minimal organic biomass content. Because of its porous nature, biochar is considered to be one of the most effective and active soil amendments. Furthermore, biochar can assist to improve soil fertility under various biotic and abiotic stress conditions, thereby advancing global food security and protection.

Native microorganisms have the potential to promote plant growth and survival because they can function as prominent biofertilizers and play an important role in biological nitrogen fixation (BNF), phosphate mobilization, possessing antimicrobial properties, and expressing the production of phytohormones and ethylene (Bhattacharyya and Jha 2012). Saleem et al. (2022) advocated that employing biochar in combination with the recommended dosages of microbial bioformulations might enhance crop productivity and quality. Biochar assists in activating the soil microbiome status for rapid attachment and mineralization of essential plant nutrients through improving the microbial-shelf life, viability and rapid plant-microbe interactions (Khadem et al. 2021). The viability of employing wood biochar as a carrier of soil microorganisms was examined by Li et al. (2020). Microorganisms can easily colonize the biochar surface, offering a good habitat and a source of labile carbon and mineral nutrients (Saleem et al. 2022). Changes in the structure and composition of beneficial microbial population numbers and activities are the prominent mechanisms through which biochar influences the microbial life and their interactions in soil. Biochar additionally protects soil microorganisms from the deleterious effects of organic and inorganic contaminants. Hakim et al. (2021) advocated the pre-inoculation of biochar with plant growth–promoting rhizobacteria (PGPR) for effective crop management, improved biochar marketing, and potential for sustainability in microbial life and interactions. According to Gorovtsov et al. (2020) integrating biochar with beneficial microorganism results in a bio-product that is more capable of maintaining ecological balance and providing adequate nutrients in a form that may be more easily utilized. The reported phenomenon might be attributed to the capacity of biochar to augment the functionality and variety of soil microbial enzymes, thereby facilitating a range of biochemical reactions within the soil ecosystem. These reactions encompass the breakdown of soil organic matter, mineralization of nutrients, and the mitigation of environmental contaminants. According to Gorovtsov et al. (2020), soil pH, water holding capacity (WHC), cation exchange capacity (CEC), and aggregation are all influenced by biochar's presence or absence, which in turn impacts the availability and accessibility of nutrients for native microorganisms present in soil. This phenomenon has an advantage in increasing the crop productivity and plant protection under climate-smart agriculture. Cui et al. (2021) suggested the application potential of biochar as a viable alternative in agriculture to hazardous chemicals in order to mitigate the worsening effects of climate catastrophe and equally to meet the increasing demand for safe and sustainable usage of global food supply and security. Maintenanace of microbial shelf life, viable spore count (colony forming unit (cfu)/ml), efficacy of microbial bioformulations, as well as their consistency and survival rate are certainly significant challenges for biochar-based microbial formulations to function under diverse environmental conditions for enhanced sustainability (Chen et al. 2022). According to Dai et al. (2021), the distinctive characteristics of biochar, such as its high alkalinity, porosity, and labile nutrient content, successfully alter the charosphere environment in favor of a particular microbiome's nutrient requirements resulting in a positive impact on microbe-assisted pathways in plants such as plant hormone signalling and behavioral responses.

The potential of biochar-based materials to enhance agricultural sustainability has been justified by Das et al. (2023). Because of its potential in soil rehabilitation, ecosystem restoration, and other advantages, biochar's widespread availability and effective use in agriculture seemed to be essential for sustainable development, worldwide. According to Melo et al. (2022), when biochar is utilized in a controlled manner, a larger crop yield of higher quality can be accomplished. This is because biochar has qualities that facilitate the slow and sustainable release of nutrients over an extended period of time. Agegnehu et al. (2017) observed that the adoption of biochar and biochar-compost-based soil management methods could increase soil organic carbon (C_{org}), total nitrogen (N_{tot}), available phosphorous ($P_{avail.}$), and exchangeable potassium ($K_{exchang.}$). Song et al. (2022) studied the ecological benefits of storing biochar products for enhanced carbon neutrality via sustainable soil management practices. However, the role of biochar in crop productivity is contingent on multiple variables such as geography, soil type and characteristics, and prevailing climate. Table 1 demonstrates the application potential of various biochar forms that have been utilized to increase crop yields in agriculture under diverse soil types and characteristics. Biochar and its application essentiality for enhancing agriculture sustainability are depicted in Fig. 1. The incorporation of biochar in agriculture improves the photosynthetic efficiency of plants, reflected by increased plant growth and vigor, while simultaneously reducing mineral leaching and emissions of GHG emissions (Wang et al. 2020). Because the majority of the components in biochar are labile, they are not susceptible to microbial degradation; thus, their structure remains intact. It takes between 1300 and 4000 years for biochar to be extensively assimilated into the soil (Han et al. 2021). Yadav et al. (2023) emphasized the sustainable biochar production procedures for improved stability and function. Charcoal made at 400 °C is more resistant to ozone oxidation than

Table 1 Influence of biochar application on crop yields and soil properties (adapted from Tian et al. 2018)

Soil type	Crop	Location	Years of experiment	Type of experiment	Biochar type	Biochar rates	Soil depth examined	Positive consequences
Light day	Maize	Australia	01	Field	Wood	0–25 t ha^{-1}	0–12 cm	+ 8–29% (grain yield)
Light clay	Maize	Australia	01	Field	Wood	0–25 t ha^{-1}	0–12 cm	+ 13–29% (grain yield)
Loam soil	-	India	02	Column	Corn	0–20 g kg^{-1}	0–40 cm	− 14–32% (nitrate loss)
Silt loam	Wheat and Maize	China	03	Field	Mushroom residue	0–90 t ha^{-1}	0–20 cm	+ 44–215% (soil organic carbon)
Clay loam	Maize	Columbia	04	Field	Wood	0–20 t ha^{-1}	0–30 cm	+ 0 − 140% (grain yield)
Sandy loam	Grass	China	02	Field	Pine	0–16 g kg^{-1}	0–40 cm	+ 2.7–10.7 g/kg (soil organic carbon)
Clay loam	Cotton	China	01	Field	Straw	0–4.5 t ha^{-1}	0–20 cm	+ 8–109% (soil organic carbon)
Clay loam	Rice	China	02	Field	Pine	0–16 g kg^{-1}	0–20 cm	+ 11.3–21.6% (rice yield)
Sandy loam	Grass	China	03	Field	Wood	0–20 mg ha^{-1}	0–40 cm	+ 0.2–0.8 g/kg (total N)
Sandy soil	-	USA	01	Incubation	Wood and Straw	–	–	− 34% (nitrate loss)
Sandy clay soil	Maize	UK	03	Field	Wood	0–50 t ha^{-1}	0–20 cm	+ 0.32 units (pH)
Light clay soil	Maize	Australia	01	Field	Wood	0–25 t ha^{-1}	0–12 cm	+ 9–25% (soil water contents)
Sandy soil and loamy soil	Oats	Germany	01	Pot	Wood	0–50 wt.%	–	+ (grain yield)
Loamy sandy soil	Corn	USA	02	Field	Peanut Hull	0–22 mg ha^{-1}	0–30 cm	+ 17–98% (Soil K)
Calcareous inceptisol	Maize	China	02	Field	Straw	0–40 t ha^{-1}	0–15 cm	+ 4.9–12.8 g/kg (soil organic carbon)
Calcareous inceptisol	Maize	China	02	Field	Straw	0–40 t ha^{-1}	0–15 cm	+ 4–12% (total N)
Calcareous inceptisol	Maize	China	02	Field	Straw	0–40 t ha^{-1}	0–15 cm	+ 11.9–35.4% (maize yield)
Haplic Luvisol	Sunflower	Spain	01	Pot	Wood and Straw	0–7.5% w/w	–	+ 0.5–1units (pH)
Haptic Luvisol	Wheat	Spain	01	Pot	Straw and Olive tree	0–2.5% w/w	–	+ 10–100% (root biomass)
Entic Halpudept	Rice	China	02	Field	Straw	0–40 t ha^{-1}	0–15 cm	+ 9–28% (grain yield)

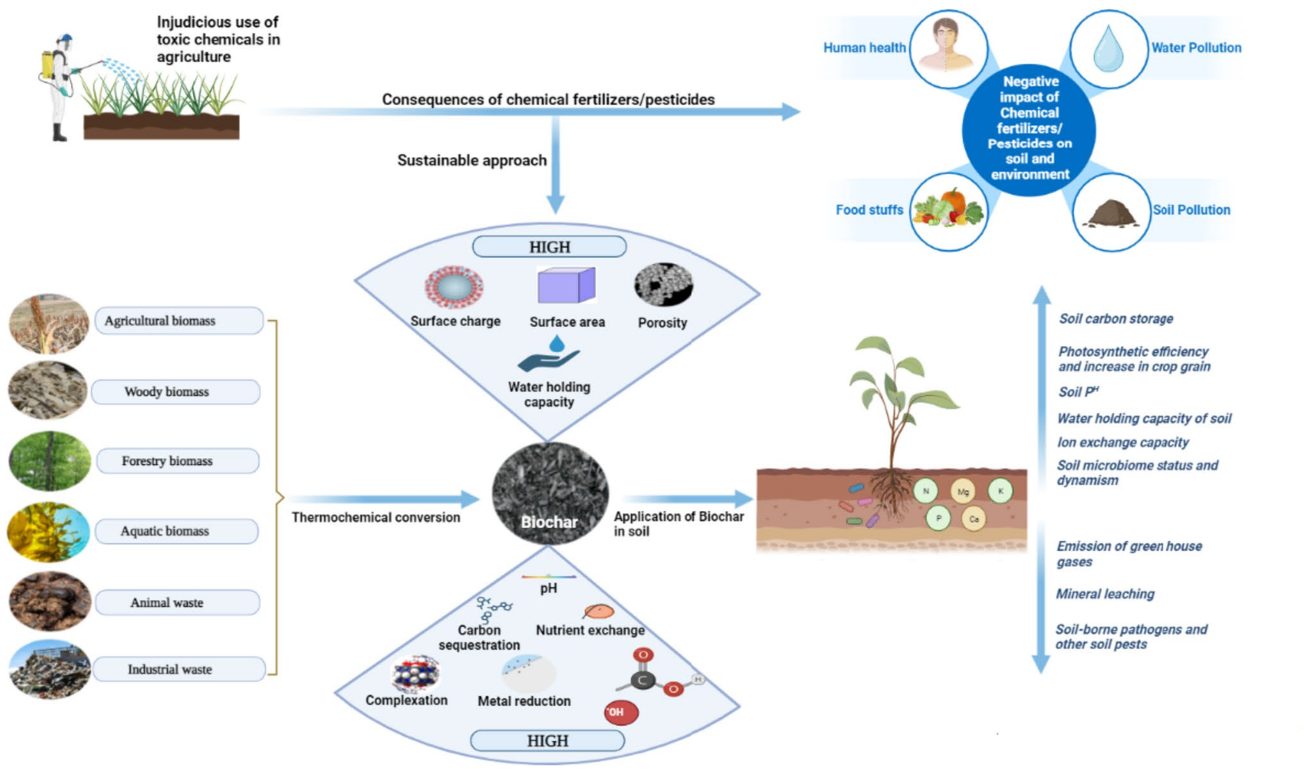

Fig. 1 Application essentials of biochar for enhancing agricultural sustainability

charcoal made at 1000 °C. Clay soil had a greater biochar impact upon soil specificity than loam soil when examined by Libutti et al. (2021), who compared the soil attributes of two distinct soil categories after biochar was amended with phosphorus fertilizer. Soil aggregation could play a vital role in maintaining the physical stability of biochar. Due to its enormous potential in carbon sequestration, enhancement of soil health and nutrient usage efficiencies in plants, and crop yield and quality, biochar is recognized as superior game-changing organic material to animal dung or compost. It may be stated that biochar can replenish soil organic matter (SOM) up to 35%. In order to establish a link between the biochar supply chain and economic and environmental performance to improve agriculture's sustainability, an in-depth evaluation on the impact of biochar on soil macronutrients like nitrogen, phosphorus and potassium, in addition; soil structure, and soil carbon stocks is seemed to be essential.

3 Methods of Preparation of Biochar and Standardization

The increasing need for biochar to maintain agricultural integrity has led to a rise in the proportion of biomass that is being processed into quality biochar (Yaashikaa et al. 2020). Examples of biomass product materials that are suitable for effective production of biochar include crop residues such as field and processed residues like nut shells, fruit pits, bagasse and yard waste, food waste, forestry waste, and animal manure (Yaashikaa et al. 2020). The process of thermochemical conversion is frequently used as one of the most popular methodologies for producing biochar. The type of biomass, the condition of the reactions, and the reactors used during the carbonization process usually determine the elemental makeup and qualities of biochar, even though it is totally made up of carbon and ash (Yaashikaa et al. 2020). The thermochemical conversion processes and the accompanying process parameters are listed in Table 2.

Pyrolysis, hydrothermal carbonization, gasification, flash carbonization, and torrefaction have been identified as common thermochemical processes used for producing quality biochar. Pyrolysis is the process of degradation of waste in anaerobic conditions at temperatures ranging from 300 to 800 °C. The solid carbon-rich product of this bioconversion process is known as biochar or char, and the volatile fraction of pyrolysis is partly condensed to a liquid fraction known as tar or bio-oil (Tomczyk et al. 2020). Additionally, the formation of a mixture of non-condensable and volatile condensable organic products

Table 2 The thermochemical conversion processes and production parameters of biochar

Standard methodologies	Operating conditions	Residence time	Yield of biochar (approx.)	References
Pyrolysis				
Slow pyrolysis	300–700 °C	> 450 s	Up to 35%	Zhang et al. 2019
Fast pyrolysis	550–1250 °C	0.5–20 s	Up to 20%	
Flash pyrolysis	800–1300 °C	< 0.5 s	Up to 12%	
Hydrothermal carbonization	180–250 °C	0.5–8 h	Up to 35–65%	Khan et al. 2019
Gasification	> 700 °C	10-20 s	Up to 10%	Yaashikaa et al. 2020
Flash carbonization	300–600 °C	< 30 min	Up to 40–50%	Zhang et al. 2021a, b
Torrefaction	200–300 °C	10–60 min	Up to 80%	Cahyanti et al. 2020
Microwave pyrolysis	410 °C 700 W	25 min	Up to 38%	Kurian et al. 2022

into low molecular weight gases, secondary tar, and char is accomplished through secondary reactions of the primary pyrolysis products. Conventional electric pyrolysis can be categorized into three distinct groups according to the operational characteristics such as heating rate, pyrolysis temperature, and residence time: slow pyrolysis, fast pyrolysis, and flash pyrolysis (Zhang et al. 2019). Compared to high temperatures, low temperature significantly results in more char production. The elemental composition and H/C (the degree of aromaticity) and O/C (the degree of polarity) ratios of raw biochars were significantly affected by elevating the pyrolysis temperature. Higher pyrolysis temperature produces biochar with lower H/C and O/C ratios, indicating increased aromaticity and decreased polarity. Pyrolysis-mediated biochar production assisted through physical, chemical, and biological activation process parameters are depicted in Fig. 2. Hydrothermal carbonization (HTC) is a thermochemical conversion process that uses heat to transform moist biomass feedstocks into hydrochar. HTC operates in a reactor at temperatures between 180 and 250 °C, under pressures between 2 and 6 MPa, and with feedstock residence times between 0.5 and 8 h (Khan et al. 2019). HTC's substantial output is hydrochar, a coal-like product, with secondary outputs of aqueous (nutrient-rich) and gaseous (mostly CO_2) phases. Dehydration, decarboxylation, and decarbonylation are the three essential steps involved in the HTC process. Neither the pretreatment nor the drying of the feedstock waste is required for HTC. Gasification is a thermochemical process that is also known as pyrolitic distillation. In this

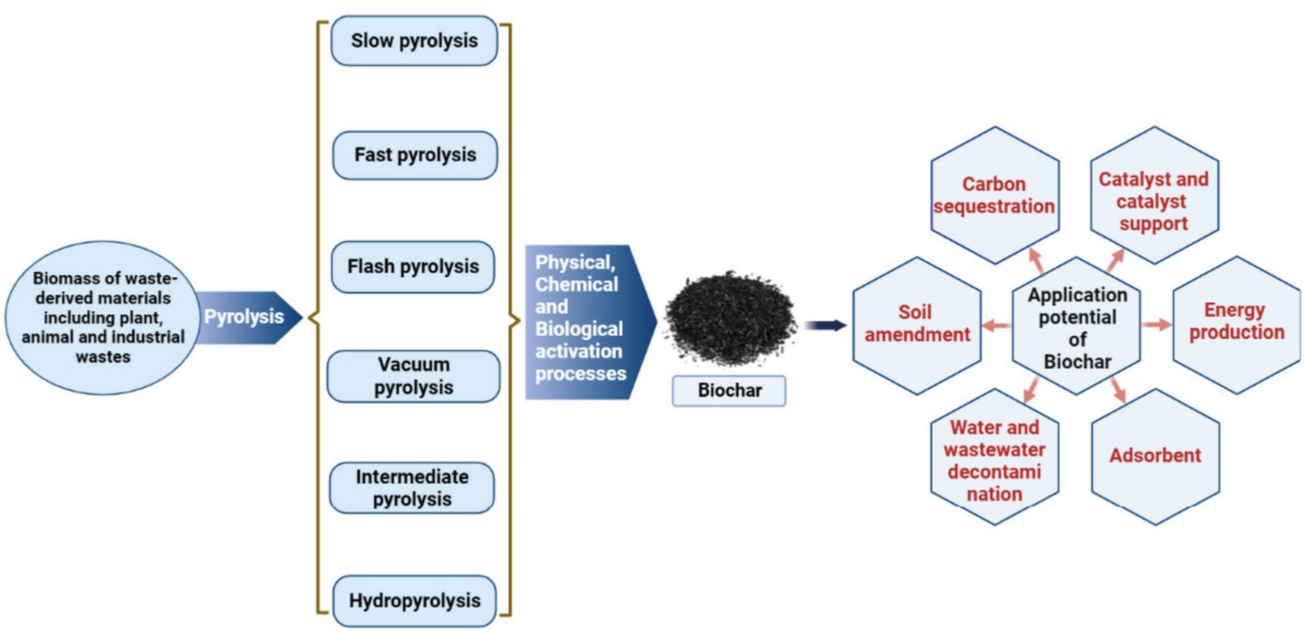

Fig. 2 Key process parameters in biochar production and it's application potential in agriculture for sustainability

process, pelletized or crushed biomass is partially oxidized by a gasification agent in a gasifier. Combustible gases are the principal product of the gasification process, while charcoal and some tars are generated as by-products. This process is carried out at high temperatures (> 700 °C) (Yaashikaa et al. 2020). The process of flash carbonization is comparatively a novel process. It quickly and effectively produces biochar from biomass. The technique involves packing biomass into a pressure vessel, pressurizing it with air (1–2 MPa), and igniting a flash fire at the bottom of the bed to transform the biomass into solid-phase and gas-phase products. The reaction period in this procedure takes approximately 30 minutes; the temperature varies from 300 to 600 °C, and the maximum yield of biochar is in the range of 40–50%. Torrefaction is a mild pyrolysis procedure carried out in an inert atmosphere between 200 and 300 °C. Devolatilization, depolymerization, and carbonization of hemicellulose, lignin, and cellulose are identified as prominent biomass processes during torrefaction. During this process, biomass becomes partially decomposed, which results in the generation of condensable and non-condensable gases. According to Tumuluru et al. (2021), the resulting product could be referred to as biochar, torrefaction biomass, or biocarbon. Microwave pyrolysis is a novel procedure for pyrolyzing biomass wastes using microwaves as the heat source (Kurian et al. 2022). In this technique, the sample is placed inside a microwave oven. The changing orientation of the electric dipoles in the material that is being heated as a result of the microwave's alternating current electric field moving in a different direction is what causes the heating, along with the concomitant loss of electrical energy. Before the pyrolysis is about to start, the air inside the cavity of the microwave oven is sucked out using a vacuum pump to create an inert environment. The pyrolysis is then performed for 25 minutes at a microwave power range of 500–700 W. Microwave pyrolysis has multiple benefits over conventional pyrolysis since it does not require drying and heat transmission processes and directly operates within the feedstock by convection and not by conduction.

4 Effect of Pyrolysis Temperature on Surface Functional Groups and CEC of Biochar

Biochar is a carbon-rich high stability material. In contrast to other aromatic structures found in soil organic matter, such as lignin, biochar has a significantly larger concentration of aromatic carbon and condensed aromatic compounds (Tomczyk et al. 2020). The condensed aromatic structure of biochar may be of different forms, including amorphous carbon (which predominates at lower pyrolysis temperature), turbostratic carbon (produced at higher temperature), and graphite carbon (Supplementary Fig. 2). The chemical bonds in the biomass are broken and rearranged during heating to temperatures between 350 and 650 °C, creating new functional groups such as carboxyl, lactone, lactol, quinine, chromene, anhydride, phenol, ether, pyrone, pyridine, pyridone, and pyrrole (Supplementary Fig. 3 and 4). According to Murtaza et al. (2022), biochar produced at high temperature (600–700 °C) has well-organized carbon layers and is very hydrophobic in nature. However, because the biomass has been dehydrated and deoxygenated, it has reduced concentrations of functional groups containing H- and O-. Surface groups can function as electron donors or acceptors, resulting in the creation of coexisting regions with characteristics that can range from acidic to basic and from hydrophilic to hydrophobic. Because of this, the ion exchange capacity of such a product may be decreased. The presence of aliphatic and cellulose-type structures in biochar generated at lower temperature (300–400 °C) results in a more diverse organic character (Zhang et al. 2021a, b). When the pyrolysis temperature rises, the structure of biochar appears to have more structured carbon layers (similar to the structure of graphene) and reduced content of surface functional groups. According to several research, biochar's CEC declines as pyrolysis temperature rises. The measurable CEC indicated that certain acidic oxygenated functional groups, such as phenolic acid and carboxyl groups, were maintained when biochar was generated at temperature up to 480 °C. The type and location of O-containing functional groups on the surface of biochar are known to affect its CEC. The carboxylate and phenolate functional groups are responsible for the negative charge sites on the biochar surface. The worker's believe that the only source of negative surface charge are carboxylate and phenolate groups, while the only source of positive charge are oxonium groups (heteroatoms in aromatic rings). However, some researchers have discovered that biochars with larger specific surface area (obtained at temperature over 600 °C) had enhanced CEC and more surface microporosity (Hossain et al. 2020) that may be associated with the release of volatile materials.

5 Efficacy of Biochar as Soil Amendments

The use of biochar as a soil amendment to enhance soil fertility and mitigate environmental effects has been studied extensively (Nepal et al. 2023). Biochar can be differentiated from charcoal due to the fact that it has qualities that can be used as soil amendment (Lehmann et al. 2021). In addition to improving the populations and community dynamics of soil microflora, biochar serves as an essential component in the mineralization of soil nutrients (Hossain et al. 2020). Since biochar has a larger surface area and porosity, it facilitates the uptake of both nutrients and water, making it an ideal environment for the successful colonization of beneficial soil microbiome populations (Saleem et al. 2022; Singh et al. 2022a, b, c). Zhang and Shen (2022) have investigated the effects of biochar on soil microbial diversity and community dynamics in clay soil. Biochar amendments were found to be effective in enhancing microbial vigourness and population levels of proteobacteria, cyanobacteria, and actinobacteria. *Nostoc*, *Skermanella*, *Frankia*, and p-proteobacteria were found to be dominant microbial species due to biochar addition in soil. Biochar amendments have been demonstrated to be advantageous in terms of changing the composition of plant root exudates, influencing soil microbial and biochemical properties, and triggering systematic plant defense mechanism. According to Zhang and Shen (2022), biochar and soil have significantly different physical structures. The differences of biochar to soil might have the potential to have an advantageous effect on native soil flora and fauna as a result of shifts in tensile strength, fluid dynamics, and gaseous transport. The deliberate application of biochar in soil improves soil organic matter, retains and utilizes nitrogen, potassium, and other micronutrients for an extended period of time, and reduces soil erosion and acidity (Yadav et al. 2023). Biochar has the ability to enhance the soil pH and CEC, decrease aluminum toxicity and tensile strength, improve natural soil habitats for earthworms as well, and improve fertilizer usage efficiency by plants. Incorporating biochar into soil has been observed to raise soil hydraulic conductivity (Ksat) by 1.8 times while boosting the mean weight diameter (MWD) of soil aggregates (Liang et al. 2021a, b). The formation of macro-aggregates in biochar-amended soil is essential for reducing soil erosion. According to Han et al. (2021), incubation time and process optimization in pyrolysis plays inevitable role in influencing biochar-mediated soil aggregation leading to soil rehabilitation and land fortification. According to Lebrun et al. (2021), 5% biochar application rate is found to be optimal for extensively used soils since it substantially improves the physiochemical parameters of soil and reduces the loss of topsoil. Soil organic matter, alkali-hydrolyzed nitrogen, ammonium nitrogen, and potassium solubility are all can be considerably increased through biochar application to the soil (Hossain et al. 2020; Yadav et al. 2023). It has been observed that a blend of acacia, croton, and eucalyptus charcoal improved the water-conservation attributes of degraded soils, leading to minimizing nutrient runoff and soil erosion activities. Because biochar is primarily alkaline in nature, it can boost rice nutrient utilization and absorption (Hossain et al. 2020) by elevating the pH of acidic soils. By measuring the soil's organic carbon content, moisture content, CEC, and the volume of peanuts produced, Pandit et al. (2020) evaluated the nutritional value of compost, biochar, and the components that assists in nutrient mobilization. These substances have the abilities to substantially mitigate GHG emissions and global warming (Cui et al. 2021). It has been measured that plant respiration and metabolic rate increase when biochar is preconditioned with farmyard manure (FYM) and animal dung for their sustainable use to ameliorate degraded lands and enhance plant productivity. The effectiveness of biochar in enhancing plant growth, reducing nutrient leaching, and improving water retention capacities of soil and microbial community dynamics has been extensively studied in both the tropics and temperate climates (Das et al. 2023). Jabborova et al. (2020) observed an improvement in plant growth and nutrient allocation in the soybean plant after co-inoculation of PGPR with biochar. The results identified the scope for utilizing chemical-free and sustainable organic farming practices for improved crop yields, root biomass, and improvements in soil biochemical properties. Figure 3 depicts a schematic representation of biochar-induced plant growth stimulation and sustainable growth responses.

Nitrogen is an essential macronutrient for normal plant growth and development (Ye et al. 2022). The use of nitrogen fertilizer has the potential to restore the nitrogen content of soil and sustain land productivity. Unfortunately, the eutrophication of surrounding water resources including the rivers and lakes is exacerbated by the excessive application of nitrogen fertilizer, resulting in significant losses of soil nitrogen and diminishing the efficiency and utilization of nitrogen fertilizer. By altering the microbial-mediated soil nitrogen and phosphorus cycles (N_2 fixation, nitrogen and phosphorus mineralization, nitrification, ammonia volatilization, and denitrification), biochar significantly reduces nitrogen and phosphorus loss from soil. Significant impacts of biochar on microbially mediated soil nutrient transformations have been demonstrated by Khadem et al. (2021). Meanwhile, biochar offered an interface for nitrogen and phosphorus ions to persist in soil microbial biomass and exchange sites, thereby assisting in limiting crop nitrogen and phosphorus availability. Their findings indicated a significant interaction between nitrogen obtained from fertilizer and carbon from applied biochar sources. They asserted that nitrogen and carbon inputs were active based on the assumption that some of the biochar remained labile. When no nitrogen fertilizer was supplied, the labile component of the applied biochar carbon leached in the form of dissolved carbon. Furthermore, their research revealed that employing biochar might contribute to reduce nitrogen leaching from fertilized soils.

The effects of sheep and earthworm dung biochar on heavy metal immobilization in contaminated calcareous

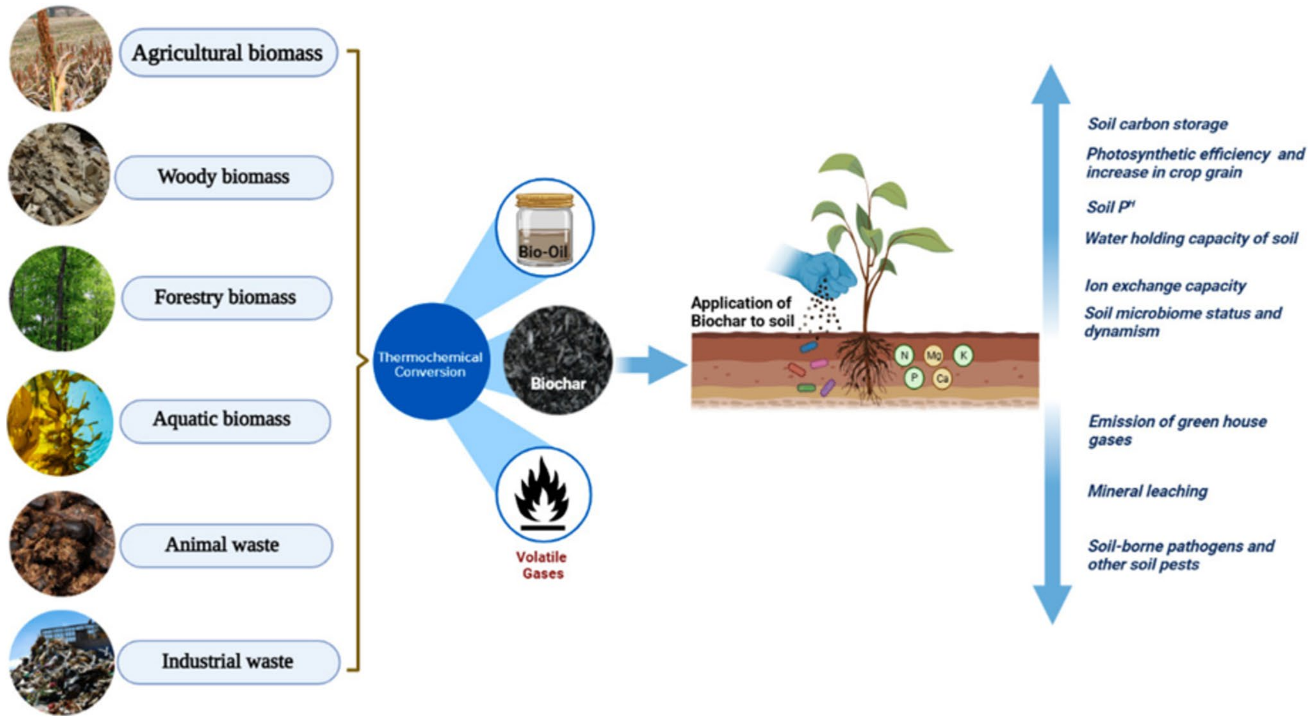

Fig. 3 Potential benefits of biochar application in soil

soils were studied by Boostani et al. (2019). The residual Pb content enhanced dramatically when biochar was added to the soil, leading to a decrease in Pb activity. Chen et al. (2019) explored the adsorption mechanisms for the removal of Pb and Cd toxicity from dairy manure biochar. Pb and Cd toxicity dramatically dropped and were transformed into carbonate minerals during precipitation. This could be due to the ability of the biochar to preferentially absorb nitrogen, which would result in reduced nutrient levels (Hossain et al. 2020). According to Lu et al. (2017), rice straw and bamboo biochar can effectively immobilize heavy metals and play vital role in reducing the mobility and redistribution of heavy metals like Cd, Cu, Pb, and Zn in contaminated soil. Zn was the most adsorption-competent metal in the experiment when sludge biochar was tested against single metals; however, the adsorption capacity of Cu declined, while Zn and Mn both increased in the experiment where polymetallic metals were evaluated. Though biochar reduces the concentration of extractable heavy metals when the soil is contaminated with complex heavy metals, due to competitive adsorption, it has distinctive adsorption effects to work with different heavy metals and the toxicity it generates.

Tea estates are known to produce biochar from wood scraps and other land clearings, such as shade tree loops and avenue plants, in addition to tea pruning litters (Sarmah et al. 2023; Yang et al. 2021). The workers have experimented to generate biochar from tea pruning litters and used the same in tea ecosystem to assess its role in enhancing the nutrient content of tea soil. They observed that tea pruning litter biochar contained about 38% carbon, 1.31% nitrogen, 0.80% phosphoric acid (P_2O_5), and 2.21% potassium oxide (K_2O) and could be used as soil amendment at a nominal rate of 4 to 8 tons ha^{-1} for enhancing sustainability in tea. Due to its alkaline composition, biochar may elevate the pH of acidic tea soils marginally, and thereby exerts positive impact on crop yield and quality as well. The effect of tea pruning litter biochar on major pathways of micronutrients like Cu, Mn, and Zn in tea ecosystem has been investigated by Sarmah et al. (2023). The results indicated the inclusion of tea pruning litter biochar as a sustainable component in agriculture including in tea. Since biochar can be generated from pruning litters, it is possible to cover the tea plantations with biochar in 3 to 4 years using their tea plant prunings. The approach gradually increases the organic matter content of the soil, rendering the tea soil more fertile and nutrient-rich. After incorporating the biochar into the tea root zone through forking activities, it showed a much better growth response (tea crop yield increased by up to 83.27%) and higher organic carbon content compared to the controlled bush in the same climate and topography. The study has focused specifically on the sensitivity of tea to dry weather situations. Wang et al. (2014) have examined the effects of crop residue biochar on soil acidity in severely acidic tea gardens situated in China. After 65 days of incubation at 25 °C, it was observed that biochar application increased soil pH, exchangeable cations, and decreased Al saturation in both Xuan-cheng (Ultisol; initial pHsoil/water = 1/2.5 4.12) and Ying-tan (Ultisol; initial pHsoil/water = 1/2.5 4.75) soils. An increase in the quantity of biochar resulted in an increase in the number of exchangeable cations and a decline in the proportion of exchangeable acidity without affecting the pH of the soil. Soil pH may not have altered at the increased biochar rate because biochar has a strong buffering capacity, which delays the liming impact by eliminating the scopes of exchangeable acidity.

6 Biochar as a Carrier Material for Microbial Formulations

The practice of integrating carrier components with microbial inoculums in soil has been around for quite a while (Bastida et al. 2021). Peat moss is one of the most common ways to transport soil microorganisms, and it has numerous advantages for ensuring that the inoculum is properly sterilized before it can be implemented. It is feasible that *Rhizobium* biofertilizers could be transported through peat moss. Vermiculite, lignite, etc. have also been used as alternative carrier materials nowadays. Su and Jin (2022) have considered vermiculite to be an efficient carrier material for the survival and active performance of beneficial microorganisms in the soil. High carbon sequestration has become more likely with the active incorporation of biochar as an effective carrier material. Sustainable agriculture relies on the widespread adoption of biochar amendment, which biologists are working to do in a variety of agricultural systems (Layek et al. 2022). Due to its low wax content, biochar may be blended with convenience, rendering it an attractive alternative to lignite as an effective carrier of microbial inoculum in soil, as proposed by Yaashikaa et al. (2020). Biochar has been utilized as a carrier medium for a wide variety of microbial formulations, including those species containing *Acidothiobacillus*, *Bacillus*, *Burkholderia*, *Paenibacillus*, *Pseudomonas*, *Rhizobium*, and many more (Kumar et al. 2022). Since biochar can be sterilized during the pyrolysis process, it appears as an excellent choice for use in the fabrication of carrier materials. It has been observed that biochar generated from pine bark wood is an effective carrier of *Bradyrhizobium* strains that has a prolonged shelf life of 1 year, and improves the yield

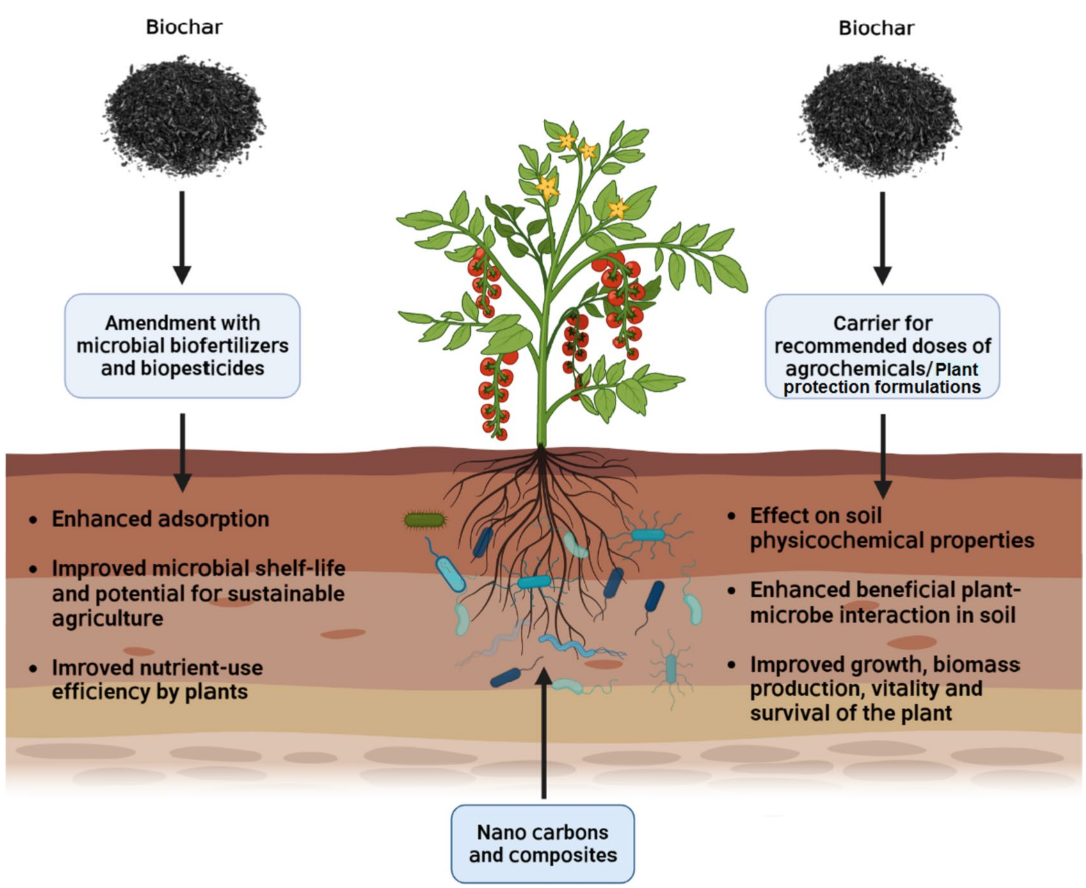

Fig. 4 Biochar as soil amendment through different pathways for improved nutrient-use efficiency in plants

performance of *Cajanus cajan* L. The addition of biochar to *Azospirillum* biofertilizer has increased its shelf life to 6 months at room temperature (Peng et al. 2021). Pinewood biochar containing *Enterobacter cloacae* UW5 has been recorded to improve soil water retention capacity and pore size, decrease bulk density, and improve prominent root architecture in cucumbers. Wheat yield and growth were found to be enhanced when biochar was used in conjunction with PGPR (Khan et al. 2021). Figure 4 illustrates different pathways of biochar amendment in soil leading to improve nutrient-use efficiency in agriculture.

In evaluating whether biochar is acceptable as a carrier medium for *Bradyrhizobium* sp., it was observed that lupin performed well under drought circumstances in terms of growth, nutrient uptake, and symbiotic performance. When a biochar-based seed coating was inoculated with *Pseudomonas libanensis*, it became apparent that the coating was advantageous in encouraging the growth of maize. Similar findings were observed after using modified acacia-based biochar as a carrier substrate for *Azospirillum lipoferum* (Ajeng et al. 2020). Biochar, according to the findings of Nepal et al. (2023) improves soil biological and functional characteristics, reduces GHG emissions, and increases carbon sequestration in soil. Biochar creates an environment to facilitate the populations of ecological balance supporting microorganisms even if it has no direct impact on the soil microbial dynamics (Gorovtsov et al. 2020; Saleem et al. 2022). Additionally, it has been reported that biochar might boost the development and survival of *Bacillus mucilaginosus*, allowing them to adsorb with biochar for agricultural sustainability. In addition, a number of research investigations focused on biochar's potential role as a transport material for beneficial fungal inoculants of tremendous agricultural potential (Ajeng et al. 2020). It has been documented that biochar has a variety of positive consequences for various kinds of fungi. The mycelial fungus can assist in the stabilization of biochar by offering structural support to the matrix found in the soil. Biochar, when used as a carrier for arbuscular mycorrhizal fungi (AMF), has been suggested as a useful soil additive for environmental remediation. Improved nitrogen cycling and resilience to abiotic stresses like drought and adverse climate have also been attributed to this synergy. According to Kochanek et al. (2022), even though biochar is a promising carrier of microbe implementation, the processes behind its effectiveness are yet unknown. It should be noted, however, that compatibility challenges connected with the use of biochar as a carrier material with microbial formulations ought to be thoroughly investigated and additional research is required to achieve the goal of biochar-mediated sustainability in agriculture.

7 Soil Microbial Community Dynamics and Biochar Functions

Rhizosphere microbiome, such as bacteria and fungus, has the potential to have a direct impact on the growth of plants (Bhattacharyya and Jha 2012; Bhattacharyya et al. 2014, 2016, 2023a). Microbial communities are, in turn, affected by biochar properties such as organic and inorganic composition and surface properties. When it comes to determining the characteristics of microorganisms, the soil food web plays an essential part. The structural and functional elements of the soil food web rely significantly on the presence of quality organic matter. Even though soil organic matter accumulates at a slower rate than other carbon cycles, it is reasonably stable for microbial degradation, facilitating soil organic matter formation. Thus, different variables, such as enhanced nutrition availability or labile organic matter content on the biochar surface, decreased competition, improved habitat suitability, and shelter possibilities, or the presence of positive priming, could explain the increase in microbial abundances in soil (Zhang et al. 2021a, b; Saleem et al. 2022; Singh et al. 2022a, b, c).

Soil nutrient cycles and plant growth may be influenced by biochar properties because of their potential to change the composition or activity of soil microbial communities (Hossain et al. 2020). Biochar could have assisted with nutrient retention by either improving it or releasing nutrients into the soil. Mineral-enriched biochar delivers enhanced nutrient recovery and CO_2 removal capabilities. Corn stover biochar incubation rates (from 0 to 14%) resulted in a considerable increase in microbial abundance (5 to 56% increases). Azeem et al. (2021) reported that using biochar produced from tea leaves as a carrier of *Bacillus cereus* improved soil microbial biomass and mung bean crop growth. Bacteria (*Devosia, Mizugakiibacter*, *Pedobacter*, *Rhodanobacter*, *Sphingomonas*), and fungi (*Amylocorticium*, *Chloridium*, *Clavulina*, *Inocybe*, *Mycofalcella*, *Rhodosporidiobolus*) biomass, as well as crop yield, were all significantly boosted after application with biochar-based biofertilizers (Li et al. 2020). It has been suggested that biochar could influence the soil microbiota through a variety of mechanisms such as changes in the availability of nutrients, shifts in the population and community dynamics of the beneficial microbiome, intense modifications to plant–microbe interactions, substrate synthesis and hyphal grazing regulation (Gorovtsov et al. 2020). Since microorganisms are less likely to seep into the soil after being adsorbed on biochar surfaces, this may boost microbial abundance and community dynamics. Because of its high surface area, biochar is able to retain a significant amount of water, which is necessary for microbial proliferation. High-temperature biochar is more effective at absorbing microbe-toxic compounds leading to providing an ideal environment for microbial enrichment (Chuchu et al. 2022). Humidity may have significant impact on microbial life and abundance. It is feasible that the microbial community experiences abiotic stress during periods of intermittent dryness. Because fungi are capable of lignin degradation in biochar more effectively than bacteria, biochar could also alter the ratio of fungi to bacteria in soil (Zhao et al. 2022). Rhizosphere microorganisms play an essential role in offering nutrients to plants and maintaining their growth by releasing nutrients from decomposing organic matter in soil (Ling et al. 2022). It is likely that uptake of nitrogen and phosphorus by plants, as well as the growth of fine roots and hair into the biochar pores, are contributing factors that may lead to significant rise in the concentration of organic nitrogen and phosphorus-mineralizing enzymes. Additionally, pH changes brought about by the use of biochar may also bring about microbial variations in the soil and environment (Yan et al. 2021).

Because of its basicity or acidity, biochar has the abilities to alter the pH of soil that substantially affects the soil microbial population dynamics (Hossain et al. 2020). Bacterial biomass carbon and ninhydrin-nitrogen were tested in soils with increasing pH values from 3.7 to 8.3 under constant conditions, demonstrating that elevated soil pH can enhance bacterial biomass carbon. Although, a higher pH has been shown to boost the bacterial population numbers while having little influence on fungal abundance. Soil pH is likewise altered by the direction, quantity, and change in soil properties, just as fertilizers and carbon levels (Yadav et al. 2020). The presence of biochar has the potential to change the composition as well as the structure of microbial communities. As a result, the trophic relationships within these communities may also undergo transformation. Zhang and Shen (2022) have observed the effects of biochar on soil microbial diversity and community structure in clay soil. Different microbial community structures and functional attributes were significantly influenced by changes in soil porosity, moisture content, nitrogen fertilizer, and potassium fertilizer other than the soil phosphate fertilizer and organic matter due to biochar amendments. Effect of biochar on soil microbial community dynamics and functional genes of a landfill cover 3 years after ecological restoration have been studied by Lu et al. (2020). Biochar-amended soil had increased concentration of organic matter, water content, total carbon, total nitrogen, and total phosphorus compared to control soil. The biochar-amended soil enriched nine microbial phyla, including the proteobacteria and acidobacteria. The usage of biochar did not result in any significant changes to the level of microbial activity; rather, differences in soil texture were found to be associated with suboptimal microbial activity. Prayogo et al. (2014) used a canonical variate analysis to examine how treatment changed the organization of microbial community structure. It was found that the first axis of canonical variate analysis explained 75.5% of the variance and the second axis explained 24.6% of the variance. This shows that post-biochar structuring variations had a positive impact on the distribution and population dynamics of beneficial microbiome.

Biochar has the potential to influence a wide variety of soil processes, including the carbon mineralization, denitrification, methane oxidation, and nutrient conversion (Chagas et al. 2022). Altering nutrition conditions including the inorganic and organic chemical sorption, alterations in water retention and infiltration characteristics and pore architecture might affect the microbial functional ecology and integrity in soil. This suggests that a wide range of factors can translate into either the physical export of carbon or shifts in pH and nutritional content (Saleem et al. 2022; Das et al. 2023). Further, nutrient mineralization may be related to labile carbon and nutrient content in the biochar (Ling et al. 2022). Soil microorganisms are propelled into action by biochar, leading to increased carbon degradation (Gorovtsov et al. 2020). Therefore, it almost never happens at the same time that fresh biochar is introduced. In addition to this, there is evidence that microbial activity can be aided by biochar in the process of nutrient transformation in soil (Yan et al. 2021). According to the findings of a study conducted by Hossain et al. (2020), biochar was found to contribute to greater nitrification in soil by binding phenolics, which would otherwise impede the process. Biochar treatment enhanced alkaline phosphatase, aminopeptidase, and N-acetylglucosaminidase activity. Plants taking in nitrogen and phosphorous may have triggered the synthesis of organic nitrogen- and phosphorus-mineralizing enzymes by growing root hairs and roots into biochar pores. Furthermore, ethylene produced from fresh biochar has the potential to lower the GHG emissions including the N_2O and CO_2 (Wang et al. 2020). After being treated with biochar, microorganisms may improve the nutrient retention capacities of soil, minimize GHG emissions, and promote the biogeochemical cycling of nutrients.

8 Biochar and Soil Nutrient Transformation

Nitrogen is lost from the soil ecosystem through processes such as leaching, denitrification, volatilization, crop removal, soil erosion, and nutrient runoff. BNF is crucial for maintaining the agricultural nitrogen cycles and it is also a major source of the natural supply of nitrogen for terrestrial ecosystems. In recent years, it has been demonstrated that biochar may alter the BNF in various leguminous plants. Increased N_2 fixation due to biochar application may be associated with the bioavailability of nutrients. Bi et al. (2022) examined the net ecological and economic benefits of biochar in reducing the load of artificial nitrogen fertilizers with organic manure in intensive vegetable production, including in common beans (*Phaseolus vulgaris* L.). They suggested that the positive result was due to the increased bioavailability of trace metals brought by biochar, such as molybdenum (Mo), a component of the nodulation-promoting Mo-Fe protein nitrogenase. Higher availability of macro- or micronutrients like Ca, magnesium (Mg), iron (Fe), or Mn is likely to be associated with biochar incorporation (Singh et al. 2022a, b, c).

Ammonification is an integral part of the nitrogen cycle in agroecosystem and plays an especially important role in organic farming. The process is driven by an array of microorganisms that are capable of denaturing proteins through enzymatic actions and removing amide groups from organic molecules (e.g., amino acids and amino sugars). Recent findings from a soil column study by Antor et al. (2022) demonstrated that the application of biochar led to an increase in the amount of net nitrogen mineralization. The use of biochar led to an increased rate of nitrogen mineralization in an organically managed lettuce field that was nearly twice as high as the control adhering to the addition of biochar. Gross nitrogen mineralization was positively correlated with the biochar H/C ratio. This indicates that high H/C biochars are more likely to decompose, releasing sufficient nitrogen into the mineral pool (Leng et al. 2019). Biochar feedstock and formation circumstances, time since application, it's capacity to absorb NH_4^+, and soil type all should be addressed when determining the scopes of biochar in influencing the soil nitrogen mineralization (Yadav et al. 2023).

Nitrogen immobilization is the process of converting inorganic nitrogen into organic nitrogen through microbial absorption and amino acid synthesis. The application of incompletely pyrolyzed biomass (fast pyrolysis at low temperature) may lead to soil nitrogen immobilization. This is due to the fact that microbial cultures would require more nitrogen that can be met by the substrate. To express this further, low-temperature biochar contains more bio-available carbon or surface functional groups that can serve as microbial substrates (Li et al. 2020). Due to its high C/N ratio, switch grass biochar can be employed in field evaluations for improved soil nitrogen immobilization and decreased total inorganic nitrogen. Furthermore, a substantial rise in cumulative and net CO_2 flux was observed, implying that biochar simulated switch grass mineralization and accelerated soil decomposition. Enhanced CO_2 evolution immediately following biochar incorporation is caused in part by the release of inorganic carbon from the biochar itself.

Denitrification and NH_3 volatilization are two primary mechanisms of gaseous nitrogen emissions. Biochar has been demonstrated to affect the N_2O flow in agricultural soil through reduction in N_2O emissions, suggesting that biochar indirectly controls soil denitrification. According to the findings of Guo et al. (2020), elevating the quantity of the bacterial N_2O reductase transcript in soil led to an increase in the amount of microbial N_2O reduction. In both in vitro and field situations, biochar application can drop soil N_2O emissions as reported by Aamer et al. (2020).

There are primarily three different processes by which biochar affects the bioavailability of phosphorus in soil (Ghodszad et al. 2021): (i) by acting as a source of available phosphorus for the soil and plants, (ii) by altering the solubility of phosphorus through changing the soil pH and the adsorption of specific chelates or formation of specific compounds, or phosphorous solubilizing bacteria, etc., and (iii) by adapting the process of phosphorus mineralization and the activity of phosphatase enzymes. By altering the soil pH and, in consequence, the strength of ionic phosphorous interactions with Al^{3+}, Fe^{3+}, and Ca^{2+}, biochar may affect phosphorous precipitation (Yang et al. 2021). Additionally, biochar might affect phosphorous precipitation by adsorbing organic molecules that usually act as chelates (such as phenolic acids, complex proteins, and carbohydrates) of metal ions that otherwise precipitate phosphorous. Increased phosphorous solubility, retention, and bioavailability can be achieved with the introduction of hydrophobic or charged biochar, which is better able to adhere to these organic molecules and form organo-biochar or organo-mineral-biochar complexes over time.

9 Biochar in Detoxification of Toxic Heavy Metals and Other Contaminants in Soil

Biochar products are used during soil remediation activities to remove heavy metals from contaminated soil by applying them at an appropriate rate and thoroughly integrating them into the contaminated soil (Guo et al. 2020). Biochar amendment stabilizes heavy metals in soil, making them less soluble and bio-accessible, in contrast to washing, leaching, and extraction processes that ultimately remove contaminated heavy metals. The overall procedure is, in a sense, analogous to chemical stabilization, in which chemicals, such as those containing phosphate and carbonate, are added to polluted soils in order to catalyze the reaction between heavy metal contamination and the chemicals, so transforming the contaminants into precipitates. Because of this, the bioavailability and ecotoxicity of heavy metals are lowered in treated soils to levels that are below the risk level, which assists in developing sustainability in agriculture. Biochar, when applied to soil, has the ability to change heavy metal ions into hydroxide ions, carbonate ions, and phosphate ions by adsorbing them on the surface of soil pores (Ibrahim et al. 2022). Reducing the bioactive, water-soluble portion of heavy metals in soil reduces the risk of heavy metal uptake and bioaccumulation by soil microorganisms and plant roots.

Because of its negatively charged surface functional groups, biochar adsorbs heavy metal cations via electrostatic attraction (Liang et al. 2021a, b). Cations are electrostatically bound to biochar particles, which maintain them in the outer sphere of the particles through adsorption activities thereby rendering them susceptible to leaching loss. Ion exchange enables heavy metal ions to be adsorbed to biochar by replacing the cations (such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and H^{+}) typically associated with the biochar surface functional groups. The specific interaction (i.e., inner-sphere adsorption) is stronger than electrostatic attraction; however, the adsorbed metal cations are readily exchanged based on the solution's pH and ionic strength.

Cationic heavy metals are stabilized in biochar through sorption and chemical precipitation mechanisms (Guo et al. 2020). In general, a lower pH and higher ionic strength can reduce the sorption of metal cations onto biochar through the process of ion exchange. This is because a lower pH will result in increased competition among cations. Heavy metal toxicity in biochar-amended soils should be checked frequently since biochar does not eliminate heavy metals, and its immobilization effect could decrease with time (Wang et al. 2020; Li et al. 2022). Biochar contains hydroxyls, carbonyls, and carboxyls, all of which are surface functional groups (Chen et al. 2019). Biochar's capacity to stabilize heavy metals via sorption-based interactions is determined by the presence of surface functional groups, reflected by CEC. Depending on the pH, these functional groups may dissociate or become protonate leading to assure biochar an electrical charge. According to the findings of Zahed et al. (2021), increasing the soil's pH through the use of biochar amendments is an effective method for lowering the level of heavy metal contamination in soil. In batch sorption experiments, it has been reported that among the biochar generated from rice straw through slow pyrolysis mechanism at various temperature ranges like 200, 400, 500, and 600 °C, the 400 °C product exhibited the highest CEC (60.65 cmolc kg^{-1}) and had the maximum sorption capacity to bind aqueous Cu^{2+}. For stabilizing soil heavy metals, precipitation is equally important as sorption activities. Biochar amendment often raises soil pH by introducing more alkalinity. Higher pH values cause cationic metals to react with the hydroxyl group of water molecules to generate metal hydroxide precipitates, which lowers the concentration of metal ions that are water-soluble (Huang et al. 2017).

10 Biochar: Mechanism of Enhancing Soil Health and Prosperity

Biochar-mediated enhancement in soil health and prosperity for mitigating the negative consequences of the climate crisis has been of major concern to soil microbiologists (Wu et al. 2023) over the last two decades. Biochar has been recognized for its ability to enhance several soil properties, including the soil organic matter, soil structure, stability of soil aggregates, the capacity of soil to retain water and nutrients, and the functional integrity of beneficial microorganisms. Consequently, these improvements contribute significantly to the plant's resilience against devastating pests and pathogens and other abiotic stressors. The principal biological components of soil can interact with biochar in a variety of physical and chemical pathways, leading to enhanced soil health and nutritional status (Gorovtsov et al. 2020). Biochar exhibits the capacity to augment soil chemistry and promote beneficial microbial communities in soil by improving the soil pH and key enzyme activities, expediting nutrient accessibility, and mitigating the negative impacts of heavy metal contaminants (Zheng et al. 2018). It has been demonstrated that biochar can enhance the activity of key soil enzymes such as phosphatases, cellulases, and proteases that were reported as essential in nutrient mineralization and the breakdown of complex organic molecules into usable forms. For instances, with the supplementation of beneficial bacteria and fungi, biochar precursor made from *Gliricidia sepium* can significantly increase the activities of catalase, dehydrogenase, and polyphenol oxidase. Hossain et al. (2020) indicated about the alterations in soil liming after the application of biochar in soil.

Water molecules penetrate the biochar pores after it has been applied to soil, causing the organic and mineral compounds on the biochar's outer and inner surface to dissolve (Joseph et al. 2021) (Fig. 5). These solutes enhance electrical conductivity and pH while decreasing redox potential in soil solutions by increasing dissolved organic carbon (DOC), cations, and anions. The process of initial rapid dissolution can occur by various mechanisms, including the dissolving of salts, ion exchange, detachment of submicrometer particles, and preferential dissolution in crystal imperfections (Wang et al. 2020). The application of biochar in the form of biochar compound fertilizer (BCF) granules leads to physical and chemical reactions during the granule production process. These reactions result in a reduced rate and extent of nitrogen compound dissolution as compared to mineral fertilizers (Shi et al. 2020). Oxygen will permeate into the biochar pores and react with redox-active organic molecules and minerals, especially Fe and Mn, with the exception of flooded soils. In acidic soil environments, an abundance of H^{+} undergoes a reaction with alkaline minerals, such as calcite and dolomite, that are found inside the carbon lattice of the applied biochar.

According to Zhang et al. (2021a, b), the incorporation of biochar into the soil increased its WHC and decreased nutrient discharge, resulting in increased plant growth and quality parameters of soil including enhanced nutrient accessibility (Hossain et al. 2020). Biochar can also affect water

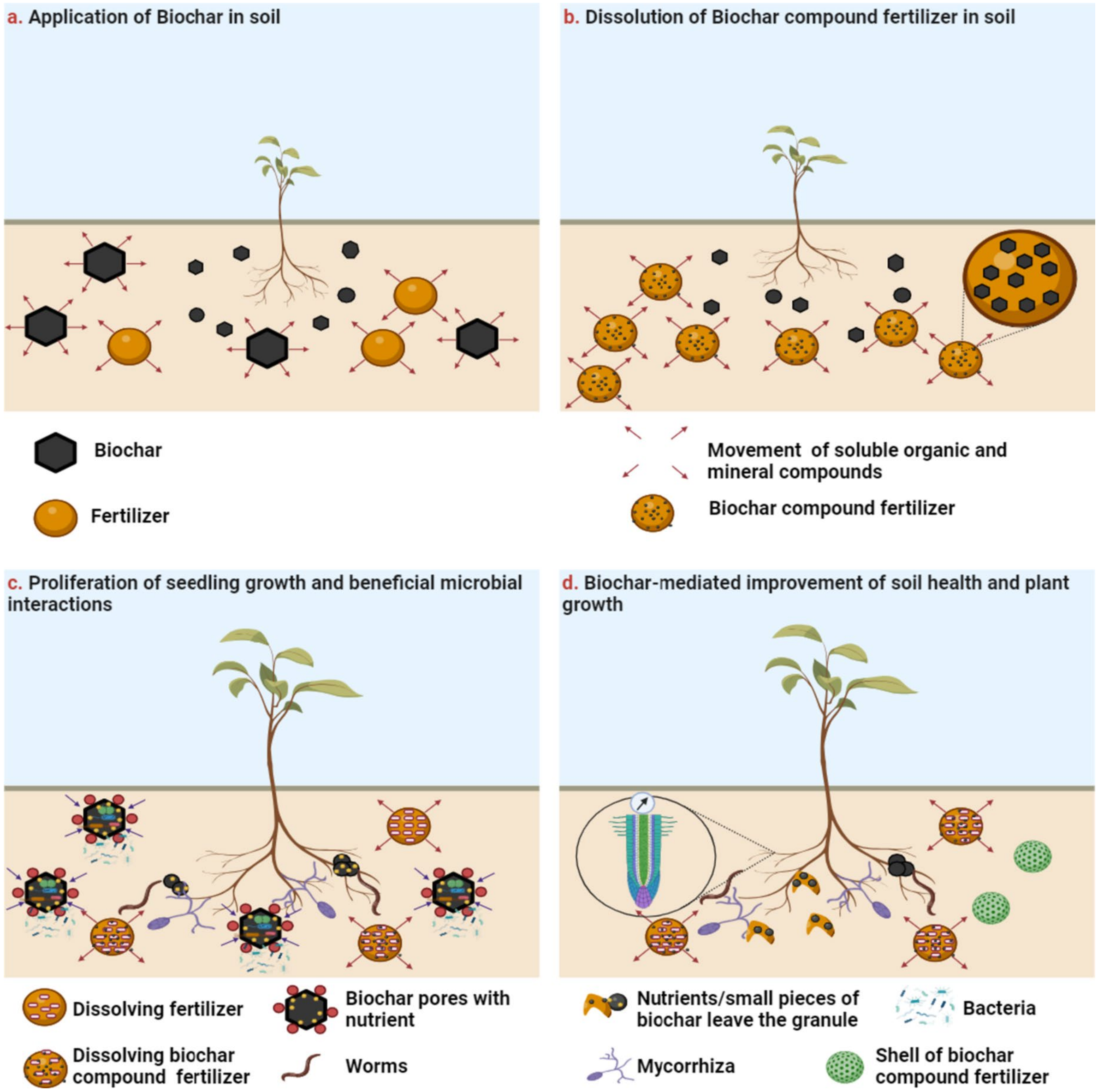

Fig. 5 Mechanism of biochar-mediated improvement in soil health. stage **a** application of biochar in soil; stage **b** dissolution of biochar compound fertilizer in soil followed by positive interactions with plant seedlings; stage **c** proliferation of seedling growth and enhancement in beneficial plant-microbe interactions; stage **d** biochar-mediated improvement of soil health and plant growth promotion

infiltrations into soils. For instance, in soils that are prone to surface sealing, it can moderate the pace at which the infiltration rate decreases during intense rainstorms. The observed results were ascribed to a rise in soil solution Ca and a decline in Na due to the presence of biochar, resulting in a reduction in the sodium adsorption ratio. Lehmann et al. (2011) suggested the application potential of biochar in acidic environments for enhancing the soil nutrient retention capacity and promoting the proliferation of beneficial microbial associations including the PGPRs and AMFs (Huang et al. 2023).

The utilization of biochar has also the potential to augment the population dynamics of nitrifying and denitrifying bacteria, leading to the improvements in essential physicochemical characteristics of soil and rhizosphere engineering (Wu et al. 2022). According to Yao et al. (2022), biochar application has the potential to increase the populations of *Nitrosomonas* and *Nitrospira* species and mostly affects the ratio of ammonium-oxidizing bacteria and archaea due to increased ammonium availability. Biochar stimulates the population of nitrifying bacteria in soil when introduced at less than 70% moisture capacity, thereby playing a significant role in increasing N_2O emission with less than 70% moisture capacity. Although biochar is capable of reducing the bulk density of soil, it is not sufficient enough to elevate the soil aeration or eliminate anaerobiosis zones under optimum humidity. Nitrate immobilization and reduced access to denitrifying bacteria may account for the lowering of N_2O emissions in this case. However, a more in-depth understanding of biochar and changes in N_2O and CO_2 emissions needs to be carried out to improve sustainability in agriculture and the environment.

Besides, biochar application has a significant impact on soil aggregate stability. Considering that these structural elements are substrates for microbial biofilms, any changes to their formation or existence in soil media have a profound impact on microbiological processes. The inherent stability of biochar's carbon structure prevents its rapid disintegration, thereby facilitating soil carbon sequestration. Zheng et al. (2018) reported that the application of biochar with corn stem precursor could increase microbial biomass by improving the soil aggregates. Additionally, it has been recorded that the use of biochar alters gene expression and chemical signalling mechanisms in soil microbial communities. According to Liang et al. (2021a, b) and Wu et al. (2023), this phenomenon has the potential to induce the upregulation of genes that are linked to the absorption and incorporation of nutrients, alongside the synthesis of bioactive chemicals that could enhance the interactions between the plants and microbes.

Furthermore, it has been investigated that biochar can detoxify the heavy metal contaminations in soil. Lu et al. (2024) reported the application suitability of biochar with *Pseudomonas* species causing the removal of Hg from contaminated lands. Alternation in superficial properties of biochar itself rather than the cell adsorption of microbes is noted as another mood of action exerted during biochar-microbe interaction in contaminated soil. In biochar-microbe interactions, the heavy metal ions are probably migrated from the soil solution into the microbial cells and then are actively pumped out after sorption on biochar by the bacteria. In order for bacteria to resist the toxicity caused due to heavy metal accumulations, the former is known for its active role in extracting toxic metal ions from their cytoplasm. When cells release CO_2 during respiration, metal precipitation may occur as carbonates, as shown in *Ralstonia* species. Kabir et al. (2023) proposed the involvement of processes such as dissolution and migration, metal precipitation, and ion exchange in enhancing the biochar microbe-mediated soil improvement and fertility, further detoxifying the metal contaminations in soil.

11 Trends in Biochar Research—A Scientometric Analysis

For the analysis of trends in biochar research, a dedicated search string is developed using the keywords, "Climate-resilient agriculture" OR "Biochar" OR "Pyrolysis" OR "Soil carbon pool" OR "Soil rehabilitation" OR "Plant–microbe interaction" OR "Agricultural sustainability" in the "All" box of the Scopus database following the study by Borgohain et al. (2022). Bibliographic information of altogether 587 papers is retrieved. Then, the analysis of co-authorship of countries, authors, and keyword co-occurrence is done. The method followed to perform this analysis is termed "enriched bibliometric technique," in which cluster analysis and network visualization are their components. For this, the state-of-the-art data mining tools VOSViewer (Van Eck and Waltman 2010) and Biblioshiny (Aria and Cucurrulo 2017) in the R-programming package are used. A set of programming codes is utilized in the R-console to get into the web interface of the Biblioshiny. These are as follows:

R-command in console	Result display
>Library (bibliometrix)	To start with biblioshiny web-interface please digit: Biblioshiny
>Biblioshiny ()	Let's to the biblioshiny web-interface through the default browser

11.1 Co-authorship of Countries

Taking a minimum number of papers affiliated to a country as 2, a network visualization map is developed using the VOSviewer tool. Of the total 99 countries that participated in this field of research, 72 countries meet this threshold of two papers. For every 72 nations, the total link strength (TLS) of the co-authorship links with other countries is calculated. The countries with the greatest total link strength are selected. USA is discovered to have a maximum of 165 papers with citations of 7119 and a TLS of 204. This was followed by India with 157 papers, 2586 citations, and a TLS of 140. Now, each circle in Supplementary Fig. 5 is termed a node and represents one country. The USA, India, and China are at the center and have close cooperation with other nations. Nodes with similar color are in a common cluster and indicate that they have been published in a common source. These are classified into nine clusters. Cluster 1 (Red) has a total of 17 countries. Some of them are Sweden, Switzerland, Netherlands, Portugal, Belgium, Finland, and Poland. Cluster 2 (Green) has 16 countries, some of them are India, China, Pakistan, Egypt, Saudi Arabia, Turkey, and Bangladesh. Cluster 3 (Blue) has 9 countries in all such as Denmark, France, Iran, Ireland, Romania, Spain, and Qatar. Cluster 4 (Yellow) has 9 countries total such as Canada, Germany, Russian Federation, Japan, and South Africa. Cluster 5 (Violet) has 5 countries such as Brazil, Chile, Columbia, Estonia, and Kenya. Cluster 6 (Shallow blue) has 5 countries like Hong Kong, Lithuania, New Zealand, Singapore, and Sri Lanka. Cluster 7 (Orange) has 5 countries in total such as Croatia, Peru, Thailand, UK, and Australia. Cluster 8 (Brown) has four countries like Argentina, Indonesia, Mexico, and Nepal. Cluster 9 (Purple) has 2 countries like Morocco and the USA (Supplementary Fig. 6). The overlay visualization map for country co-authorship (Supplementary Fig. 5) symbolizes the paper number from different countries in the period 2019 to 2022. The USA had the maximum papers in 2019 (Blue node) but with time countries like Morocco, Jordan, UAE, Argentina, and Iran have become prominent in publication count though these papers are in collaboration with prolific nations like China, India, and USA.

11.2 Keyword Co-occurrence

Taking the minimum number of keywords co-occurring to be 3, it was found that of the total 3910 keywords, 620 keywords meet this threshold. For each 620 keywords, the total strength of the co-occurrence links with other keywords is calculated. The keywords with the greatest link strength are selected. Now, these keywords with similar color represent a particular cluster with common occurrence. The total number of clusters encountered is 8. Cluster 1 (Red) has 127 keywords representing the theme "Agricultural Practice" and "Crop Production." These includes like "Agroforestry," "Agronomy," "Fertilizer Application," "Irrigation System," "Sustainability," "Soil Testing," and "Soil Quality." Cluster 2 (Green) represents the theme "Plant Growth" has keywords like "Plant Growth Promoting," "Plant Development," "Plant Leaf," "Plant Roots," "Plant Seed," "Plant Stress," "Stress Tolerance," "Signal Transduction," and "Abiotic Stress." Cluster 3 (Blue) has 90 keywords representing the theme "Biosynthesis" having the keywords like "Biofuel," "Biogas," "Carbon Fixation," "Biochemical Cycle," "Microbiology," "Soil Microbiology," and "Microbial Diversity." Cluster 4 (Yellow) with 75 keywords represents the theme "Microbial Community" with the keywords like "Microbial Activity," "Soil Microorganism," "Resilience," "Fungi," "Fungus," "Community Composition," and "Bacterium." Cluster 5 (Violet) has 69 keywords representing the theme "Soil" with keywords like "Bioremediation," "Plant," "Soil Pollutant," "Nanotechnology," "Pesticide," "Ecosystem Restoration," and "Soil Pollution." Cluster 6 (Shallow blue) represents the theme "Climate Change" and has keywords like "Climate Resilience," "Genetic Diversity," "Crop Improvement," "Crop Productivity," "Microalgae," "Plant Stress," "Plant Breeding," and "Signal Transduction." Cluster 7 (Orange) has 52 keywords in total representing the theme

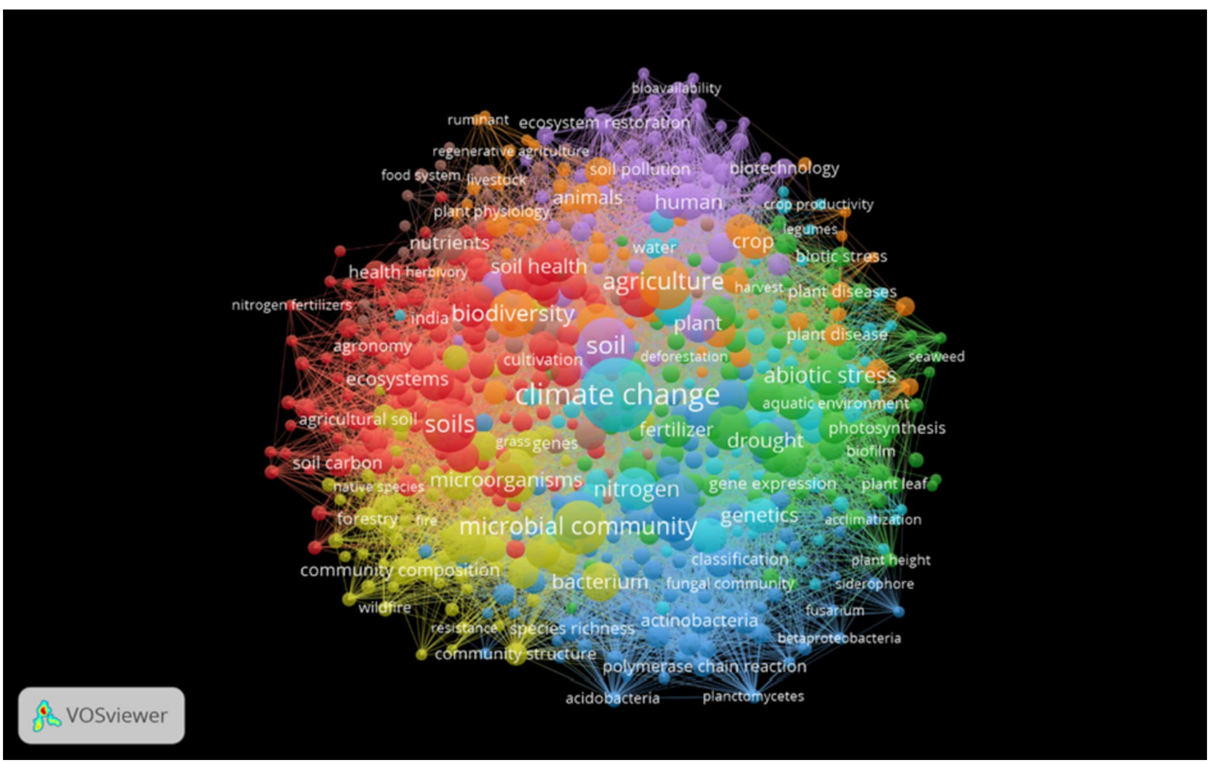

Fig. 6 Keyword co-occurrence network

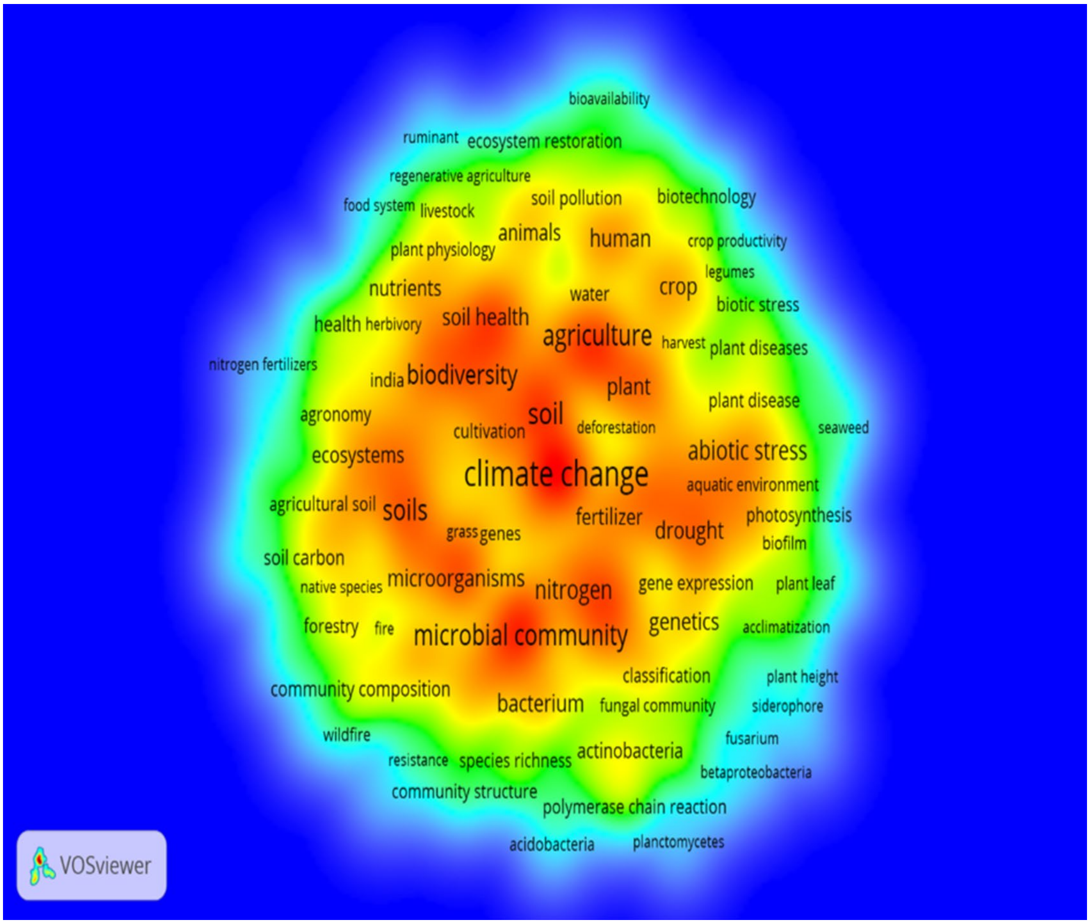

Fig. 7 Density visualization map for prominent keywords

"Agriculture" like "Biodiversity," "Ecology," "Ecosystem," "Machine Learning," "Plant Disease," "Physiology," and "Prevention and Control." Cluster 8 (Brown) with 40 keywords represents the theme "Waste Management." It has keywords like "Quality Control," "Pollutant Removal," "Waste Water Treatment," "Water Quality," "Resource Management," and "Recycling" (Fig. 6).

Figure 7 presents the density map of keywords with high frequency created with VOSviewer. The depth of the color presents a keyword, and the font of the keyword is proportional to the frequency of occurrence of the keyword. The deeper the color of the node representing a keyword, the more frequently a keyword appears. The deepest color in the center of the figure has keywords like climate change, soil, biodiversity, plant, drought, microbial community, nitrogen, and soil health. As we move outwards from the core, the frequency of occurrence of the keyword decreases like crop productivity, biotic stress, ecosystem restoration, soil carbon, and health herbivory (green). Keywords in the periphery are in the blue color like actinobacteria, nitrogen fertilizers, polymerase chain reaction, fusarium, and betaproteobacteria.

12 Ethics, Approval, and Implementation of Biochar

The International Biochar Initiative (IBI) recognized biochar as an authorized alternative to petroleum products in the North American market. The IBI certification is widely regarded as one of the most reliable certifications that consumers can use to get the goods they want. Biochar that meets the requirements of IBI is only certified by them, but not for sustainability or life cycle issues. The researchers have also identified the potential of biochar as a sustainable alternative in the development of electrochemical printed platforms.

Another certification program that is widely being used in European countries is the European Biochar Certificate (EBC). The scientists working on biochar developed EBC to meet the industrial standards of Europe. Sustainable production, low carbon footprint with minimal environmental impact, high energy efficiency, and low hazard are all assured with EBC-certified biochar products. According to the IBI and EBC, the minimum quantity of carbon should be higher than 10% and 50% of the dry mass (Chagas et al.

2022). More recently, the authorized body has also begun to certify small-scale producers with an annual production of fewer than 20 tons. In order to implement biochar certification in India, the Society of Biochar Initiatives, India, was established in January 2010 (Layek et al. 2022). Leng et al. (2019) argued that biochar certification could be considered as a trade barrier and an invaluable tool for assessing the reliability of procuring biomass feedstock for biochar synthesis. Furthermore, they argued that sustainability frameworks range from voluntary certification to legislation to ethical practice standards. Updating certification standards in recent years has assisted the startups access previously inaccessible industries. Additionally, it is an added responsibility of the certification program to address any compatibility concerns that arose throughout the implementation of the biochar, globally.

13 Future Prospects and Challenges

Biochar amendment is one of the most significant research topics that must be conducted to ensure the continued security of food commodities around the world (Leng et al. 2019). It can be used as a source of organic amendment in sustainable agriculture either directly or indirectly. By carefully controlling the feedstock and pyrolysis conditions, biochar could be used for strategic soil management programmes to improve sustainability under climate-smart agriculture (Lehmann et al. 2021; Nepal et al. 2023). Additionally, biochar is proven as a cost-effective tool in enhancing the soil fertility and sustainable crop improvement at large even for the marginal farmers, globally. In order for agriculture to effectively make use of this organic soil amendment, biochar needs to be designed and implemented in an appropriate manner using process optimization (Yaashikaa et al. 2020). In an effort to organically nurture future generations towards climate-smart agro-technologies, it is seemed to be essential to boost the global food security mechanism through biochar's successful application in combating inorganic chemicals and pesticides (Lu et al. 2020). According to Guo et al. (2020) biochar has the potential to become one of the most promising sustainable industries in agriculture, if it's mechanisms of action and other positive consequences are properly understood.

Although the adoption of biochar in global agriculture serves numerous advantages, the production costs associated with its manufacture and usage are still inconsistent. Depending on the biomass feedstock and the production technique, biochar might occasionally have negative consequences. Certain volatile chemicals that persist on the surface of biochar may significantly restrict plant growth, as reported by Lin et al. (2022). Maaz et al. (2021) observed a negative correlation between the biochar's mineralizable content and nitrogen solubilization. Thus, agricultural experts have a significant obstacle when it comes to the implementation of biochar in soil, globally. Enhanced certification and ethical criteria must be implemented to make biochar a practical and widely accepted alternative for their uses in sustainable agriculture. Efforts should, therefore, be generated to produce cost-effective biochar production systems to meet the global demands for sustainability and climate change mitigation. Additionally, there should be more enthusiasm created in favor of standard certification programs all over the world in order to give a boost to the use the organic amendments in agriculture and ensure that the entire world benefits from the steadfast implementation of this sort of technology. Future research programs must investigate pertinent concerns in order to fill the knowledge gaps, especially when conducting long-term experiments using biochar as organic and sustainable solutions for enhanced sustainability.

14 Conclusions

The implementation of biochar as a soil amendment has provided a significant boost of assurance to agriculture, the global tea industry, and marginal farmers worldwide. Though biochar is well-known for its efficacy in maintaining agricultural sustainability, more research on the action mechanisms of biochar at different soil habitats and associated microclimate for the adoption of biochar-based technology in agriculture under changing climate conditions is necessary. Biochar's performance as a carrier material for microbial inoculants in multilocational field trials has been impressive. This is due to the fact that biochar is established to boost soil health through its beneficial interactions with soil microflora and fauna, its ability to help microorganisms to fix atmospheric nitrogen, mitigate greenhouse gas emissions, improve soil physical and chemical qualities, and other such variables associated to improve agricultural sustainability. In the long run, the scientific community, planters, stack holders, and farmers need to be thirsty for a complete understanding of biochar. Studies on soil enzyme activity, the effects of implementing biochar over short- and long-term periods, the development of large-scale manufacturing processes, commercialization technologies, feedstock kinds, and environmental issues all necessitate additional attention.

Abbreviations AMF: Arbuscular mycorrhizal fungi; BCF: Biochar compound fertilizer; BNF: Biological nitrogen fixation; Corg: Soil organic carbon; CEC: Cation exchange capacity; CFU: Colony forming unit; DOC: Dissolved organic carbon; EBC: European Biochar Certificate; $K_{exchang}$: Exchangeable potassium; FYM: Farmyard manure; GHG: Greenhouse gas; HTC: Hydrothermal carbonization; IBI: International Biochar Initiative; MRLs: Maximum residue limits; MWD: Mean weight diameter; PGPR: Plant growth promoting rhizobacteria; SOM: Soil organic matter; TLS: Total link strength; N_{tot}: Total nitrogen; WHC: Water holding capacity

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Author Contribution PNB: conception and design of the research and graphical representations, data collection, analysis and interpretation of results, and writing of the original manuscript, validated, revised the final manuscript, formatted, and submission.

SPS: gathering of information and generated the data, assisted in the preparation of original manuscript.

BS: preparation of graphical representation and figures, assisted in the manuscript writing.

AKP: revised the original manuscript and data collection.

JD: gathering of information and generated the idea for original manuscript preparation.

KM: assisted in data generation and reference arrangement.

DL: assisted in the revision of the original draft.

BCN: assisted in the revision of the manuscript.

DJB: assisted in the construction of functional groups through ChemDraw.

DJB: assisted in the preparation of network visualization maps for scientometric analysis.

Data Availability The data that supports the findings of this study are available in the main manuscript and in the electronic supplementary information files. Further, the data may also be obtained from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests.

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