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Biochar-Soil-Plant interactions: A cross talk for sustainable agriculture under changing climate

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Biochars provide several agricultural and environmental benefits, such as soil health improvement, better crop growth and yield, carbon sequestration, decreasing greenhouse gas (GHGs) emissions, and regulation of nutrient dynamics. This review highlights the role of biochar in transforming the soil's physiochemical and biological properties, and their impact on improving seed germination and seedling growth, altering crop physiological attributes, enhancing crop resistance against biotic and abiotic stresses, improving crop productivity, curtailing GHGs, and controlling nutrient leaching losses. However, the type of feedstock used, pyrolysis temperature, application rate and method, soil type and crop species largely influence the biochar performance under different environmental conditions. Application of biochars at low rates help to promote seed germination and seedling growth. Biochar modified the abiotic and microbial processes in the rhizosphere and increased nutrient mineralization and enhanced the nutrient availability for plant uptake. Hence, biochar enhanced the plant resistance against diseases, reduced the availability of heavy metals and improved the plant resilience against environmental stressors. By providing a comprehensive analysis about the variable impacts of biochars on soil physicochemical properties, plant growth, development and productivity and mitigating environmental problems, this review is quite valuable for developing an efficient soil and crop specific biochar with desired functionalities. It could be helpful in improving crop productivity, ensuring food security and better management of environment. Furthermore, this review identifies the knowledge gaps and suggests future outlooks for the commercialization of biochar applications on large-scale.

KEYWORDS

agricultural sustainability, biochar, crop yield, food security, soil ameliorator, carbon sequestration

1 Introduction

Degradation of soil resulting from extensive agricultural practices and changing climatic conditions pose serious threats to global food security (Al-wabel et al., 2015). The exponentially increasing greenhouse gas (GHGs) emissions due to various anthropogenic activities are also detrimental to the environment and sustainable farming systems (Kumar et al., 2018). Additionally, the increasing world population, which is expected to reach 9.8 billion by 2050, will also put the world's agricultural system under enormous pressure (Ayaz et al., 2021). Hence to feed the burgeoning population, meet the exacerbating food demand, and mitigation of climate change impacts need benign and cost effective strategies which can improve soil health, enhance crop yield and ensure a sustainable farming system and environment (Singh R. et al., 2022). Endowed with unique attributes such as larger specific surface area (SSA), abundant surface functional groups, porous structure, better cation exchange capacity (CEC), embedded minerals, strong adsorption capacity, micronutrients, and high environmental stability, biochar has appeared as a promising material for soil management, soil fertility improvement, reduction in GHGs and environmental management (Abhishek et al., 2022).

Biochar is a carbonaceous material generated from the decomposition of various feedstocks by the pyrolysis process (slow, intermediate, fast pyrolysis, and gasification) under oxygen-restricted conditions (Rady et al., 2016). A wide array of positive impacts is associated with biochar addition, such as increased soil microbial activities, enhanced soil nutrient uptake by plants (Zornoza et al., 2016), improved soil nutrient availability (Ding et al., 2016a), and decreased nutrient leaching (Yin Y. et al., 2021). Furthermore, it improves soil aeration, porosity, bulk density, infiltration rate, aggregate stability, water holding capacity, hydraulic conductivity (Foster et al., 2016), stabilizes heavy metals, and limits their bioavailability to crops growing in hostile or poor quality soils (Gasco et al., 2016a). Biochar also promotes microbial abundance (Zheng et al., 2017) and alleviates heat, drought, and salinity stress effects on crops. It enhances crop growth and productivity (Murtaza et al., 2021a), increases biological N fixation in legumes (Osman et al., 2022), and facilitates carbon sequestration. However, the outcomes mentioned above largely depend on biochar type, the temperature at which biochar is prepared, biochar dose, and soil type.

Due to the heterogeneity of biochar and the complexity of the physio-biochemical characteristics and microbiological processes underlying its effects, biochar manifests different responses under different conditions (Downie et al., 2009; Joseph et al., 2021). Therefore it becomes crucial to elucidate the soil and plant responses against various biochars prepared under different conditions with several diverse properties, particularly under changing climates (Kavitha et al., 2018). It would help to elaborate the underlying mechanisms that govern plant responses related to biochar addition and optimization of biochar preparation method, feedstock type, dose, and method of biochar application for a specific crop grown in a particular soil type. Such optimization would render biochar commercialization on a large scale with multiple benefits such as soil health improvement, yield increase, GHG reduction, and climate change mitigation. Although a variety of recent reviews (Kavitha et al., 2018; El-Naggar et al., 2019; Sakhiya et al., 2020; Bolan et al., 2022; Abhishek et al., 2022; Amalina et al., 2022; Uday et al., 2022) have presented potential benefits of biochar applications across different fields. However, synthesis and current knowledge on biochar-soil-plant interactions is direly needed to elucidate the soil and plant responses to different biochars by considering the type of feedstock, pyrolysis temperature, and biochar application and management practices under different environmental conditions. By providing a comprehensive analysis about the variable impacts of biochars on soil physicochemical properties, plant growth, development and productivity and environmental stress mitigation, this review is quite valuable for developing a soil and crop specific biochar with desired functionalities. It could help to improve crop productivity and sustaining food security under changing climatic conditions.

2 Biochar as a soil ameliorator

Biochar's physiochemical properties can directly and indirectly affect the soil attributes. After biochar's addition to soil, its contribution to soil's physical structure may be significant, as it influences the soil aeration, water holding capacity (WHC), bulk density (BD), and distribution of pore size, porosity, and surface area of soil. Furthermore, several biological and chemical properties of soil can be altered through biochar addition (Figure 1). All these impacts of biochar are discussed in the section given below.

2.1 Effects on physical attributes of soil

Several studies described that biochar addition improves the physical attributes of soil *via* reducing bulk density, increasing porosity, and enhancing water retention and aggregation (Baiamonte et al., 2015; Ding et al., 2016b; Carvalho et al., 2020; Seitz et al., 2020). Different kinds of biochars, when added in a sufficient amount into different soils, substantially amend the various soil physical attributes (Table 1). Soil bulk density (BD) is an important indicator of soil physical condition because it indicates the arrangement and packing of soil particles (Singh et al., 2019; Bhat et al., 2022). Low soil BD enhances soil composition, decreases soil compaction, and improves WHC and nutrient release (Tang et al., 2022). Biochar application decreases both the bulk and particle densities of soils (Munoz et al., 2016). This decrease could be attributed to the lower BD ($.6\ g\ cm^{-3}$) and particle density ($1.5–2.0\ g\ cm^{-3}$) of biochars as compared to the $1.25\ g\ cm^{-3}$ BD and $2.4–2.8\ g\ cm^{-3}$ particle density of soils (Yu et al., 2019). Biochar BD varies depending upon the type of feedstock and preparation conditions. For instance, BD of wood biochar is $1.30\ g\ cm^{-3}$, woody forest residue biochar is $.09\ g\ cm^{-3}$, straw biochar is $1.30\ g\ cm^{-3}$, maize cob biochar is $.29–.36\ g\ cm^{-3}$ and rice husk biochar is $.37\ g\ cm^{-3}$ (Sun and Lu, 2014; Obia et al., 2016; Zhang et al., 2021).

The reduction in soil BD after biochar addition results in an overall increase in soil porosity (Qin et al., 2016). The increase in soil porosity is attributed to the biochar porosity (70%–90%) and further contributed by increased soil aggregation, reduced bulk density, reduction of soil packing and interaction with mineral soil particles (Blanco-Canqui, 2017). Biochar application elevates the total porosity especially the micropores because they help to form porous material (Yang C. et al., 2021). The micropores enhance the water retention, whereas macropores improve the drainage (Baiamonte et al., 2019).

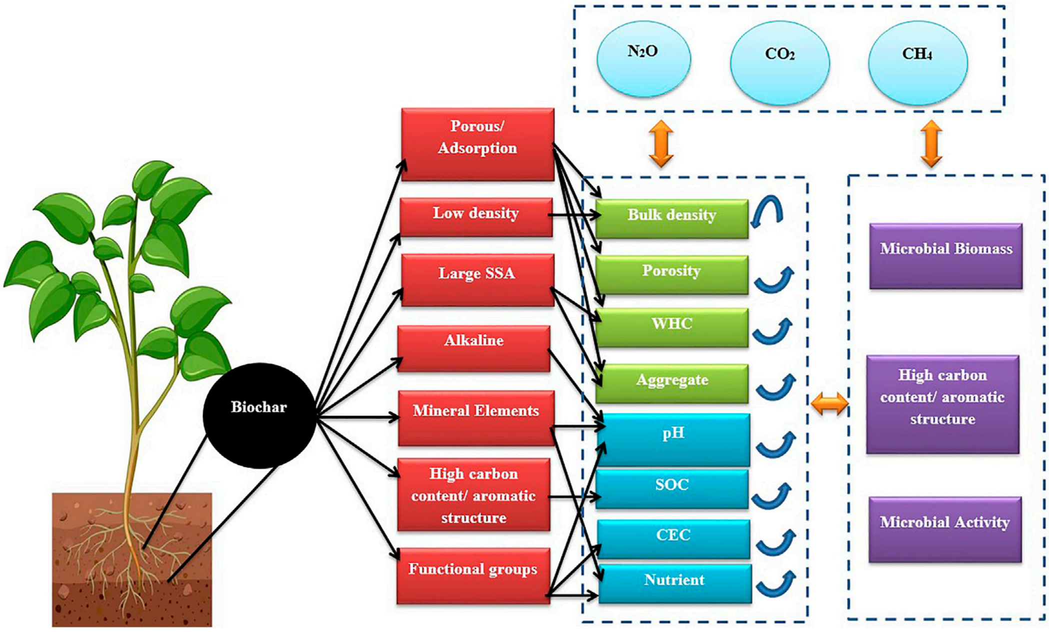

FIGURE 1
Effect of biochar application on soil physicochemical and biological properties; Carbon dioxide (CO_2), Cation exchange capacity (CEC), Nitrous oxide (N_2O), Methane (CH_4), Soil organic carbon (SOC), Specific surface area (SSA), Water holding capacity (WHC).

The soil porosity was observed to increase in the range of 5–25 μm after biochar amendment (Rasa et al., 2018). Increase in soil porosity can enhance the movement of gases, water, and heat in the soils (Yu et al., 2019). The type of feedstock used for biochar production significantly influences the soil porosity pattern (Yang Q. et al., 2021). Woody biochars contain higher porosity compared to the biochars prepared from crop residues, which causes difference in the biomass cell structure, composition, size, and shape (Edeh et al., 2020). Soil WHC is also affected by the porous structure of the biochar (Bhat et al., 2022). The high porosity and specific surface area (SSA) increase the WHC, reduce the soil water permeability resistance, and change the water flow direction and residence time in soil (Abrol et al., 2016). The improvement in soil WHC after the addition of biochar is attributed to the rise in pore space of soil and biochar mixture. This mixing resulted in increased number of water holding sites due to large number of pores which increased the WHC of soil amended with biochar (Yang C. et al., 2021).

2.2 Effects on chemical attributes of soil

Biochar application may change the soil's chemical attributes, such as increasing soil organic carbon, CEC, and pH (Abbasi and Anwar, 2015). However, alteration in soil chemical attributes by biochar application is mainly dependent upon biomass, biochar production temperature, types of soils, and biochar application rates (Table 2). It is considered that alkaline biochars (having $pH > 7$), when added to soil, elevates the pH of soil (Roberts et al., 2015). The biochar pH is largely dependent upon the type of feedstock used, and it may vary from acidic to alkaline. The biochar produced from different agricultural residues, raised the pH of soil from 4.59 to 4.86, 4.8 to 6.3, and 4.3 to 4.6 (Abhishek et al., 2022). Levesque et al. (2021) observed enhanced soil pH by 1 unit after application of *Acer saccharum*-biochar into clay soil. It was attributed due to the biochar's high ash content and pH, great liming factors contributing to enhance pH of soil. He et al. (2021) applied rice straw biochar to notice the change in the attributes of acidic paddy soil. They observed that pH buffering capacity and resistance to paddy soil acidification were efficiently improved with biochar application. Biochar application after the wet-dry cycle increased the pH of acidic paddy soil (Hafeez et al., 2021). They proposed that biochar is a dominant solution to remediate acidic soil. The basic mechanism is that the weak acid functional groups on the surface of biochar mainly appear in the form of organic anions under neutral and alkaline soils. However, under soil acidification, these organic anions protonated with H^+ and converted into neutral molecules, thus inhibiting the soil acidification and decreasing pH of soil (Wu et al., 2020).

Mostly studies focus on the effect of biochar application in acidic soils due to its potential of increasing pH (Novak et al., 2014; Edenborn et al., 2015), however discussion regarding the effect of biochar on calcareous soils is very limited (Zhang D. et al., 2015). This could be attributed to the buffering capacity of the calcareous soils resisting the alkaline effects of biochar (Usman et al., 2016; Al-Wabel et al., 2017).

CEC is an indirect measure of soil capacity to retain nutrients and water (Alkharabsheh et al., 2021). The biochar CEC is determined as the number of cations adsorbed on the surface of biochar (Zhang et al., 2021). Feedstock material, pyrolysis temperature, and functional groups are the key factors that govern the biochar CEC (Murtaza et al., 2021b). The CEC of biochars reduces with the elevation of pyrolysis temperature owing to the loss of functional negatively charged groups and low pyrolysis temperature (300°C–450°C)

TABLE 1 Effect of biochar addition on the soil physical attributes.

Biochar type	Pyrolysis temperature °C	Treatment	Soil water holding capacity	Aggregate stability	Hydraulic conductivity (ms^{-1})	Bulk density (g cm^{-3})	Soil porosity %	References
Oak wood	650	Control soil	—	1.70	—	1.70	—	Mukherjee et al., 2014
		Treated soil	—	1.40	—	1.30	—	
Hardwood	400	Control soil	1.73	—	—	.95	—	Case et al. (2012)
		Treated soil	1.69	—	—	.87	—	
Birch	400	Control soil	0.49	—	—	1.30	50.90	Karhu et al. (2011)
		Treated soil	0.54	—	—	1.25	52.80	
Agricultural residue	450	Control soil	0.11	—	—	1.65	46	Jones et al. (2010)
		Treated soil	0.16	—	—	1.55	48	
Oat husk	500	Control soil	—	—	6.9×10^{-5}	1.70	—	Lim et al. (2016)
		Treated soil	—	—	8.4×10^{-6}	1.05	—	
Rice husk	600	Control soil	—	—	1.7×10^{-7}	1.29	49	Pratwi and Shinogi, (2016)
		Treated soil	—	—	6.4×10^{-7}	1.13	56	
Peanut hull	500	Control soil	—	—	8.2×10^{-5}	1.33	50	Githinji, 2014
		Treated soil	—	—	03×10^{-5}	.36	78	
Maize straw	350	Control soil	0.25	2.78	2.8×10^{-5}	1.05	13	Herath et al. (2013)
		Treated soil	0.26	2.88	3.7×10^{-5}	.95	10	
Corn straw	550	Control soil	0.25	2.78	2.8×10^{-5}	1.05	13	Herath et al. (2013)
		Treated soil	0.26	3.10	6.7×10^{-5}	.94	19	
Pine chips	500	Control soil	—	-	6.9×10^{-5}	1.70	—	Lim et al. (2016)
		Treated soil	—	-	9.9×10^{-6}	1	—	
Corn straw	500	Control soil	—	.30	3.09×10^{-5}	1.26	—	Igalavithana et al. (2017)
		Treated soil	—	.37	1.65×10^{-6}	1.24	—	
Coconut shell	800	Control soil	2.34	—	—	1.29	10	Liu et al. (2018)
		Treated soil	3.71	—	—	2.14	23	
Rice hull	450	Control soil	1.86	.21	—	—	—	Wang et al. (2021a)
		Treated soil	1.97	.64	—	—	—	
Reed straw	300 and 500	Control soil	—	22.1	—	2.14	29	Liu et al. (2020b)
		Treated soil	—	177	—	6.36	39	

(Palansooriya et al., 2019). Sufficient availability of O_2-containing functional groups on the surface of biochar leads to anionic surface charge, which increases the CEC of soil after biochar application (Lu et al., 2022). Biochar application significantly increased the CEC by 3%–40% compared to control soil (Laird et al., 2010). Similarly, the CEC of extensively weathered soil was enhanced from 7 to 11 c mol kg^{-1} after applying biochar from the tamarind plant (Jien and Wang, 2013; Wang et al., 2022). Fang et al. (2016) reported that the CEC of corn straw biochar produced at 450°C was 26.36 c mol kg^{-1} and decreased to 10.28 c mol kg^{-1} at 700°C. Munera-Echeverri et al. (2018) revealed that the CEC was low until the temperature surpassed 420°C due to the nutrient content in the feedstock changed with temperature. Abhishek et al. (2022) presented that the high CEC facilitated the heavy metals removal from the polluted soil.

Soil organic matter (SOM) is a crucial factor affecting the soil health (Battaglia et al., 2021). The biochar amount and stability used as a soil improvement play a key role in enhancing the SOM (Alkharabsheh et al., 2021). Adding biochars derived from silver grass, umbrella tree, rice straw, and crop residues caused an increase of SOM content by 42%–72% in sandy soils and 32%–48% in loam soils (El-Naggar et al., 2018). In another investigation (2 years) Adekiya et al. (2020) found that application of hardwood biochar at the rate of 30 Mg t ha^{-1} increased the SOM content by 77, 18, and 9% compared to control (un-amended soil), 10 and 20 Mg t ha^{-1} biochar

TABLE 2 Effect of biochar addition on the soil chemical attributes (% change compared to control).

Biochar type	Pyrolysis temperature °C	Biochar pH	Soil type	Soil pH	Experiment type	Addition rate	pH	CEC	SOC	Available N	Available P	Available K	Total P	Total K	Total N	References
Swine manure	400	10.9	Clay loam	6.7	Microcosm incubation	.5%	4.4	18.7	12.2	—	317	20	24	—	13	Jin et al. (2016)
						1.5%	7.4	48.3	15.9	—	577	111	82	—	27	
Sewage sludge	500	8.7	Loamy	8.4	Pot	1%	.57	-	186	—	563	39	—	—	148	Yue et al. (2017)
						5%	2.16	-	577	—	1567	114	—	—	709	
Swine manure	400	8.7	Silt loam	5.3	Microcosm incubation	.5%	3.7	-	14.8	—	264	21	20	—	9.60	Jin et al. (2016)
						1.5%	11.3	-	17.2	—	798	153	81	—	68	
Pine chip	400	7.5	Loamy sand	5.5	Field	11 Mg ha^{-1}	1.6	—	—	19.9	—	—	—	—	—	Gaskin et al. (2010)
						22 Mg ha^{-1}	1.1	—	—	17	29	15.4	—	—	—	
Sewage sludge	500	10.9	Loamy	8.4	Pot experiment	10%	3.6	-	1122	—	2150	198	—	—	1409	Yue et al. (2017)
						20%	7.6	-	2067	—	2741	358	—	—	2582	
Wheat straw	450	10.40	Inceptisol	8.5	Field experiment	20 t ha^{-1}	—	—	48	—	22.6	-	—	—	—	Zhang et al. (2015a)
						40 t ha^{-1}	—	—	102	—	45	-	—	—	—	
Peanut shell	400	10.12	Loamy sand	5.59	Field	11 Mg ha^{-1}	—	—	—	—	2.4	38.8	—	—	88	Gaskin et al. (2010)
						22 Mg ha^{-1}	3.90	—	—	—	23	76	—	—	162	
Hardwood	550	8.4	Sand	5.90	Pot experiment	15 g kg^{-1}	—	—	—	—	—	—	—	14.1	8.3	Borchard et al. (2014)
Conocarpus	400	9.8	Sandy	8.41	Greenhouse	40 g kg^{-1}	—	—	248	—	—	36.2	—	—	—	Usman et al. (2016)
						80 g kg^{-1}	—	—	349	—	—	63	—	—	—	
Hardwood	550	8.4	Silt	6.3	Pot	15 g kg^{-1}	—	—	—	—	—	—	-	20.2	6.90	Borchard et al. (2014)
Apple tree	550	9.82	Acidic	5.50	Pot experiment	80 g	9.40	—	—	—	—	—	2.21	—	20.21	Gao et al. (2017)
Coconut shell	800	10.55	Acidic	5.62	Field study	2.5% and 5%	7.12	44.4	—	—	—	—	4.7	—	—	Liu et al. (2018)
Hardwood	500, 550 and 600	—	Sandy	7.38	Pot study	1% w/w	7.58	—	22.87	—	—	—	—	—	—	Wu et al. (2019)
Rice hull	450	10.28	Contaminated soil	8.56	Pot experiment	3%	7.9	3.6	—	—	4.61	261.47	—	—	—	Wang et al. (2021a)
Rice husk	—	—	Sandy	8.3	Pot culture experiment	3%	8.5	4.17	75.21	—	4.89	231.98	—	—	—	Wang et al. (2021b)

addition.

TABLE 3 Effects of biochar addition on soil biological attributes.

Biochar type	Pyrolysis temperature °C	Soil type	Biochar application rate	Target soil property	Effect of biochar application	Experiment type	References
Insignis pine	600	Loamy soil	12 Mg ha^{-1} and 50 Mg ha^{-1}	Soil fauna	Decreased feeding activity of soil fauna	Field study	Marks et al. (2016)
Corn straw	400	Acidic soil	2, 4% and 8%	Enzymatic activity	Decreased the acid of soil	Laboratory	Zhai et al. (2015)
					Increased the P activity		
Eucalyptus deglupta	350	Acidic clay loam	30, 60, and 90 g kg^{-1}	Mycorrhizae	No changes in the number of spores and root colonization	Glass house	Rondon et al. (2007)
Bamboo and woodchip	700 and 600	Clay loam and loam	.1, 1, 2, and 5%	Enzymatic activity	Increased the urase activity	Laboratory and pot experiment	Ouyang et al. (2014)
					Enhanced P activity and accelerate the soil enzymatic action		
Corn residue	600	Silt loam	3 Mg ha^{-1}, 12 Mg $ha^{-1}$and 50 Mg ha^{-1}	Soil fauna	No impact on rate of feeding	Field study	Domene et al. (2014)
Acacia mangium	400	Acidic	10 L m^{-2}	Mycorrhizae	Improved colonization rate and amount of root	Field study	Yamato et al. (2006)
Poultry manure	400	Sand	22 Mg ha^{-1}, 45 Mg $ha^{-1}$and 90 Mg ha^{-1}	Soil fauna	Earthworm weight and mortality loss	Mesocosm	Liesch et al. (2014)
Rice straw	600	Sand	1% (w/w)	Microbial activity	Enhanced relative abundance of Proteobacteria and their associated genera in soil	Field study	Zou et al. (2018)
Coconut shell	800	Acidic soil	2.5% and 5%	Soil enzymatic and microbial activity	Fungal, bacteria, *actinomyces* counts, acid phosphatase, dehydrogenase, and urease while invertase was not affected	Field study	Liu et al. (2018)
Hardwood	500, 550 and 600	Contaminated soil	1% w/w	Microbial community	Relative abundance of Proteobacteria, Bacteroidetes, and Actinobacteria increased, whereas the abundance of Acidobacteria and Germmatimonadetes decreased	Pot study	Wu et al. (2019)

TABLE 4 Impacts of biochar addition on plant growth, development and crop productivity.

Biochar	Application rate	Culture system	Crop	Effects	References
Rose and teak wood	16 t ha^{-1}	Open field	Rice	Improved the saturated hydraulic conductivity of the top soil and the xylem sap flow. Higher grain yields with low P availability and improved the response to N and NP chemical fertilizer treatments	Kochanek et al. (2022)
Peanut hull	0–200 t ha^{-1}	Pots	Quinoa	Biochar application increased growth, crop production drought tolerance, leaf-N and water use efficiency. Decreased proline and chlorophyll levels. The large application rate of 200 t ha^{-1} biochar did not improve plant growth compared to 100 t ha^{-1}	Zhang et al. (2022)
Wheat straw	0–40 t ha^{-1}	Open field	Maize	Maize yield was increased by 15.8% and 7.3% without N fertilization, and by 8.8% and 12.1% with N fertilization under biochar amendment at 20 t ha^{-1} and 40 t ha^{-1}. Application of biochar to calcareous and infertile dry croplands poor in soil organic carbon will enhance crop productivity and reduce GHGs emissions	Rondon-Quintana et al. (2022)
Citrus wood	1%–5% (w/w)	Pots	Tomato and pepper	No differences between control and treatments in leaf nutrient content. Nor did biochar affect the field capacity of the soilless mixture	Kader et al. (2022)
olive stone, almond shell, wheat straw, pine wood chips, and olive-tree pruning	.5%–7.5% (w/w)	Greenhouse (pots)	Sunflower	Type and rate of biochar-application rate had significant effects on sunflower seed germination, improved soil properties and increase crop production	Kimura et al. (2022)
Poultry waste	0%–1% (w/w)	Greenhouse (pots)	*Brassica* *Campestris* L	Reducing the metals (Pb and Cd) uptake as well as improving growth promoter. Improve the soil physical and chemical conditions. Photosynthetic and accessory pigments production is increased	Awasthi et al. (2020)
Hardwood and woodchips	8 t ha^{-1}	Open field	Grape	Application of higher amounts of biochar has no effect on plant growth parameters of vine or vine health. No significant difference between the treatments for grape quality parameters like tartric, malic, gluconic, volatile and total acids, glycerin glucose to fructose ratio, and ammonium	Sangeetha et al. (2022)
Coconut shell	0%–15% (w/w)	Greenhouse	Willow	Biomass production increased whereas the plant Cd and Zn contents remained unchanged. Biochar Application decreased leaching Cd and Zn from the soil	Timmis and Ramos (2021)
Acacia waste	5 Kg $tree^{-1}$	Open field	Apple	Plant water status, photosynthetic capacity, Stomatal conductance (gs) and leaf N, leaf micro-nutrients were not influenced by biochar treatment. The study has demonstrated that the positive impacts of biochar on tree responses can potentially be maximized by the addition of organic fertilizer in the form of compost	Molina et al. (2022)
Green waste	0%–5% (w/w)	Greenhouse (pots)	Wheat	Growth and yield of wheat were increased particularly under high salinity level by biochar Application. Positive effect on Photosynthetic rate, stomatal conductance. Stomatal density Chlorophyll content index and total leaf nitrogen Content. Leaf Na^+ and K^+ concentrations and Na^+/K^+ ratio were significantly affected by biochar	Kochanek et al. (2022)
Softwood and hardwood	0%–15% (w/w)	Greenhouse (pots)	Potato	Biochar was capable to ameliorate salinity stress by adsorbing Na^+. Plant growth, tuber yield, and midday leaf water potential were increased whereas ABA concentration in the leaf and xylem sap was decreased	Akhtar et al. (2015b)

(Continued on following page)

TABLE 4 (*Continued*) **Impacts of biochar addition on plant growth, development and crop productivity.**

Biochar	Application rate	Culture system	Crop	Effects	References
Pine wood and cotton stalk	5 and 30 t ha^{-1}	Open field	Maize and cotton	Higher leaf water content, chlorophyll stability index and seed cotton yield while leaf accumulated proline was decreased under biochar application. One year of biochar amendment did had a significant effect on biomass of the soil biota groups	Pressler et al. (2017)
Corn cob	0–20 t ha^{-1}	Pots	Soybean	Applied 20 t ha^{-1} of biochar increased significantly seed vigor, germination percentage, shoot length, membrane stability index, chlorophyll and carotenoid contents of soybean seedlings compared to control. Sugar and proline contents decreased while protein content and rate of seed germination remained unaffected	Gomez et al. (2022)
Poultry manure	0%–15% (w/w)	Greenhouse	Sunflower	Fertilization with poultry litter biochar of 400 g/pot, increased soil salinity and reduced the growth and production components of sunflower	Pankaj and Pandey (2022)

Application of straw biochar and rapeseed stalk biochar also improved the SOM content in a red soil (Yang and Lu, 2020).

Amending soils with biochar also improves the soil organic carbon (SOC) content (Alkharabsheh et al., 2021). However, such increases in SOC are largely dependent on type of feedstock, pyrolysis temperature and soil types (Al-Wabel et al., 2017). Generally, biochars prepared at low pyrolysis temperatures contain a higher labile C compared to biochars fabricated at high pyrolysis temperature (Lévesque et al., 2018). Yin et al. (2014) in an incubation study observed a higher accumulation of SOC with rice-straw biochar prepared at 250°C than biochar generated at 350°C. This could happen due to the contribution of partially pyrolyzed portion of the biomass in biochar (produced at low temperature) to SOC. Furthermore, high temperature treated biochars carry large content of fixed carbon (aromatic C-C bonds) making biochar more stable, whereas low temperature biochars contain more labile substrates (C-H bonds) (Cardinael et al., 2017). Biochar enhances the SOC either by decomposition *via* soil microbes or through preservation of existing natural SOC (Al-webal et al., 2017). Overall, the effect of biochar addition on soil chemical properties is solely depend upon the type of feedstock, pyrolysis temperature, soil types and biochar application rates. Therefore, to get maximum benefit from biochar amendment, special attention should be paid to the biochar production conditions.

2.3 Effects on soil biological attributes

Biochar applications not only amend the soil physiochemical attributes but also alter soil biological attributes (Table 3) (Manirakiza et al., 2021). Biochar application affects the activity and community structure of soil microbes due to its large SSA, pore space, functional groups, surface volatile organic compounds, minerals and porosity (Gao and Deluca, 2016; Zhu et al., 2017). These alterations could modify the soil structure, reduce nutrient leaching, increase the nutrient cycles, form labile carbon compounds for microbial growth, increase aggregation, enhance nutrient immobilization and retention, and accelerate the plant growth mechanism (Murtaza et al., 2021a; Xu et al., 2021). Biochar particles and pores provide a habitat for the intrusion of filamentous microbes and fungi (Yin D. et al., 2021). Biochars, rich in sugars and yeasts, promote the growth of bacteria (Gram-negative) and fungi (Kocsis et al., 2022). Biochar alkalinity may stimulate the growth of Gram-negative and Gram-positive bacteria (Zimmermann et al., 2012; Osman et al., 2022). Sun et al. (2012) observed the bacterial populations were more dynamic and active in biochar-treated soil than fungal populations under field conditions; this may be attributed to the biochar's higher surface area and biochar carbon (Liu et al., 2022). Moreover, pyrolysis temperature, biomass type, and carbon content strongly influence dehydrogenase activity, microbial habitats, N immobilization and mineralization (Ameloot et al., 2015).

The high SSA and porous nature of biochar serve as favourable habitats for diverse soil microbes (Ye et al., 2017). The porosity and SSA of biochar largely depend on feedstock type and pyrolysis temperature, high temperatures result in higher porosity and SSA (Palansooriya et al., 2019). The microbes become attached to the biochar micropores by electrostatic forces, hydrophobic attraction, or the precipitate formation, thus resist leaching, and increase their abundance (Abhishek et al., 2022) Moreover, soluble substances such as water, alcohol, sugars, acids and ketone molecules present

TABLE 5 Effect of biochar application on seed germination and seedling growth under different soils.

Biochar type	Pyrolysis condition °C	Biochar pH	Application rate	Soil type	Effect of biochar on seed germination	Reason of effect on seed germination	References
Rice husk	500	7.9	1, 2% and 5% w/w	Karst calcareous soils	Biochar treatment significantly increased the *Robinia pseudoacacia* L. seed germination rate on day 3	Increase in soil capillary water holding capacity and non-capillary porosity after biochar application suggested an improvement of soil effective moisture and soil aeration	Bu et al. (2020)
woodchip	500	8.4	2% w/w	Karst calcareous soils	Seed germination rate in biochar-treated soils reached 100% on day 7, 2 days faster than control treatment	Improved soil capillary water holding capacity, in conjunction with increased soil available P	Bu et al. (2020)
Castor	550	8.7	1% and 5% w/w	Sandy	Biochar amendment in castor resulted in faster germination rates when compared to control soil	May potentially lead to summer drought-escape and advancement of harvesting time in castor plants	Hilioti et al. (2017)
Wheat	500	8.9	1% and 2% w/w	Saline soil	Improved the wheat seed germination under salinity	Biochar amendment eliminates the negative impacts of stress by lowering the activity of superoxide dismutase	Jiang et al. (2022)
Rice straw	300	-	1%	-	Rice straw biochar solutions with a high concentration restrained the germination of rice and tomato seed, found that high amount of carbonaceous material suppressed plant seed germination	Increase in soil capillary water holding capacity	Zhang et al. (2019)
Pine chips	350	5.74	1%	Coxville	Decreased germination and early seedling growth	Inhibitory effects of biochar were caused not only by phenolic compounds on its surface, but also by the blocking effect on epidermal openings resulting in a reduced transfer of nutrients and water	Olszyk et al. (2018)
Woodchips	550	6.89	5 t ha^{-1}	Farming soil	Effects on seedling radicle extension growth were more pronounced (*Picea mariana*, *Pinus resinosa*, and *Betula papyrifera*)	likely mechanisms involve “priming” effects resulting from increased pH and potassium availability or sorption of germination-inhibiting phenolics in the litter layer	Thomas. (2021)
Corn cob	350	7.10	.5, 1, 1.5, 2, 2.5, and 3% w/w	-	Increasing corn-cob application rate have neutral to positive effects on seed germination and seedling growth of maize, improved germination rate by 3% than control treatment	High nutrient retention and water holding capacity	Ali et al. (2021)
Walnut shells	550	8.25	10, 20, 40, 80, and 120 Mg ha^{-1}	-	Significantly higher germination rate and growth indices observed with the 40 and 80 Mg ha^{-1} biochar rates, respectively. Biochar application generally increased seed germination at rates ≤40 Mg ha^{-1} and seedling growth indices at rates ≤80 Mg ha^{-1}	Biochar application to soil increases some soil properties such as pH, water holding capacity (WHC), soil organic carbon (SOC), and contributes to soil nutrient retention	Uslu et al. (2020)
Raintree	-	-	15 t ha^{-1}	Agricultural soil	Germination percentage of paddy increased in case of Raintree biochar was above the control level but the difference was not significant	A significant effect of treatments was found on soil potassium, phosphorus and nitrogen	Shamim et al. (2018)
Corncob	450	7.1	10 and 20 t ha^{-1}	Agricultural soil	Under water stress seed vigor and Soybean germination percentage decreased significantly compared to control	This could be due to the disruption of various metabolic and physiological processes in the cell such as disruption in ion uptake	Hafeez et al. (2017)
Moss	400	8.6	1.17%	-	Positive effect of biochar on *Betula platyphylla* seedling growth was observed. Biochar addition significantly increased seedling height	biochar increased the soil water holding capacity, reduced the water loss rate	Xinghui et al. (2020)
Green waste	350	-	3, 5% and 10%	Agricultural soil	Recorded highest germination percentage (94%) of *Vigna mungo*	Biochar increased water availability surrounding the seed, resulting in more favourable seedling environments	Parvin et al. (2022)

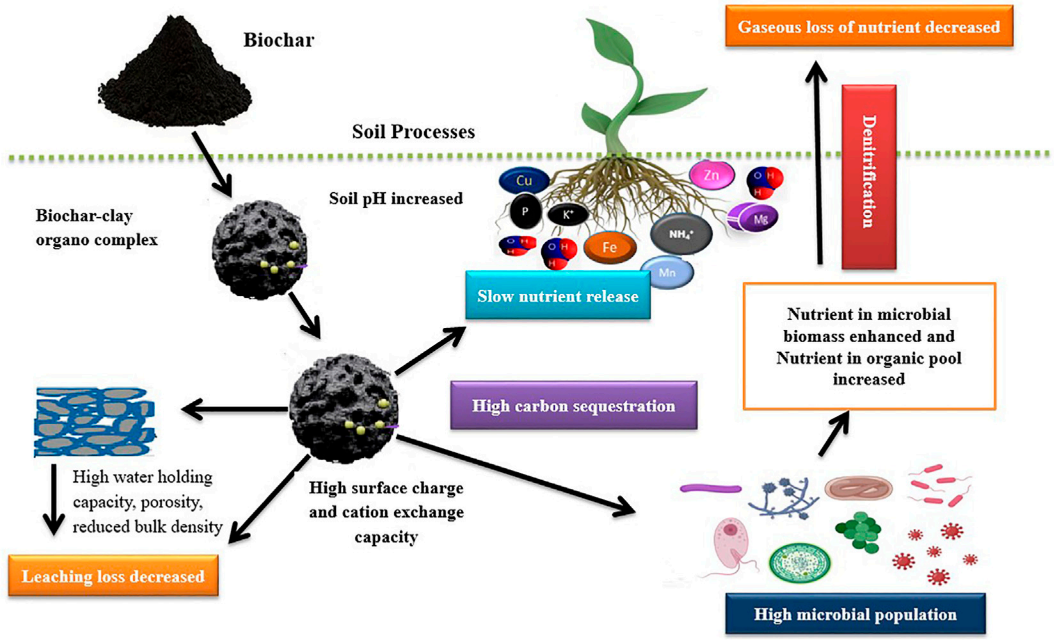

FIGURE 2
Biochar induced modifications in soil properties and its impact on plant growth and development; Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Phosphorus (P), Potassium (K), Ammonium (NH_4), Zinc (Zn).

in micropores and mesopores of biochar alter the microbial composition and abundance in soils (Adnan et al., 2020). An increment in the microbial activity and population of filamentous fungi, *Bacillus* species and *Pseudomonas* species have been observed with biochar addition in pepper cultivated soils. An application of maize stalk biochar at the rate of 50, 100, and 200 Mg ha^{-1} resulted in a 6.6%–31.2% higher fungal abundance compared to un-amended soil (Yao et al., 2017). In another study, Karimi et al. (2020) reported 20%–124% increase in soil microbial biomass in a calcareous soil supplemented with corn residue biochar at 1% and 2% (w/w) compared to control. Domene et al. (2014) found that the microbial abundance could enhance from 366 μgCg^{-1} (control soil) to 730 μgCg^{-1} (biochar treated soil). Also, microbial abundance was increased by (5%–50%) with the increase in biochar application rate (from 0%–14%) for various incubation times. Jin et al. (2016) found that litter-derived biochar enhanced the activity of phosphomonoesterase and decreased the activity level of acid phosphomonoesterase in silt loam and clay loam soils, respectively. An elevation in N and P retention in soil was noted due to change in microbial community structure and increased microbial activity in response of biochar application (Palansooriya et al., 2020). Biochar also found to play a crucial role in biological N fixation in legume crops by regulating different mechanisms including, increasing nodule formation, immobilizing N, enhancing P supply and altering the soil pH (Mia et al., 2014; Semida et al., 2015; Partey et al., 2016; Semida et al., 2019). Most probably, changes in resources (C and nutrients), physico-chemical factors, water availability or access to habitat may accelerate the competition among soil microbial communities which causes an alteration in community structure and composition (Semida et al., 2019).

Despite having the positive role of soil microbes in the soil, various soil pathogens can negatively impact the crop growth in the form of diseases (Bass et al., 2019). Biochar showed substantial potential to rectify the problems created by the soil pathogens. Jaiswal et al. (2018) reported that biochar can deactivate and immobilize the enzymes involved in cell wall deterioration and detoxified the metabolites produced by *Fusarium oxysporum* f. sp. *radicis lycopersici* and, protected the crop plants against soil pathogens. In another investigation, Gao et al. (2019) reported that the soil of tomato plants infected with *Ralstonia solanacearum* bacteria was improved with wheat straw biochar and severity of bacterial wilt was reduced with increase in total C, N, C:N ratio, K, P, pH and electrical conductivity. Biochars can potentially inhibit pathogenicity in plants by improving resistance, enhancing nutrient content, and detoxifying and adsorbing harmful chemicals in the polluted soils (Schmidt et al., 2021; Tan et al., 2022).

Biochar's effects on enzymatic activity in soils depend on the nature of the substrate-enzyme interfaces in the presence of biochar, which are linked with biochar surface area and porosity (Bailey et al., 2011). Biochar with higher porosity and surface area would most likely decrease the extracellular enzymatic activity, given that the functional groups on the biochar would tend to bind the enzymes and substrates and therefore interfere with substrate diffusion on the active sites of the enzyme (Osman et al., 2022). Biochar treatment has both positive and negative effects on soil enzymatic activity. These impacts depend on biochar application rate and soil type (Table 3). Soil enzymes indicate the soil quality because they are directly related to soil microbial activity and biogeochemical cycling of nutrients (Palansooriya et al., 2019). For instance, increase in dehydrogenase activity was observed in different soils amended with different types of biochars (Bhaduri et al., 2016; Irfan et al., 2019). Such increase in dehydrogenase activity could be attributed to the labile organic matter and a high content of volatile matter of biochars (Gasco et al., 2016b). An increase in the activity of extracellular enzymes (β-glucosidase,

TABLE 6 Effect of biochar application on soil and plant physiological attributes.

Feedstock	Pyrolysis temperature °C	Application rate	Soil; plant	Effects on the soil–plant system	References
Poultry manure	300–350	0–100 t ha^{-1}	Sandy loam; Soybean	Drought tolerance; increased plant height (3.3%–4.03%), relative water content (4.35%–4.92%), chlorophyll content (7.25%–17%), proline accumulation (22.58%–38.7%)	Mannan et al. (2017)
Cotton residues	350–450	0–4 t ha^{-1}	Sandy loam; Corn	Improved relative water content (~25%), photosynthetic pigments (20%–60%), antioxidant activity (15%–59%); increased root length (~50%), root dry weight (>100%), shoot length (~25%), shoot dry weight (>50%)	Sattar et al. (2019)
Rice straw	450–550	0%–5%	Sandy loam; Wheat	Augmented plant growth (35%–52%), chlorophyll content (58%–63%), gas exchange (40%–85%); decreased metal concentrations (37%–42%), oxidative stress (14%–36%)	Abbas et al. (2018)
Hardwood and coniferous wood	750	0%–2.5%	Sandy loam; Reed	Increased plant weight (42%–70%), stomatal conductance (from .04 to .17 mol H2O m^{-2}.s^{-1}), transpiration rate (from 2.92 to 2.99 mmol H2O.m^{-2}.s^{-1}), and water use efficiency (~5%); increased soil pH (from 7.7 to 8.2), WHC (from 21% to 38%)	Abideen et al. (2020)
Rice husk	700	0–20 t ha^{-1}	Clay; Corn	Enhanced chlorophyll content (20%–35%), relative water content (~25%), plant height (~10%), cob length (~25%), grain yield (>100%); decreased flowering time (~8 days reduced), proline content (>50%)	Mannan and Shashi (2020)
Wheat straw	500	0–37.18 g kg^{-1}	Clayey loam; Wheat	Improved spike length (6.52%), thousand-grain weight (6.42%), grains per spike (3.07%), biological (9.43%) and economic yield (13.92%); increase water use efficiency (~20%), chlorophyll content (75%–100%)	Haider et al. (2020)
Woodchips	550–600	0%–3%	Sandy soil; Corn	Increased plant growth (6.5%–7.9%), water use efficiency (~20%); Improved WHC (soil moisture enhanced from 2.2% to 6.2%)	Kumar et al. (2022)
Lantana camara	450	0%–3%	Sandy loam; Okra	Increased leaf area (~50%), plant height (~20%), photosynthetic rate (~30–80%) WUE (>300%); increased soil pH (from 7.28–9.06), EC (from 3.03 to 13.01), moisture (from 1.21% to 18%), OM (from .5%–1.9%)	Whitman et al. (2019)
Olive tree prunings	450	2%	Vertisol; Wheat	Increased fine root proliferation, plant biomass (5%–50%); decreased soil compaction (9%); increased soil moisture (40%), EC (~50%), carbon content (~50%), nitrogen content (~50%)	Tomczyk et al. (2020)
Peanut hulls	500	0%–100%	Loamy sand; Tomato	Decreased bulk density (from 1.325 to .363 g cm^{-3}), particle density (from 2.65 to 1.60 g cm^{-3}); increased porosity (from .500 to .773 cm^{3} cm^{-3}); increased leaf quality (plant wilting rate rose from 4.67 to 9.50 with higher values denoting minimum wilting)	Mack et al. (2021)

a-glucosidase, β-xylosidase, and β-D-cellobiosidase) involved in soil sulfur (S) and C cycling was noted in a fluvo-aquic soil amended with biochar (Wang et al., 2015). In another study, elevation in dehydrogenase enzyme activity was observed in a red soil treated with .5% (w/w) bamboo and oak-wood biochar (Demisie et al., 2014). In the same study, β-glucosidase activity was increased in soil supplemented with only bamboo biochar at .5% and 1%. However, increase in urease activity was noted with oak wood biochar (.5% and 2%) and bamboo biochar (.5%) (Demisie et al., 2014; Palansooriya et al., 2020). Several studies (Ameloot et al., 2014; Paz-Ferreiro and Fu, 2016; Singh, 2016) also revealed that biochar manifest differential effects on enzyme activities across different types of soils. A manure-derived biochar decreased the activity of acid-phosphomonoesterase in clay-loam soil whereas activity level of alkaline-phosphomonoesterase was increased in silt-loam soils (Jin et al., 2016). Recently, a global meta-analysis (Pokharel et al., 2020) on biochar application and soil enzyme activities demonstrated an increase in the activities of extracellular enzymes including, phosphatase (25%), urease (23%) and dehydrogenase (20%). On the other hand a decrease of −13%, −7%, and −6% in phenol oxidase, β-glucosidase, and acid phosphatase, respectively was also observed. It is obvious that soils blended with biochar showed augmented proliferation of soil microbes benefitting the soil in several ways. However, more studies are needed to explore the long term effects of biochars on soil microbes and unveil the ecological roles of biochars.

TABLE 7 Effect of biochar addition on crop yield.

Biochar type	Pyrolysis condition °C	Biochar pH	Application rate of biochar	Soil type	Soil pH	Effect of crop yield	Reason of effect on yield	References
Acacia bark	400	7.01	25 and 50 t ha^{-1}	Silt loam	8.2	First year maize yield increased by 20% after biochar application and 2nd year increased by 12	Biochar application retained soil N and P	Arif et al. (2016)
Swine manure	600	10.40	2% w/w	Sandy	8.3	Positive effects on crop yield	Enhanced the NPK uptake by plants	Subedi et al. (2016)
Corncob	350	8.02	2 and 6 t ha^{-1}	Sandy	5.9	Increased the groundnut and corn yield	Biochar addition enhanced the level of P and K in corn stover	Martisen et al. (2014)
Bio solid	600	7.50	20 t ha^{-1}	Fine sand	5.80	Decreased the corn growth	Biochar addition exhibited no impact on N uptake	Gonzaga et al. (2017)
Poultry litter	300	8.1	10 g kg^{-1}	clay loam	7.80	Significantly lettuce growth and biomass as well as yield	Significantly enhanced the level of NPK of lettuce leaves and decreased the Cu, Mn, Zn and Fe level	Gunes et al. (2014)
Poultry manure	300	8.7	5 g kg^{-1}	Clay loam	7.8	Increased the bean and corn growth and yield	Increased the level of Mn, Cu, Zn, Fe, Ca, and NPK in maize and bean plant	Inal et al. (2015)
Kunai grass	500	10.20	10 t ha^{-1}	Loam	5.5	No impact on the yield of cabbage	Not effect on N uptake	Baiga and Rao, (2017)
Wood biochar	900	9.3	7 t ha^{-1}	Sandy loam	6	Within 3 years, no impact on wheat yield	Mg, P, and K contents in wheat gain enhanced	Sanger et al. (2017)
Rice husk	350	9.1	15 t ha^{-1}	Clay	5.18	Not exhibited positive impact on the maize yield	No impact on N uptake by corn plant	Nguyen et al. (2016)
Rice straw	550	10.20	4.5 t ha^{-1}	Sandy loam	6.1	Increased the yield of grain by 8%–10% than control	Biochar addition significantly increased the uptake of nutrients by grain than control	Liu et al. (2016)
Wood biochar	350	9.10	20 t ha^{-1}	Sandy	6.3	No impact on growth and yield of potato, strawberry and barely	Biochar addition had slight effect tissue level of Mg, Ca, K, P, and N irrespective of crop. Biochar decreased tissue Mn and increased Mo in strawberry	Jay et al. (2015)
Bamboo	600	9.80	4.5 t ha^{-1}	Clay loam	6.16	Did not greatly enhance the rice grain yield	Improved the content of K of rice grains	Liu et al. (2016)
Sawdust	300	5.2	20 t ha^{-1}	Sandy	8.80	Increased soybean grain yield	Significantly impact on soil available P	Mete et al. (2015)
Poultry manure	550	8.9	10 t ha^{-1}	Fine textured	4.3	Enhanced the maize yield than control	Improved the nutrients uptake	Van Zwieten et al. (2010)
Apple tree branches	550	9.82	80 g	Mine soil	5.50	Efficiently stimulates plant growth, increases the uptake of heavy metals by roots	Generates a barrier effect that decreases the transfer of heavy metals from roots to shoots	Guo et al. (2021)
Rice husk	—	—	1%–3%	Contaminated soil	6.53	Enhanced plant growth	Biochar application significantly improved soil properties and enhanced soil enzyme activity	Wang et al. (2021b)
Wheat straw	600	7.45	.5, 1% and 1.5%	Metal-contaminated soil	5.11	Improved the growth of rice plant as well as yield	Increased the photosynthetic pigment and gas exchange properties of rice plants	Irshad et al. (2020)
Rice straw	450	8.2	—	Salt stressed soil	—	Increased the soybean plant growth, root architecture characteristics and biomass yield	Improve the nutrient acquisition, chlorophyll content, soluble protein and sugarcontent, also reduced the elevated levels of Na^{+}, glycinebetaine, proline, hydrogen peroxide in plants under salt stress	Mehmood et al. (2020)
Corn straw	500	10.02	—	Typic haplocalcide	7.7	Increased plant growth, plant height, shoot dry weight, root dry weight, chlorophyll content and leaf area	Improve the redox capacity of soil, improve the activities of soil urease, catalase, alkaline phosphatase and soil retained more water	Khajavi-Shojaei et al. (2020)

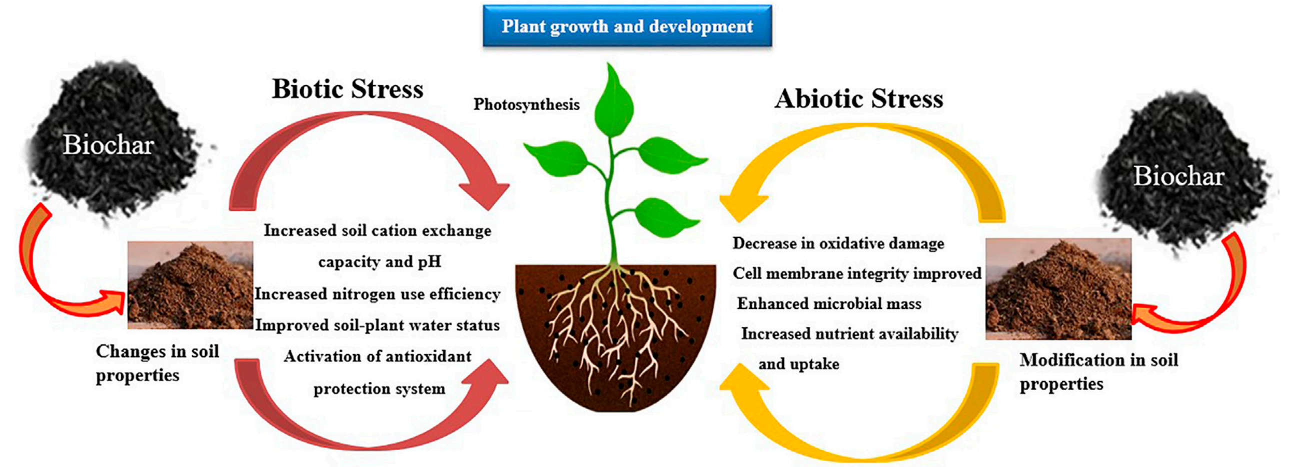

FIGURE 3
Improvement in plant resilience against biotic and abiotic stresses through biochar application.

3 Effect of biochar addition on soil nutrients

How biochar addition affects soil nutrient status has been reviewed extensively in different types of soils under various environmental factors (Schmidt et al., 2021). Biochar affects nutrients cycling in soils through retention and sorption, increasing or decreasing their bioavailability by reducing or increasing leaching and emissions (Tisserant and Cherubini, 2019). The transformation of nutrients in biochar-treated soils varies depending on biochar types, carbonization conditions, and soil types (Al-Wabel et al., 2017). Lehmann et al. (2002) advocated two primary methods for stimulating the rates of nutrient retention and decreasing nutrient leachability; (a) biochar addition enhances the adsorption sites, which accelerate the nutrient retention rate, and (b) biochar may perform as a slow releasing nutrient material. The N availability is the most substantial and key nutrient for the plant growth and it is greatly exposed to denitrification, leaching and volatilization (Abhishek et al., 2022). Biochar regulates the soil N through its surface chemistry, by affecting soil pH and influencing the soil microbial communities (Mia et al., 2017; Padhye, 2017). Mandal et al. (2018) reported that the retention of N is influenced by biochar owing to enrichment of O_2-enrich functional groups (hydroxyl, aromatic ring carbonyl and aliphatic ether). Many researchers (Cayuela et al., 2014; Mandal et al., 2018; Borchard et al., 2019) highlighted that the maize biochar addition can accelerate the N content in soil through enhancing the net N mineralization, which increases nitrification process, affects denitrification and reduces the NH_3 volatilization, and enhances the NH_3 and NH_4^+ adsorption in soil. Marks et al. (2016) reported that adding pinewood-biochar decreased the N mineralization in the form of nitrate ions to amounts equal to ammonium. Likewise, Yao et al. (2017) applied the biochar to loamy sand, where available N contents reduced or remained unaffected due to the adsorption of ammonium, resulting in reduced available N. Furthermore, Jones et al. (2012), investigated the long-term effects of biochar addition on soil N mineralization in mull soils and observed that biochar addition had no substantial impact on nitrate ions, ammonium, and the total N amounts in the soil.

Additionally, biochar produced under different pyrolysis conditions showed variable soil N immobilization and mineralization results. For example, 43% N was immobilized in the soils after biochar addition, which was produced at a higher temperature. In contrast, applying biochar obtained at a low temperature resulted in 7% N mineralization (Bruun et al., 2012). Furthermore, the application rate of biochar also substantially impacted the mineralization of N by decreasing the concentrations of nitrate ions and ammonium in the soil (Bruun et al., 2012). Applying biochar produced at 400°C and 600°C accelerated the uptake of ammonium in the soil, substantially decreasing the soil inorganic N (Bruun et al., 2012). Butnan et al. (2017) compared the biochar applicability produced at 350°C and 500°C. The gross mineralization, labile N fraction and recalcitrant fraction and got enthused after the biochar (350°C) improvement in the soil than biochar produced at 550°C. Additionally, with biochar application, the N-cycle hastened and hence enhanced the gross mineralization of N, nitrification and NH_4^+ consumption rate by 185%–221%, 10%–69% and 333%–508%, respectively. This was possibly occurred because biochar application increased the soil aeration/porosity, enhanced and stimulated the growth of heterotrophic/aerobic microbial community (Yi et al., 2020). Additionally, nitrates content in soil doubled the concentration of ammonium following the biochar addition, possibly due to the negatively charged surface of biochar and high mineralization of N (Shenbagavalli and Mahimairaja, 2012). Jones et al. (2012) reported that wood-derived biochar did not substantially impact N mineralization or nitrification when applied to agricultural soil. Transformation of inorganic N with higher rates resulting from biochar addition could be explicated through (1) increased soil organic mineralization and net N, (2) denitrification enhanced because of the stimulation of denitrifying bacterial communities, (3) nitrification increased accelerated *via* a large number of ammonia oxidizers (Jones et al., 2012).

The availability of phosphorous in the soil to plants is affected by the application of biochar, which is regulated by the CEC or anion exchange capacity that leads to phosphorous incorporation (Si et al., 2018). Abhishek et al. (2022) revealed that phosphate complexes form at high pH with Mg^{2+} and Ca^{2+} and at low pH with Al^{3+} and Fe^{3+}. The biochar inhibits the development of phosphate precipitates, and

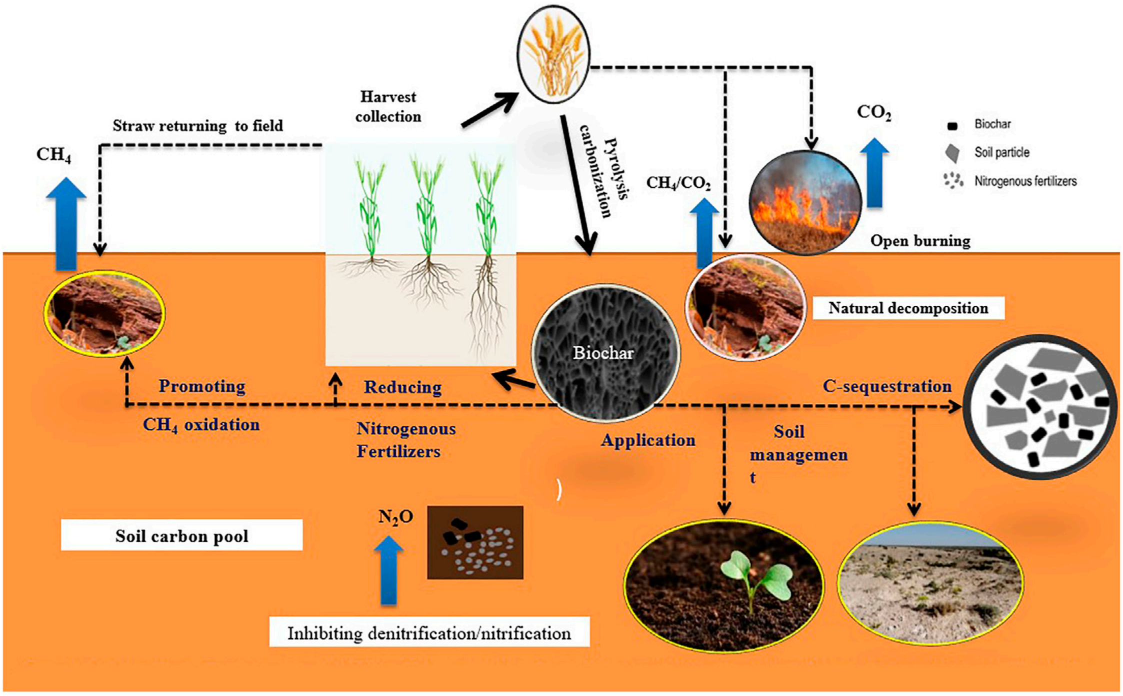

FIGURE 4
Mechanism of greenhouse gas (GHG) reduction and soil carbon (C) sequestration through biochar application; Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_{2O}).

hereafter, the phosphorous availability rises in the plants. Xu et al. (2016) carried out a field study on maize in Indonesia. They exhibited that biochar adding to soil increases the available phosphorous, which elevates the maize yield afterward. They found the biochar application increase the phosphorous for the plants even in less available soil phosphorous conditions. Li and Chan, 2022) reported that sharp decline of P content in clay soil after biochar addition; it was due to the chemical adsorption of P the surfaces clay-mineral and temporary immobilization of P *via* soil microbes. Kelly et al. (2015) noticed a significant enhancement in P content of clay soil after hardwood-derived biochar application with the rate of 5, 10, 15 g kg^{-1}. An increase of 54% P extractability (~20 mgkg^{-1}) was achieved in the clay-soil amended with biochars, whereas this increase was 42% (11 mgkg^{-1}) in the control. Wang et al. (2015) conducted a pot experiment to examine the effect of biochar addition (0, 5, 10, and 25 g kg^{-1} soil) on the soil K dynamics in two types of soil (alfisol and Entisol). Both soil K increased in response to biochar addition, with the impacts more prominent in the Alfisol.

Biochar can improve the availability of soil P by changing the soil microbial communities, as it can provide the suitable growth conditions in the form of porous habitat and C supply for soil microbes (Dai et al., 2021). Zhou et al. (2020) reported an increase in soil P availability and activity of related enzymes by improving the growth of P-solubilizing bacteria (*flavobacterium*, *pseudomonas* and *thiobacillus*) in forest soil with rice-husk biochar application. These alteration could be credited to increased WHC and soil pH (Liu et al., 2017). Biochar enhanced the plant available P in soils by 45% and microbial biomass P by 48% (Gao et al., 2019). The manure and crop residue derived biochars exhibited higher P content than other feedstocks (Gul and Whalen, 2016). Biochar P is less mobile than the P from agricultural residues and it may act as a slow-release P fertilizer. Biochar can be a P-recycling route from agricultural residues. The results of a meta-analysis revealed that biochar amendment significantly improved the P availability in soils for 5 years. Several other investigations (Gao et al., 2019; Glaser and Lehr, 2019; Dai et al., 2021; Schmidt et al., 2021) described that manure and crop residues derived biochars increase availability of P, biochars prepared at high pyrolysis temperature release less P and P availability is reduced in alkaline soils (pH > 7.5) due to the liming effect of biochar. The biochar addition also affects other essential macronutrients such as Ca, Mg, Na, P, and K. For instance, Sigua et al. (2015) reported that biochars of poultry litter and pinewood 50:50 blend considerably improved the soil amounts of Ca, Mg, Na, P and K by 307%, 687%, 2,315%, 669%, 830% respectively, compared to control. Meta-analyses have revealed that biochar addition commonly increases P availability, especially when applied to neutral or acidic soils, and for biochar produced from low C:N feedstocks and at low temperatures (Gao et al., 2019; Glaser and Lehr, 2019). However, biochars prepared from Ca-rich and K-poor feedstocks (e.g., sewage sludge) reduce the P availability because pyrolysis can convert plant-available organic P into inorganic P that is less available in the short term (Rose et al., 2019; Buss et al., 2020). Gunes et al. (2014) demonstrated that the availability of K, P, and N was elevated in alkaline soil with biochar application, with no substantial impact on the macronutrient availability to the plants. Understanding the effects of biochar amendment on soil chemical properties is essential to determine appropriate application regimes under given field conditions. Additionally, a

TABLE 8 Effect of biochar addition on carbon sequestration and GHGs emission.

Experimental conditions							impacts		
Experiment type	Biochar type	Application rate (t/ha^{-1})	Soil type	Duration	CO_2	NH_3	N_2O	CH_4	References
Pot	Sawdust	2%–60%	Corn field	100 days	Reduced	Reduced	Reduced	Decreased 20%	Spokas and Reicosky. (2009)
Field	Wood	60	Wheat soil	420 days	No difference	—	Reduced by 59%–88%	No difference	Castaldi et al. (2011)
Pot	Maize stalk	24	Paddy ultisol	116 days	—	Reduced	—	Reduced by 61%	Feng et al. (2012)
Field	Wood	30	Wheat soil	420 days	No difference	—	Reduced by 26%–76%	No difference	Castaldi et al. (2011)
Field	Wheat straw	40	Paddy soil	150 days	—	—	Reduced 21%–28%	Enhanced by 41%	Zhang et al. (2010a)
Field	Wheat straw	40	Paddy soil	450 days	—	—	Reduced by 40%–51%	Enhanced by 34%	Zhang et al. (2010b)
Pot	Maize stalk	24	Paddy inceptisol	116 days	—	Reduced by 13%	—	Reduced by 63%	Feng et al. (2012)
Field	Bamboo	2–6	Wheat soil	100 days	Reduced by 5.5%–72%	Reduced by 74%	Reduced by 81%	Decreased by 72%	Zhang et al. (2020b)
Field	Wheat straw	2–18	Paddy soil	120 days	-	Decreased by 65%	Reduced by 97.3%	Reduced by 92.8%	Awasthi et al. (2017)
Field	Wood	27	Paddy ultisol	140 days	Reduced by 22%	Reduced by 35.3%	Reduced by 35.3%	Reduced by 83.6%	Chowdhury et al. (2014)
Field experiment	Chipped forest residue	5, 10, 20, and 30	Boreal arable	2 years	Decreased more than 50%	Reduced	No effect noticed	Significantly reduced	Kalu et al. (2022)
Field	Agricultural waste	—	—	30 days	Increased the emission more than other GHGs	Decreased by 30%	Reduced by 57%	Enhanced the emission	Li et al. (2022)
Field	Rice hull	30	Inceptisol	3years	emissions by 33%	Increased emission significantly	No effect	Enhanced the emission by 31%	Gross et al. (2022)
Field experiment	Corn straw	40	Anthrosol	234 days	Increased the emission	Decreased by 17%	Reduced	Enhanced the emission	Jiang et al. (2021)
Laboratory experiment	Wheat straw	1% and 2%	Red soil	180 days	Increased emission by 5.8%–9.9%	No effect	Emission increased by 22.8%–27.5%	Reduced emission by 19.8%–28.2%	Liu et al. (2021)

comprehensive comparison of different feedstocks produced at different pyrolysis temperatures is needed to identify and optimize the feedstock effects on nutrient release dynamics and biogeochemical cycling of nutrients in soils treated with biochars.

It can be visualized from the above discussion that biochar application significantly influences soil BD, aeration, porosity, WHC, CEC, pH, nutrient balances, and other parameters of soil quality due to its physicochemical properties and intrinsic structure (Singh et al., 2021; Murtaza et al., 2022a). Higher carbon and mineral content in the biochar are beneficial for improvement of soil health, fertility, and crop growth and yields (Table 4). The application of biochar also increases the microbial biomass, WUE, and NUE when added as soil amendment (Yu et al., 2019). All these modifications induced by biochar in soil physiochemical and biological properties offer great benefits to the agri-systems (Bhat et al., 2022). For instance, biochar enhances the amount of water available to plants, which could help in reducing irrigation frequency and it has great significance in water limited semi-arid regions (Alkharabsheh et al., 2021). Biochar particles with high porosity and large SSA contributed to increased plant available water. Taskin et al. (2019) investigated the effects of poultry manure biochar on chickpea (*Cicer arietinum* L.), maize (*Zea mays* L.), soybean (*Glycine* max L.) and bean (*Vigna radiata* L.) crops and observed positive effects on growth and other growth related parameters, mainly due to improvement in soil water holding capacity induced by biochar. Tomato height, weight, number of flowers, and fruit yield were also improved after 7.5 t ha^{-1} rice husk application (Adebajo et al., 2022), and similar results were obtained in faba bean varieties with higher grain yield, fruit protein content, and plant height due to the increased of soil available K and N after biochar addition (Essa et al., 2021). Increased rape shoot biomass (from 2.31 to 4.23 g) and grain yield after rice biochar application was the result of an improvement of soil chemical conditions (soil pH and cation exchange capacity) and nutrient availability (total C and N), together with changes in the associated microbiota (Shahab et al., 2018; Farid et al., 2022). The application of up to 10% (v/v) of wheat straw biochar increased P uptake in barley plants in controlled conditions and in maize plants grown in rhizoboxes (application rate of 15 g kg^{-1}), with an increased shoot biomass and N use efficiency due to a fine root proliferation and an increase in the amount of N and P in soil (Tartaglia et al., 2020). wheat straw biochar application (5–40 t ha^{-1}) promoted the growth and yield of lentil by increasing the organic C content and improving other physicochemical characteristics of the soil, and it was also able to increase maize yield by 23.7% by promoting N uptake (Allohverdi et al., 2021). There are several reports that highlight no or negative effects of biochar application alone or in combination with organic and inorganic fertilizers in soil plant systems. For instance, Rivelli and Libutti, (2022). Applied biochar and other organic amendments (vermicompost from cattle manure and three composts, respectively, from olive pomace, cattle anaerobic digestate with wheat straw, and cattle anaerobic digestate with crop residues and wheat straw), to the soil at two rates (to provide 140 and 280 kg N ha^{-1}, respectively), but biochar did not affect the growth or the qualitative traits of Swiss chard. In another study, Singh et al. (2020) explored the effect of different combinations of chemical fertilizers, rice-husk ash biochar and farm yard manure on agronomic and eco-physiological responses of wheat crop. Sole application of farmyard manure and chemical fertilizer showed better (5%–26% higher) crop eco-physiological responses, whereas sole biochar and biochar plus farmyard manure application manifested poor responses (2%–15% lower) compared to the control. These results revealed that combined application of rice husk ash biochar and farmyard manure limit the crop growth. These were the few examples indicating that how changes in soil physiochemical and biological properties caused by biochar affect crop growth and productivity. A detailed impact of such changes on different plant development phases under different environmental conditions is described in the following section.

4 Interpreting the biochar-soil- plant nexus

4.1 Promote seed germination and early seedling growth

The effects of biochar application on seed germination (Table 5) consisted of inhibition to activation. A high application rate of biochar can have destructive impacts, while a low application rate of biochar can be stimulatory. This section will explain the mechanisms affecting the germination and seedling growth described in the literature.

Seed germination starts with water absorption and ends when the radicle appears from the seed coat. The four main aspects regulating the effect of biochar treatment on seed germination are 1) release of phytotoxins, 2) salts released from biochar in soil solution, 3) alteration in porosity and WHC of soil, and 4) release of karrikins (germination-regulator hormone) (Joseph et al., 2021). Biochar type, pyrolysis condition, and dose have diverse effects on germination rate and speed. The specific sensitivity of different plant seeds to toxins, water availability, hormones, and salinity may cause variable results (Hasannuzzaman and Fujita, 2022). For instance, in a pot experiment, wood-derived biochar at 80 Mg t ha^{-1} suppressed the tomatoes' germination. At the same time, sewage sludge, wheat husk, and paper residue-derived biochar added with the same dose had no impact on lettuce, cucumber, cress, tomatoes, and lentil seed germination (Gasco et al., 2016a). Other investigations that used a range of manure and woody biochars at a rate of 10 Mg t ha^{-1}–40 Mg t ha^{-1} observed nil or positive impacts on germination (Van Zwieten et al., 2010; Khan et al., 2014; Mete et al., 2015; Gasco et al., 2016b; Das et al., 2020).

Uslu et al. (2020) reported the negative effects (inhibition of seed germination) in different fodder crops at high biochar application rate (120 Mg t ha^{-1}) in a laboratory experiment. Aqueous extracts of various biochars have accelerated seed germination and seedling growth (Zheng et al., 2017). Seed growth and development of early seedlings can be affected due to biochar impacts on soil physical attributes. For example, by enhancing soil aeration and decreasing soil bulk density, biochar can provide oxygen for germination and to improve seedling development through seeding emergence (Obia et al., 2018). Biochar's chemical impacts on water and soil solution can affect the seed and early seedling growth. For instance, by increasing pH, the alkaline biochars enhance the heavy metals and Al toxicity that can decrease root development in acidic-soils (Shetty et al., 2020). A high dose of biochar with high concentration of soluble salts could suppress seed growth and development by osmotic stress (Sun et al., 2017; Shetty et al., 2020). Kochanek et al. (2016) reported that the biochars comprising organic molecule karrikins, can promote seed growth and seedling development.

French and Iyer-Pascuzzi, (2018) demonstrated that the gibberellin pathway accelerates germination and seedling development through wood-derived biochar in tomato genotypes. Polyphenols and phenols released from biochar can efficiently break the seed dormancy, improve germination, and accelerate the seedling development mechanisms (Reynolds et al., 2018). Biochar comprises organic contaminants, PAHs, and heavy metals generated during the partial combustion process that can suppress germination and seedling development due to a high application rate (Gasco et al., 2016a; Gasco et al., 2016b; Das et al., 2020). Nevertheless, lower application rates, and low concentration of free radicals could be favourable as reactive oxygen can interact with various hormones of plants that stimulate the germination process (Gomes and Garacia, 2013).

It can be summarized from above discussion that mostly biochars and biochar based formulations are helpful in promoting seed germination and growth of seedlings when applied at moderate rates. However, application of biochars at relatively higher rates e.g., more than 40–50 Mg ha^{-1} could restrict seed germination and early growth due to the release of phytotoxic organic compounds and soluble salts. Furthermore, the mechanisms responsible for positive effects of biochar include water-soluble organic compounds that accelerate the seed germination and growth, chemical reactions that dismiss the inhibitory effects of phytotoxic compounds and heavy metals. The aforementioned effects largely depend upon the temperature, biochars prepared at low temperatures contain higher amounts of organic molecules and promote seed germination and seedling growth at low application rates. Therefore, the abovementioned factors should be considered prior to the application of biochar in the crop fields to get optimum benefits.

4.2 Biochar as a plant growth regulator

Biochar application either decreases or increases plant growth (Deenik et al., 2010). According to previous literature, the changes in plant growth (increase or decrease) depend on soil, biochar type, and biochar preparation temperatures (Figure 2). For example, Kwapinski et al. (2010) reported inhibition of corn growth through soil treatment with biochar derived from silver grass prepared at 400 °C. However, growth was promoted by biochar obtained at 600°C. Moreover, soil treatment with biochar at an application rate of 68 t ha^{-1} significantly enhanced the growth of cowpea, wheat, and rice (Vaccari et al., 2011; Zheng et al., 2017). In comparison, applying 10% animal manure-derived biochar reduced the sunflower plant height, number of leaves, achenes, and stem diameter (Furtado et al., 2016). Corn-derived biochar pyrolyzed at 400°C added at 20 t ha^{-1} did not considerably increase the growth of *Glycine max*on loam soil (Hafeez et al., 2022). Changes in soil properties have often resulted with biochar addition, leading to increased plant growth (Solaiman et al., 2010). Solaiman et al. (2012) reported that the application rates and biochar type considerably impacted the growth of clover, mug beans, and wheat in the laboratory experiment. In a glasshouse experiment, the growth of radish, soybean, and wheat was enhanced with papermill derived biochar at the application rate of 10 t ha^{-1} (Van Zwieten et al., 2010). Furthermore, biochar addition to hostile sandy-soil increased the growth of corn by increasing photosynthesis rate, plant-soil water relations, decreased bulk density, and enhanced moisture retention (Haider et al., 2015). Thus, biochar addition may control the poor germination and plant growth induced by poor soil attributes (Furtado et al., 2016).

Artiola et al. (2012) reported that pine-derived biochar applied at 2% in a pot study with a sandy-loam and alkaline soil had poorly affected lettuce growth in 2% biochar-treated soil. Moreover, rice plant growth, dry mass weight, and tiller number significantly increased in various varieties grown in treated soil with rice straw biochar at the rate of 15 kg ha^{-1}. While the wheat growth was positively affected by 5% biochar application (Akhtar S. S. et al., 2015). Plant dry and fresh weights of pepper and tomato except romaine were increased by application of poultry manure-based biochar-to loam soil at the rate of 400 kg ha^{-1} (Vaccari et al., 2015). Burke et al. (2012) reported that the growth of cotton was promoted by hardwood-derived biochar when applied at the rate of 5–10 t ha^{-1}. The growth and yield of *Chenopodium quinoa* and lettuce were enhanced by 300% in a hostile loam-sandy soil treated with 2% biochar (Trupiano et al., 2017).

Luigi et al. (2022) showed that biochar seems to promote the development of the tomato seedlings, especially at concentrations ranging from 1% to 20% (w/w with peat) without showing any antimicrobial effects on the beneficial soil bacteria at the tomato rhizosphere level and even improving their growth, because the application of biochar enhanced the soil pH as well as the retention of both the soil water and nutrients (Yang et al., 2022). Biochar ameliorated substrate characteristics (available N increase of 17% and total C increase 13%), resulting in a promotion effect on plant root, shoot, and leaf morphology, the biochar-treated plants had a greater number of leaves (38 and 68 at the vegetative and fruit stages, respectively) than the untreated plants (32 and 49, respectively). The biochar also increased leaf area with a rise of 26% and 36% compared with the values measured in the untreated plants. Moreover, the amendment increased twofold root length, root surface area, and root, stem, and leaf biomasses in comparison with untreated plants (Simiele et al., 2022), could have a promoting effect on plant growth as an indirect consequence of its positive effect on growth medium parameters such as water holding capacity and pH enhancement, increased nutrient availability (Malik et al., 2022). Xi et al. (2020) reported that the 2% (w/w) rice biochar application increased soil available N and K, resulting in taller lettuce plants, with longer roots, stronger leaves and stems, as well as greater leaf area. The growth improvement may be related to the impact of biochar on the physicochemical characteristics of the soils. Similarly, Huang et al. (2019) proposed that rice straw biochar contributed to the increase of total soil N content, making it more available to *Phragmites communis* and promoting its growth. But rice biochar can also stimulate C and N cycling by changing the microbial community. For example, increased rape shoot biomass (from 2.31 to 4.23 g) after rice biochar application was the result of an improvement of soil chemical conditions (soil pH and cation exchange capacity) and nutrient availability (total C and N), together with changes in the associated microbiota (Gomez et al., 2022).

Biochar-extracted liquor [1%–5% (w/w) in water] also promoted plant height and root growth in rice seedlings. The mechanism of action proposed was based on the overexpression of the ABP1 gene and the accumulation of its protein product. Accordingly, molecular modeling showed a molecule on the biochar surface that was able to interact with the ABP1 protein (Gelova et al., 2021). Liu Z. et al. (2021) found that application of 1% rice straw biochar, enhanced the N use efficiency of rice plants and resulted in increased shoot and root biomass (26%–29%), which were attributed to the enhancement of soil microbial biomass after biochar treatment. The application of wheat straw biochar (5–40 t ha^{-1}) promoted the growth of *Lens culinaris* L. by increasing the organic C content and improving other physicochemical properties of the soil (Khorram et al., 2018). Taken together, biochar application positively augmented the growth and development of plants by increasing the availability of nutrients, water, SOC and improving the soil biological activities.

4.3 Impacts on plant physiological aspects

Various physiological aspects do or do not respond to biochar addition (Table 6) due to factors such as biochar and soil type (Asai et al., 2009; Singh et al., 2020). For example, soil treatment with biochar decreased the content of leaf chlorophyll in rice plants grown in poor-quality soil (Asai et al., 2009). Younis et al. (2015) conducted a pot experiment. They observed that transpiration (42%) and photosynthetic rates (45%), protein content (20%), anthocyanin (60%), lycopene (30%), carotenoids (29%), chlorophyll (40%), and stomatal CO_2 level (22%) were improved. The concentration of amino acids and sugars were decreased with the increasing application rate of cotton biochar from 3%–5%. Increased P uptake, availability, and corn growth after biochar application were also observed (Mau and Utami, 2014). Compared with the control, an increase in chlorophyll contents, rate of photosynthesis, and stomatal conductance of the jute plant were found after biochar was mixed into the soil at the rate of 3 kg m^{-2} (Seehausen et al., 2017).

Haider et al. (2015) described that adding biochar in hostile sandy soils increased plant growth *via* increasing photosynthesis rate and plant-soil water relation under drought and well-watered conditions. In corn and wheat grown on loamy soil, biochar positively influenced physiological parameters. Where biochar application at the rate of 5% positively impacted xylem Na^+ and K^+, stomatal conductance, and photosynthesis rate more than the control. However, biochar application did not affect the photochemical ability of the photosystem-II (Akhtar S. S. et al., 2015; Seehausen et al., 2017). Various physiological parameters such as leaf nutrient level, leaf gas exchange, water status, and nutrient recovery of apple plants were positively affected *via* biochar addition (Eyles et al., 2015). Stomatal conductance, photosynthetic ability, vapor pressure and transpiration rate, and N and P leaf concentration significantly increased compared to control under biochar treatment (Eyles et al., 2015; Hafeez et al., 2017).

A significant rise in P, Mg, K, and N contents in tomato plants was found after biochar addition at the rate of 14 t ha^{-1} (Vaccari et al., 2015). Moreover, water use efficacy, transpiration and assimilation rate, and leaf water potential were positively influenced in lettuce grown in biochar treated soil (Trupiano et al., 2017). Akhtar S. S. et al. (2015) observed that biochar increased soil sorbing Na^+ content and enhanced xylem K^+ content, and decreasing N uptake, thereby elevating the potato yield (Akhtar S. S. et al., 2015). The biochar application significantly enhanced biomass and photosynthetic pigments development in plants. The treatments also increased membrane stability index by 45.12% and enhanced water using efficiency by 218.22%, respectively. The increase in antioxidant activities was 76.03%, 29.02%, and 123.27% in superoxide dismutase, peroxidase, and catalase, respectively (Tanveer et al., 2022). It was due to the application of biochar decreases the Pb and As toxicity and enhanced the production of the photosynthetic pigment in *Salix viminalis* L. They enhanced the production of chlorophyll, biomass and, gas exchange attributes in plants (Visconti et al., 2020) and antioxidants was increased by biochar because of the biochar reduces oxidative stress by the synthesis of ascorbate peroxidase, glutathione reductase, superoxide dismutase, and catalase (Kaya et al., 2020). EL Naggar et al. (2021) used of rice straw biochar (15 t ha^{-1}) and found the enhancement in photosynthetic pigments.

These results were associated with the maintenance of the integrity of cell membranes and the reduction of the oxidative damage of leaf tissues by enhancing catalase (CAT), peroxidase (POX), superoxide dismutase (SOD), and glutathione reductase (GR) activities (Gomez et al., 2022). Biochar significantly increased net photosynthetic rate, transpiration rate, stomatal conductance, and water use efficiency during the plant growth period, relative to control and shown that biochar has great potential in improving chlorophyll fluorescence (Wang S. J. et al., 2021). That's probably because biochar has the effect of increasing the chlorophyll content of leaves (Feng et al., 2021), which can ensure the synthesis of various enzymes and electron transporters in the process of carbon assimilation, thereby improving the function of leaf photosynthesis (Hou et al., 2021).

4.4 Effects on crop yield/productivity

Biochar application effects on crop productivity are variable due to feedstock composition, pyrolysis conditions, soil properties, and crop and experimental conditions. Various studies show that biochar addition has beneficial impacts on the productivity of different crops (Table 7). For instance, the yield of corn was enhanced by 40% after the addition of salwood-derived biochar (Yamato et al., 2006), 114% by corncob and wood biochar (Cornelissen et al., 2013), and 98% by the treatment of biochar-derived from manure (Uzoma et al., 2011). Compared to controls, the lantana and pine needles-derived biochars enhanced the grain yield of *Triticum aestivum* by 6%–24%. This is attributed to more efficient enzymatic activities and P and N uptake *via* grains (Bhattacharjya et al., 2015). Biochar addition at the rate of 40 t ha^{-1} in sandy loam soil increased rapeseed yield by 36% and potato yield by 53% (Liu S. et al., 2020).

Biochar application also enhances the crop productivity grown in alkaline soil, depending on the pH of applied biochar (Zhang H. et al., 2015). For instance, biochar application to alkaline soil (8.38 pH) at the rate of 20 t ha^{-1} and 40 t ha^{-1} enhanced the yield of maize by 18% (Vaccari et al., 2015). Major et al. (2010) presented that the maize yield was significantly increased after wood-derived biochar application (at the rate of 20 t ha^{-1}) to alkaline soil (9.2 pH). The positive impacts of biochar application on alkaline soil depend on the type of biochar. Biochars produced at slow pyrolysis have low pH due to a large amount of aliphatic and volatile compounds (Spokas and Reicosky, 2009). Also, biochar addition has a negative or no impact on crop productivity in alkaline soils. For example, Hansen et al. (2016) conducted a pot study for biochar application at the rate of 1% in sandy loam soil (pH 9.8). Biochar addition exhibited no impact on the growth and yield of the barley crop. In a field experiment, adding wood biochar prepared at fast pyrolysis showed no effects on the corn yield in alkaline nature soil under water stress conditions (Foster et al., 2016). Marks et al. (2014) described that the poplar and pine wood-derived biochar by fast pyrolysis and gasification significantly inhibited the yield of ryegrass and lettuce at the 19 t ha^{-1} addition rate in calcareous soil (pH 8.9). Generally, biochar effects on crop yield are more prominent in acidic soils, well-weathered and low fertile soils dominated by sesquioxides and kaolinite (Sohi et al., 2010; Xu et al., 2013).

In acidic soils, the positive effects of biochar addition on crop productivity are attributed to increasing soil CEC because of biochar's large surface area and porous structure. It amends the physical attributes of soil by increasing the soil WHC and decreasing the soil bulk density. Additionally, it enhances nutrient use efficiency and supply of essential nutrients, controls nutrient loss, accelerates microbial activity and their functions, stabilizes phototoxic elements in soil, and reduces the impact of biochar, such as increasing pH (Singh H. et al., 2022). Biochar addition increased the nodulation, biological nitrogen fixation, and yield of various legume species, including soybean, alfalfa, and red clover (Lai et al., 2022). Mete et al. (2015) reported an increase in biological N fixation of bean with the biochar application at the rate of 78 and 100 t ha^{-1} Mia et al. (2014) observed that biochar addition increased the total biomass, nodule number, and biological N fixation. Possible processes driving the impacts of biochar addition on biological N fixation in legumes such as 1) higher pH of soil improve the Mo availability, an essential nutrient needed in biological N fixation mechanism, 2) Higher concentration of available N immobilization which is associated to biological N fixation enhancement, 3) Strong impact of biochar on nodule production *via* efficient use of Nod and flavonoids feature, 4) Biochar addition accelerates the concentration of available P to phosphorus-deficient soils (Chen K. et al., 2022; Chen X. et al., 2022).

Various studies have reported that biochar addition had negative or no effects on the productivity of crops. For example, biochar application at the rate of 15 g kg^{-1} to silty and sandy soils did not enhance the corn yield (Borchard et al., 2014). Nelissen et al. (2015) found no effect of biochar application on the barley crop yield in sandy soil. Lai et al. (2013) observed that the Walnut hull-derived biochar produced at fast pyrolysis did not affect the yield of lettuce, Swiss chard rice, and bell pepper, despite the available K and pH of the soil being considerably higher. Kloss et al. (2014) conducted a greenhouse experiment and observed a decrease in mustard and barely yield after adding the vineyard pruning, wheat straw, and woodchips-derived biochars in chernozem, cambisol, and planosol soils but the yield of red clover remained unaffected. Furthermore, maize-derived biochar application at various rates to fertile soils did not impact the corn yield under field and pot experiments (Guerena et al., 2013).

Simiele et al. (2022) reported that the biochar-treated plants showed a higher number of flowers and fruits, although the mean fruit biomass and morphology remained unchanged. Additionally, higher values of Trans-and cis-lycopene, total soluble solids, and titratable acidity were found in the biochar-treated plants when compared with the untreated ones (Simiele et al., 2022). The promotion of fruit quantity and quality could be attributable to the high total P content in the biochar-treated substrate and the high total N concentration in roots of the biochar-treated plants observed at high level. Indeed, according to other reports, there might be a relationship between the phosphorous and nitrogen contents in both growing substrates and plant tissues and the promotion of fruit production by improving the vegetative and reproductive properties of tomato plants (Hameeda et al., 2019), also attributed to the increased values of lycopene, titratable acidity, and total soluble solids when biochar was used as a soil amendment (Guo et al., 2021). The continuous application of 20 t ha^{-1} of rice biochar to a rice field resulted in plant growth promotion and an increase of 14%–26% in soil N uptake, 7%–11% in internal N use efficiency, and a 6% in grain yield (Gomez et al., 2022). Bai et al. (2019) showed an enhanced yield (up to 35%) in different rice-wheat rotated soils, probably due to the release of plant macronutrients and micronutrients contained in the rice biochar. Nan et al. (2020) reported a clear improvement in soil bacterial cooperative relationships after treatment with rice biochar in a 4-year field trial. The complexity of the rhizosphere bacterial community was enhanced, most probably due to an increase in total soil C content, alongside with an increased total N content and soil available K and magnesium (Mg), which increased rice yield up to 14.5%. Yin D. et al. (2021) observed an increased rice yield (38%–41%) after the application of N-enriched rice straw and waste wood biochar, due to increased levels of soil C and N contents, as well as iron (Fe) availability. In addition, the application of biochar from wheat straw (20 t ha^{-1}) in rice fields increased yield by 17%, as a consequence of a higher N and P supply, together with an improvement of more than 10% in the N use efficiency (Liu et al., 2021). Overall, improvement in soil physical, chemical and biological properties due to the biochar application caused an increase in crop yield or productivity. However, further studies should focus on optimization of biochar preparation conditions based on soil type, crop species and experimental settings. This could facilitate accuracy of biochar in terms of biochar type, preparation conditions and methods, application time, application rate, and recovery processes and it may help in promoting the application of biochar across diverse environmental conditions at large scale.

4.5 Effect of biochar addition on heavy metals uptake by plants

In plants, absorption of metals occur through the root cortical cells *via* competitive absorption of essential elements and adopted by symplastic and apoplastic pathways (Tangahu et al., 2011; Haider et al., 2021). Generally, mass flow is responsible for the transport of contaminants to the surface of the roots (Tran and Popova, 2013). These metals may be absorbed *via* apical portion of the root or the entire surface depending on the nature of the metal. Furthermore, metal uptake also relies on root development and capacity (Begum et al., 2019; Haider et al., 2021). Many investigations have revealed that biochar application is greatly helpful in reducing the absorption of soil contaminants (trace metals) in plants (Palansooriya et al., 2020; Joseph et al., 2021; Murtaza et al., 2022b; Haider et al., 2022). Chen et al. (2018) observed the incorporation of biochar into soils, resulting in an average reduction in plant tissue concentrations of Zn, Cu, Pb, and Cd by 17%, 25%, 39%, and 38%, respectively. Various studies indicated a substantial reduction in heavy metals bioavailability after using biochar at higher rates, such as 10 Mg ha^{-1} (Wang L. et al., 2020). Biochar surface with oxygenated-functional groups can stimulate the immobilization of heavy metals through different mechanisms (physisorption, electron shuttling, reduction, anion attraction, cation attraction, precipitation, and ion exchange) (Xu et al., 2019). Liming effects of biochar increase the pH of acidic soil, enhancing negatively charged exchange sites on the clay particles and raising cationic metals (Joseph et al., 2021).

Lei et al. (2019) presented that the biochars derived from manure contain higher Ca content than plant-based biochars and, therefore, can immobilize the Cu^{2+} and Cd^{2+} *via* ion exchange. Stable residues generated in the biochars with higher P can immobilize the lead (Pb) by the β-$Pb_9(PO_4)_6$ formation. In contrast, higher calcite and alkalinity in biochar promote the insoluble $Pb_3(CO_3)_2(OH)_2$ formation (Li et al., 2016). Biochar surface particles containing C-coated minerals are mainly efficient in reducing heavy metals' bioavailability (Kumar et al., 2020). Willow-derived biochar at high temperatures facilitate adsorption of heavy metals from sewage sludge *via* physisorption and chemisorption mechanisms (Bogusz et al., 2019). Khan et al. (2013) reported that various feedstocks that carry high heavy metal contents could decrease the bioavailability of the heavy metals in some soils. For instance, biochar derived from sewage sludge reduced the bioaccumulation of Pb, Ni, Cu, Co, Cr, and As but enhanced Zn and Cd in acidic soil. Biochar can improve the anionic metalloid mobility by reducing the positively charged sites, which reduces the arsenic binding sites with increased soil pH (Vithanage et al., 2017).

Nkoh et al. (2022) reported that the effect of biochar application to polluted soils is the reduction of pollutant uptake by plants, with some exceptions for Fe and Mn. The reductions were estimated at 22.8% (Mn), 33.0% (Ni), 18.3% (Zn), 3.03% (Pb), 41.5% (As), 56.0% (Cr), 25.8% (Cu), and 26.2% (Cd). The underlying mechanisms for this reduction in the bioavailability of heavy metals in soils are diverse with charged metals being fixed *via* ion exchange, physical entrapment on biochar's surfaces and changes in soil chemistry (Li et al., 2022). Amending heavy metal polluted soils with biochar reduced the overall daily intake of heavy metals (12.5%), hazard quotient (30.0%), and cancer risk (30.6%). However, these effects can be quite diverse depending on biochar properties, soil properties and the chemistry of concerned heavy metals (Nkoh et al., 2022). For maize plants grown on Pb-polluted soil, biochar treatment reduced the bioavailability of Pb (II) by 71% and the exchangeable Pb(II) by 99%. Compared to the un-amended soil, biochar treatment significantly decreased the associated Pb (II) toxicity to the maize plant (Zhu et al., 2020). Lebrun et al. (2020) examined the growth of Salix viminalis in arsenic and Pb (II)-contaminated soils amended with biochar, iron grit, and compost. They found that biochar-treated soil provided a favourable growing environment for the plant by considerably reducing the toxicity and bioavailability of the contaminants. Also, the phytotoxicity of Cd (II) to rice plants was significantly decreased when biochar was added to polluted soil (Yue et al., 2019). Natasha et al. (2022) observed that biochar application to soils has the potential to decrease the uptake of Zn, Pb, Cu, Cd, Ni and As, by 22%, 28%,38%, 40%, 44% and 48%, respectively in plants. In this study, with more data points, they estimated a 26.2% (Cd), 25.8% (Cu), 56% (Cr), 41.5% (As), 3.03% (Pb), 18.3% (Zn), 33.0% (Ni), and 22.8% (Mn) reduction rate of heavy metals uptake by plants when grown on biochar amended soils.

Biochars containing large surface area, sufficient pore volume and abundant functional groups play crucial role in heavy metal sorption (Ahmad et al., 2018). However, electrostatic interaction and sorption precipitation between heavy metals and biochars are the main mechanisms of heavy metal sorption governed by biochar (Lian and Xing, 2017). Additionally, surface coprecipitation, metal ligand complexation and ion exchange also contribute to the metal sorption on biochars (Ding et al., 2016a). Furthermore, the sorption affinity and capacity of heavy metals largely depend upon surface functional groups rather than pore volume and surface area (Yu et al., 2019). Oxidation of bichar induces carboxlic functional groups on biochar surface which elevated the adsorption capacity of Al^{3+}, as oxygen enriched functional groups acted as coordinated sites for the Al^{3+}. Cd adsorption on biochar was mainly regulated by the ion exchange (Lian and Xing, 2017; Haider et al., 2022). The sorption of Pb^{3+} on biochar surface was attributed to: 1) interaction of heavy metal with surface functional groups; 2) exchanges of heavy metal with cations (Ca^{2+}, Mg^{2+}) of biochar (Yu et al., 2019). Generally, biochars prepared at middle and low temperatures exhibit the highest adsorption capacity for metal cations (Xiao et al., 2018).

Biochar application appeared as a promising approach for mitigation of heavy metal contamination in plants, which may lead to a higher agricultural productivity and protecting plant community. However, biochar remediation efficiency is largely dependent upon the biochar type, plant species, biogeochemical properties of soil, and specific trace metal. Therefore, future strategies need a comprehensive analysis on determining the optimal methods of biochar production, type of biochar, plant species, popularization, and improving emphasis on suitability, adsorption potential, and sustainability of biochar as an optimum remediation tool against heavy metals while safeguarding the food quality.

5 Role of biochar in resistance to biotic and abiotic stresses in plants

Recently, the beneficial effects of biochar (Figure 3) in reducing plant diseases, including mildew in crops, wheat rust, and other pathosystems and factors, have been examined by various authors (Frenkel et al., 2017; Tian et al., 2021; Wu et al., 2022). More recently, 13 photosystems have analyzed the biochar impacts on plant diseases, and Bonanomi et al. (2015) summarized and reviewed that data. They presented that 85% of these investigations showed positive effects of biochar addition in reducing the severity of plant diseases, around 3% exhibited that addition induced the disease, and about 12% had a neutral impact. During this study, they did not consider that plant resistance/susceptibility to diseases depended on the applied dose of biochar. Frenkel et al. (2017) reviewed the 15 pathogens (such as nematodes, oomycetes, and fungi) data and compared the impacts of different treatments of biochar with control on disease severity and reduction. Biochar application at a high rate did not affect the plant diseases in 60% of the pathogens and 70% of photosystems than control (Jaiswal et al., 2014). In tomato, the use of wheat straw biochar reduced the disease incidence of bacterial wilt caused by *Ralstonia solanacearum* by up to 75%. This was due to an increase in the diversity and activity of rhizosphere microorganisms, together with alterations of the rhizosphere organic acid and amino acid composition. In addition, this increased microbial rhizosphere activity led to an increased supply of N and P to the plants, resulting in an increased plant biomass and length (Tian et al., 2021). Application of rice hull or rice husk biochar has reported interesting results to enhance the biomass of tomato plants and reduce *Meloidogyne incognita* infection by triggering defense-related genes such as PR-1b and JERF3 (Arshad et al., 2021). Rice biochar has also been helpful in alleviating the effects of the replanting disease (mainly caused by the accumulation of soil-borne pathogens (Wu et al., 2022). In this respect, an application of 80 g k^{-1} of rice husk biochar resulted in higher root length, surface area, and volume of apple tree seedlings, reducing the negative effect of the apple replant disease, and actively suppressing *Fusarium solani* infection (Wang Y. et al., 2019; Wang Y. Y. et al., 2019). In a similar way, the combination of rice hull biochar and plant growth-promoting rhizobacteria led to increased leaf area and biomass of *Radix pseudostellariae,* stimulated soil beneficial organisms, and suppressed pathogens through the increased production of soil metabolites, thus alleviating the effects of the replanting disease (Wu et al., 2022). Under biotic stress, the use of maize biochar can also improve crop responses. In pepper, the application of biochar from maize stalk reduced the incidence of Phytophthora blight (caused by *Phytophthora capsica*) by up to 50%, due to an increase in the abundance and diversity of biocontrol fungi within the genus *Aspergillus*, *Chaetomium* and *Trichoderma*. In addition, this biochar also improved soil qualities related to plant growth and development by increasing soil organic matter and N, P, and K content (Wang G. et al., 2020). Moreover, many studies on biochar exhibited that a relatively low application rate of biochar controlled the disease's severity, but higher application rates did not show positive impacts on eradicating plant diseases (Jaiswal et al., 2015). In recent decades, many studies have reported that biochar addition increases crop yield under normal circumstances and enhances productivity under adverse conditions, including heavy metals, drought, and salinity (Joseph et al., 2021). For example, biochar slightly elevated the permanent wilting point, retaining a greater amount of water at field capacity than water contained at the permanent wilting point (i.e., increased plant-available water) (Hafeez et al., 2017). Thus, enhancement in WHC of the biochar-treated soils can be applied as an agent for increasing plant-available water (Hafeez et al., 2017). In field and pot experiments conducted on sandy clay and sandy loam soils, biochars applied at the rates of 20 t ha^{-1} enhanced the wheat and soybean germination, seedling growth, and grain yield by reducing the water stress (Hafeez et al., 2017). Haider et al. (2015) presented that adding biochar in hostile sandy soils enhanced plant growth *via* increasing plant-soil water relations under drought and well-watered conditions. Tammeorg et al. (2014) found that biochar application improved the grain yield under water stress conditions. Adding biochars at high rates can control the adverse impacts of salt stress on the growth and development of plants (Akhtar S. S. et al., 2015). For example, applying 50 t ha^{-1} of biochar can mitigate the mortality rate induced by salt in Jute and extend the survival rate of *P. vulgaris*. Moreover, adding biochar at the rate of 5% increased crop yield in salt-induced soils, possibly by transforming the salt stress *via* Na^+ adsorption and enhancing K^+ content in the xylem, thereby improving potato yield (Akhtar S. S. et al., 2015). The dual application of maize stalk and rice husk biochar significantly enhanced the growth, physiology, productivity, grain quality, and osmotic stress tolerance of rice plants, as well as nutrient uptake and soil properties, probably due to the activation of the enzymatic antioxidant machinery, for example improved activity of antioxidant enzymes including POX, APX, and CAT (Hafeez et al., 2021). Under abiotic stress situations, wheat straw biochar promotes tolerance of different crops. In this respect, an increased nutrient supply to plants can improve their tolerance against abiotic stresses, e.g., in tomato plants, wheat biochar amendment increased vegetative growth, yield, and quality parameters under saline irrigation, due to the adsorption of Na + ions and the release of Mg^{+2}, Ca^{+2}, and K^+ (Zhu et al., 2020). Similarly, the application of wheat straw biochar in soybean plants subjected to salinity and drought increased the N content in the soil, favouring plant growth (Zhang H. et al., 2020). Another mechanism through which wheat straw biochar can increase plant tolerance to drought is the improvement of soil hydrophysical properties (soil water content, bulk density, and water holding capacity) reported in tobacco plants (Liu et al., 2021). Under abiotic stresses, such as drought and salinity, the application of biochar from maize has reported significant increases in plant tolerance. In quinoa plants, maize cob biochar increased the plant antioxidant machinery; reducing the accumulation of reactive oxygen species (ROS) and increasing nutrient uptake under drought and salinity stress (Nehela et al., 2021). However, in licorice plants grown with maize biochar in growth chambers, the increase of plant tolerance under salt stress was a consequence of an increased soil microbial enzymatic activity and nutrient supply to the plant (Egamberdieva et al., 2021). Biochar has also been shown to enhance salinity tolerance, alleviate drought stress, and mitigate the toxicity induced to plants by inorganic and organic soil pollutants. Drought stress alleviation in biochar-amended soils occurs through enhanced water holding capacity thanks to large surface area-to-volume ratio of biochar (Chew et al., 2022). Similarly, decrease in osmotic stress thanks to improved soil water content in addition to reduced Na^+ uptake due to Na^+'s transient binding on sorption sites on biochar alleviate soil salinity stress for plants in biochar-amended soils (Chew et al., 2022). Kumar et al. (2022) reported a decrease in thermal diffusivity (.6%–21.5%) and thermal conductivity (.3%–32.2%) in sandy loams after biochar addition. Further, there was a decrease in bulk density (24.7%–34.6%) and thermal diffusivity (10.4%–50.8%) of soil, and an improvement in moisture content after biochar addition. These changes decrease soil thermal conductivity (24.7%–59.8%), which ultimately moderates soil temperatures and influences plant growth and biochemical processes in soil. Xiong et al. (2020) re-affirmed that thermal properties are directly correlated with soil moisture and inversely related with soil bulk density and the addition of biochar reduces soil's thermal properties. Further, soil depth, moisture content, and biochar application rates affect soil temperature and volumetric heat capacity.

Biochar modifies the abiotic and microbial processes in the rhizosphere and increases nutrient mineralization and enhances the nutrient availability for plant uptake. Organic matter turnover increases in the soil due to accelerated microbial activity which improves nutrient availability. Hence, biochar enhanced the plant resistance against diseases, reduced the availability of heavy metals and improved the plant resilience against environmental stressors. However, future studies should consider the preparation and formulation of novel treatment methods to prepare modified biochars with improved physicochemical properties enabling a better amelioration of adverse impacts of biotic and abiotic stresses in plants.

6 Application of biochar for soil carbon sequestration/greenhouse gases emission (GHGs)

Applying biochar to various types of soils not only increases the soil fertility but also plays a key role in carbon sequestration/GHGs reduction (Figure 4). Dissolved organic carbon or soil carbon as presented in Table 8, represents carbon sequestration by biochar addition, thus increasing the storage of C in the soil and reducing GHGs emissions (Tang et al., 2022). Carbon sequestration to artificial or natural removal of atmospheric CO_2 and its storage in a stable solid form (Song et al., 2022). Naturally, atmospheric CO_2 can be directly absorbed through plants by photosynthesis process. Part of the absorbed CO_2 is released back into the atmosphere through respiration, and the rest is sequestered first as plant biomass and then as soil organic carbon during the decomposition process of the plant biomass (Zhou et al., 2022). Further decomposition of soil organic carbon discharges the C as CO_2 into the atmosphere within a short duration. Thus, the entire mechanism is carbon neutral (Kalu et al., 2022). Biochar is stable and its great content of aromatic C that is harder to decompose than plant biomass is the basis of the C sequestration paybacks of biochar. The pyrolysis of plant biomass breaks the natural C cycle and realizes carbon sequestration through biochar storage in the soil (Cara et al., 2022). It is assessed that around six GtC/yr of carbon biomass is accessible for biochar creation worldwide if 10% of net primary production is utilized, from which 3 GtC/yr of biochar can be created (Pan et al., 2022).

Carbonizing agricultural biomass residue (mainly livestock manure and crop straw) and storing the resulting biochar in soils through agricultural soil management have the benefit of solid waste recycling and show pronounced potential for sequestration of C (Nair and Mukherjee, 2022). Rendering to a calculation technique based on a life cycle assessment, 610 Mt/yr of livestock manure and 585 Mt/yr of crop straw are created in China, and converting them into soil biochar can sequester 172 and 264 Mt CO_2 e/yr, respectively (Deolikar and Patil, 2022). Yang C. et al. (2021) assessed the C sequestration potential of several crop waste-derived biochars *via* life cycle assessment at the state level and noticed that the annual C sequestration potential in China could reach around 500 $MtCO_2e$/yr. These findings proved the high C sequestration capability of crop wastes-derived biochars.

Layek et al. (2022) applied biochar derived from corn residue to a maize field under drip irrigation with mulching condition, and study findings exhibited that the sequestration of C enhanced by 16% in the upper 15-cm soil and CH_4 emission reduced by 132% after 30 t/ha of biochar addition. Moreover, the biochar treatment enhanced the yield of corn by 7.4% over 2 years. This example suggests that proper application of biochar could contribute to agricultural soil management and climate change mitigation simultaneously. An assessment of the biochar life cycle manifests that reduction in GHGs emissions is mainly associated with changes in feedstock production, biochar production, and storage and stabilization of C in biochar, reduction in emissions of N_2O from the agriculture sector (Osman et al., 2022). Generally, biochar treatment decreased the total GHGs (Castaldi et al., 2011). Nevertheless, biochar application impact on various GHGs such as N_2O, CH_4, and CO_2 varies significantly. Biochar treatments usually decrease CO_2 production by enhancing carbon stabilization (Castaldi et al., 2011). Non-etheless, no significant impact was observed in the case of soil CO_2 respiration during the field study (Hamamoto et al., 2022). The differences created from techniques applied for CO_2 calculation, CO_2 that originated from the biochar was subtracted from the biochar-soil combination to ascertain the biochar effect on the soil respiration (Zhao et al., 2022). Biochar's impact on methane emission varied significantly. Feng et al. (2012) reported that the paddy methane emissions substantially reduced after biochar treatments, possibly not due to the suppression of methanogenic growth. It might have resulted from the variable proportion of methanogenic to methanotrophic richness. Methane fluxes did not differ considerably in response to different treatments (Castaldi et al., 2011).

In some cases, total methane emission was found to be increased with biochar addition. It could have happened due to the inhibitory effect of biochar chemicals on the methanotroph's activity (Zhang A. et al., 2010). In contrast, a net reduction up to 50% in CH_4 emission was observed in saturated peat soils after biochar application, which was attributed to the increased activity of methanotrophs in the oxic rhizosphere (Cong et al., 2018; Nguyen et al., 2020). Under well-drained conditions, the CH_4 consumption was decreased by ash-rich biochars, probably due to an increased electrical conductivity in the soil solution thus hindring the methanotroph activity (Pascual et al., 2020). Moreover, sorbed hydrocarbon elements of biochar could decompose and emerge as a competitive source of substrates, stimulating CH_4 emissions by reducing CH_4 oxidation activity (Jandl et al., 2013). Biochar applications have been reported to decrease N_2O emissions in laboratory experiments (Case et al., 2012; Lehmann et al., 2021).

In biochar amended field, fluxes of soil N_2O ranged from 26%–79% as compared to nitrous oxide fluxes observed in control (Castaldi et al., 2011). The fixed N increased from 50% without biochar addition to 70% with biochar addition at the rate of 90 g kg^{-1}, and N_2O fluxes reduced (Rondon et al., 2007). On the contrary, high N-enriched biochars have promoted the emission of N_2O (Zhang H. et al., 2010). These results exhibited the efficiency of biochar addition to influence the proportions of N-cycling in the soil *via* improving ammonia adsorption and nitrification rates and enhancing ammonia storage through increasing the soil CEC (Dawar et al., 2021), hence changing the efficacy of N input into soil system (Osman et al., 2022). Biochar manufactured from woody feedstocks and agricultural waste substantially impacts the NH_3, N_2O, and CH_4 emission mitigation. These emissions can be decreased significantly by applying biochar at the rate of 10% w/w. Biochar pyrolyzed at higher temperatures strongly impacts the mitigation of N_2O and CH_4 emissions. However, biochar produced at low temperatures is more efficient in decreasing NH_3 emissions (Yin X. et al., 2021).

Biochar application provided combined benefits of carbon sequestration and GHG emission reduction which are the key to achieving carbon neutrality goals. However, efficacy of biochars in enhancing C sequestration and reducing GHGs could be improved by preparing specific biochars based on the scientific results demonstrated by different studies. Therefore, attention should be paid to the development of special biochars to get maximum benefit from this commodity to make our environment more sustainable.

7 Biochar application for agricultural sustainability

Biochar is a potentially strong candidate for improving agricultural sustainability by increasing soil health, crop yields and decreasing the use of chemical fertilizers. Various applications of biochar utilization and future research directions are described below.

1. Biochar may comprise toxic elements, including heavy metals, dioxin, and PAHs. It cannot be eliminated once it is added to soils. The toxicity of biochar must be measured before biochar application as a soil conditioner to decrease long-term hazards to crops and soil.
2. Biochar incorporation into alkaline soils is not as productive as in addition to acidic nature soils regarding crop yield. Usually, slow pyrolyzed biochars have low pH values and, therefore can be

efficient for amending high pH soil (alkaline soil). Biochars can be added in combination with humic acid and acidic chemical fertilizers. Future investigation should focus on functional biochar addition to alkaline calcareous and sandy soils of arid areas; feedstock selection, preparation temperatures are vital when designing the functional biochars.
3. Biochar's recommended addition rates to enhance the advantages under specific circumstances are not well-defined yet. Generally, utilizing large amounts of biochar is not conceivable for small-scale farmers. Therefore cost-benefit investigation regarding the use of biochar must be implemented across various cropping systems. Applying biochar in pots while growing nursery plants can be a cost-efficient method for small-scale farmers to follow biochar technology.
4. The impacts of biochar addition on beneficial microbes under field experiments remain largely unclear. However, the co-application of bacteria and biochar can stimulate plant growth and development and increase nutrient use efficiency.
5. The laboratory scale research should be synchronised with field studies. Difference in weather, soil qualities and environmental conditions may render discrepancy between laboratory and field studies. Therefore, long-term and broad scale field investigations are needed to explore the impact of biochar on different soil properties.
6. The long term studies are needed on processes that affect the capture and release of heavy metals in the long term to plan an optimum scheduling of biochar re-application.
7. Studying the effects of biochar properties on microbial nutrient cycling and root membrane potential will facilitate the development of optimal formulations to increase nutrient uptake efficiency.
8. Biochar based carbon trading market could be establish to recognize the GHG reduction and carbon sequestration benefits. The farmers willing to use biochar should be facilitated with incentives.
9. In view of high costs of biochar, more research on biochar modifications (using pre-or post-treatments) are crucial to maximize the advantage of "low dose with high efficiency".

8 Conclusion

Biochars are broadly diverse and can have several impacts on soil attributes, crops growth and production. The feedstock and the pyrolysis conditions largely influence the properties of biochar and its effects on agricultural ecosystems. Biochar formulations applied at an optimal rate can significantly increase yields under site-specific soil constraints, nutrient, and water-limited conditions. Low temperatures pyrolyzed biochars may improve the availability of nutrients and crop productivity in both types of soils (alkaline and acidic). In contrast, biochars derived at high temperatures may increase soil carbon sequestration for the long-term. The average yield increases of 10%–40% were observed with biochar addition. Biochar reduces the availability of heavy metals, enhances plant resistance potential to various diseases, and increases resilience to different environmental stressors (biotic, abiotic drought, and salt). Biochar accelerates microbial activity, which can enhance the mineralization of nutrients and promote the nutrient uptake mechanism by plants. Biochar selection, its application rates, and compatibility with cropping systems should be considered before biochar addition. Sequestering large amounts of carbon biochar reduces GHGs emissions. A clear understanding of variable effects of biochar on soil and plant systems could facilitate biochar preparation for specific applications through proper feedstock selection by adjusting process conditions and pre- or post-production treatment of biochar that govern the pH, nutrient availability, and adsorption capacity. Guidelines regarding the selection and production of biochar to meet specific soil and environmental constraints should be developed.

Author contributions

Original draft (GM and ZA); writing, review and editing (MU, BA, DN, AU, AK, SB, SME and RI); data collection (DN, MUH, AU and AK); resources and supervision (ZA, GM, IA, MUH and AT); Funding acquisition (SB, IA and SME).

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Conflict of interest

Publisher's note

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