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Biochar ameliorates heavy metals and polycyclic aromatic hydrocarbons in the soil-plant interface

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ABSTRACT

Biochar (BC), a carbon-rich material produced through the pyrolysis of organic feedstocks, offers a promising approach for remediating soils contaminated with heavy metals (HMs) and polycyclic aromatic hydrocarbons (PAHs). This review focuses the role of BC in ameliorating HMs and PAHs contamination at the soil–plant interface. Biochar incorporation enhances soil health by improving physico-chemical properties (e.g., water retention, nutrient availability, cation exchange capacity) and stimulating microbial activity. Moreover, it mitigates the phytotoxicity of HMs and PAHs by immobilizing them through direct adsorption, complexation, and precipitation, thereby reducing their bioavailability to plants. A notable knowledge gap remains concerning contaminant mobilization and residual effects following BC application. However, this review primarily emphasizes the sorption capabilities of BC, while providing limited exploration of its multifaceted effects on plant growth under co-contaminated soil conditions. Furthermore, variations in feedstock type, pyrolysis conditions, and application rates lead to inconsistent outcomes, limiting large-scale field adoption. Also, this review highlights the need for future research to: (i) evaluate BC's long-term performance in diverse agroecosystems, (ii) assess the potential ecological risks and food safety concerns, (iii) explore synergistic applications of BC with other soil amendments, and (iv) develop standardized protocols. Addressing these knowledge gaps will facilitate the safe and effective integration of BC into sustainable agricultural practices and environmental remediation strategies.

1. Introduction

Soil contamination by heavy metals (HMs) and synthetic organic pollutants is a growing issue worldwide that threatens sustainable agriculture and food safety (Crisan et al., 2024). These persistent pollutants can be taken up by plants, thereby entering the food chain and posing significant risks to the ecosystem and human health (Cheng et al., 2025; Hameed et al., 2024). They adversely affect plant growth, physiology, and biochemistry ultimately reducing crop yields and compromising the quality of agricultural produce. (Sarfraz et al., 2024). Plants exposed to HMs typically suffer from severe phytotoxicity, primarily due to the increased production of active radicals, including reactive oxygen species (ROS) (Zulfiqar et al., 2022; Li et al., 2022). These ROS lead to disruptions in chlorophyll biosynthesis, degradation of lipid membranes, and imbalances in cellular redox homeostasis (Hameed et al., 2024). Similarly, polycyclic aromatic hydrocarbons (PAHs) can be absorbed through roots or foliage, inducing cellular toxicity in plants. (Jiang et al., 2025). The accumulation of these pollutants in edible tissues of plants leads to contamination of the food chain (Guo et al., 2023). Recent studies have demonstrated that human exposure to such pollutants via consumption of contaminated foods causes severe health problems (Zheng et al., 2024). Therefore, safeguarding public health

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and food security requires both the prevention of pollutant emissions and the effective remediation of contaminated soils within sustainable agricultural frameworks (Shetty et al., 2023).

A range of physico-chemical and biological methods, including soil washing, vitrification, chemical oxidation, electrokinetics, solidification/stabilization, bioremediation, and phytoremediation, have been employed to remediate contaminated soils (Zheng et al., 2024; Jiang et al., 2020). Among these, biochar (BC) amendment has emerged as a particularly feasible alternative (Wu et al., 2017). BC is widely recognized for improving soil quality, enhancing crop productivity, and increasing resilience to environmental stresses (Ma et al., 2022; Wu et al., 2017; Jing et al., 2020). Biochar is a carbon-rich material produced via the pyrolysis of agro-industrial wastes (e.g., corn stalks, rice husks, wood chips, etc.) under oxygen-limited conditions at temperatures ranging from 200 ℃ to 900 ℃ (Fig. 2). Besides pyrolysis, other techniques like gasification, hydrothermal carbonisation, flash carbonisation, and torrefaction can also effectively convert feedstock to bulk-BC but result in materials with different properties (Ippolito et al., 2020; Zhang et al., 2017). The effectiveness of BC is driven by key physicochemical properties, including high specific surface area (SSA), porosity, pH, cation exchange capacity (CEC), and inherent nutrients (e.g., nitrogen, potassium, phosphorus; Khan et al., 2022; Ma et al., 2024). These characteristics collectively confer multiple benefits, such as enhanced soil structure and fertility, improved microbial activity, increased carbon sequestration, and effective immobilization of soil pollutants (Shi et al., 2024; Zhang et al., 2020; Xiao et al., 2018).

A key advantage of BC lies in its strong capacity to immobilize soil contaminants, thereby mitigating their adverse effects on plants (Haider et al., 2022; Lu et al., 2025). Biochar can directly or indirectly interact with HMs and PAHs in soil through several mechanisms including (i) ion exchange, (ii) electrostatic attraction, (iii) co-precipitation, and (iv) complexation (Singh et al., 2025). This sequestration decreases pollutant phytoavailability and consequently reduces their uptake by plants (Natasha et al., 2022). The BC-induced reduction in pollutant bioavailability further limits the uptake of HMs and PAHs by plants, thereby decreasing phytotoxicity and ROS generation, and alleviating oxidative stress (Hasnain et al., 2023). Consequently, the application of BC to contaminated soils can alter the biogeochemical behavior of pollutants at the soil–plant interface through both direct and indirect pathways (Sarfraz et al., 2024). However, depending on feedstock types, pyrolysis conditions, and application rates and duration, BC addition may have unintended consequences for both the soil and ecosystem (Ippolito et al., 2020), due to the gradual release of various toxic compounds (e.g., HMs, benzene, PAHs, phenols, and carboxylic acids) over time (Qian et al., 2016; Wang et al., 2015).

Previous research has extensively documented the sorption and desorption capabilities of BC in soils contaminated with either HMs or PAHs (Cheng et al., 2025; Fan et al., 2022). However, data on its potential impacts on plant growth in multi-contaminated soils remains limited. The sorption of pollutants by BC in soil may be influenced by the existence of other essential nutrients, as they compete for binding sites (Ippolito et al., 2020). Consequently, it is critical to develop a comprehensive evaluation system to assess the multifaceted effects of BC-amended soil in relation to specific soil management objectives (Wang et al., 2017). This present review offers a comprehensive analysis of previously published research, highlighting potential trends related to BC-induced changes in the physical, chemical, and biological properties of soils, morpho-physiological characteristics of plants and the transfer of pollutants between soil and plants. For this purpose, a systematic literature search was conducted using the Web of Science database to establish a robust information base on BC applications for sustainable agriculture and contaminated-soil remediation (Fig. 1). The database was assessed on 20 August 2024, focusing on publications from 2010 to 2024, utilizing the primary search terms "biochar" and “soil”. Based on this scope, the review is guided by the following objectives: 1) To examine how BC production parameters govern its properties and subsequent effects on soil health; 2) To elucidate the distinct mechanisms for immobilizing HMs and enhancing PAHs degradation; 3) To evaluate the role of BC amendments in enhancing plant growth and stress resilience in contaminated soils; and 4) To outline key knowledge gaps and future directions for effective field application of BC. To achieve these objectives, this review systematically synthesizes findings on the effects of BC application on soil properties and the remediation of HMs and PAHs within the soil–plant system.

2. Production and properties of biochar

Biochar is a carbon-rich material produced primarily through pyrolysis, a thermochemical process that decomposes biomass such as agricultural residues, food waste, and sewage sludge in oxygen-limited conditions at temperatures typically above 300 ℃ (Haider et al., 2022; Fig. 2). The characteristics of BC are highly variable and are determined by key production parameters, including pyrolysis type (fast or slow), feedstock, temperature, and residence time (Chi et al., 2024; Qiu et al., 2023). Feedstock selection is a critical determinant in BC production due to the inherent heterogeneity of biomass (Wang et al., 2017). The primary constituents of biomass (lignin, cellulose, and hemicellulose) have distinct chemical structures and decompose differently during pyrolysis; this variability presents a fundamental challenge in predicting and controlling the characteristics of the BC (Zhang et al.,

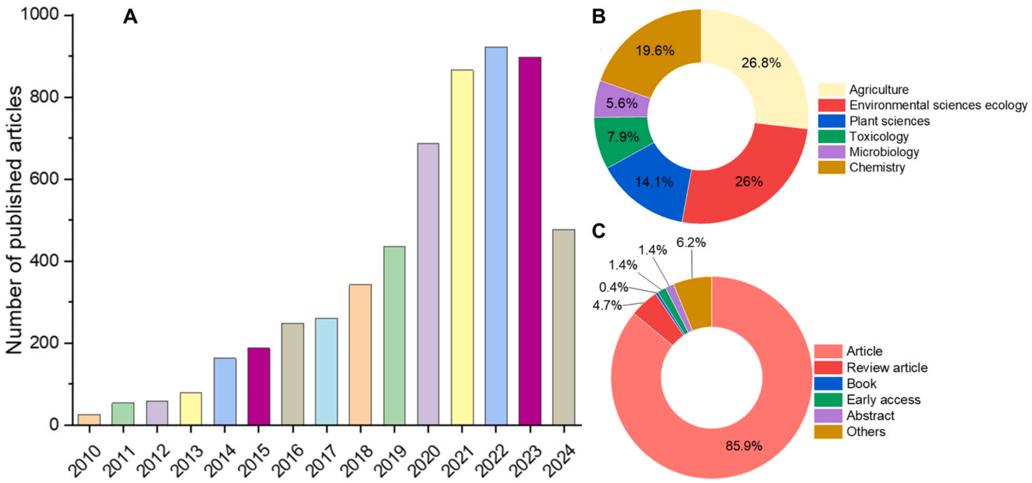

Fig. 1. Summary of publications retrieved using the keywords “biochar” and “soil”. (A) Number of papers published between 2010 and 2024; (B and C) Publications on biochar in different areas of research. Data accessed from the Web of Science database on 20 August 2024.

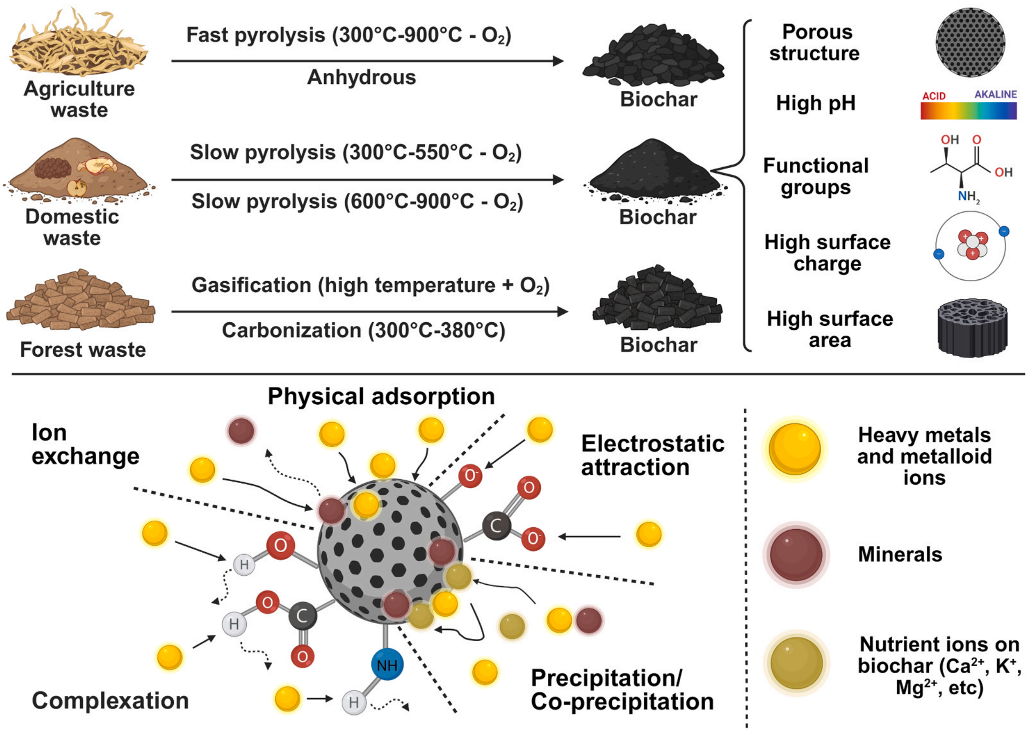

Fig. 2. Postulated mechanisms of biochar production, properties and interactions with various contaminants. Biochar possesses several mechanisms for contaminant immobilization such as 1) physical adsorption; 2) ion exchange between target metal and exchangeable metal in biochar; 3) electrostatic attraction of cationic and anionic metals; and 4) precipitation of target metal(loid)s.

2023). Biochar derived from lignocellulosic biomass (e.g., rice straw, wheat straw) has been effectively used for HM adsorption in soil remediation (Haider et al., 2022). Furthermore, co-pyrolysis of different feedstocks (e.g., seaweed with corn straw) can create synergistic effects, enhancing the BC's suitability as a soil amendment by modifying its nutrient content (Ippolito et al., 2020). While non-lignocellulosic feedstocks like animal manures and sewage sludge are also used, their application is less common for remediation due to concerns about higher inherent contaminant loads (e.g., HMs, pathogens) which could pose secondary pollution risks in soil (Singh et al., 2025). This underscores that pyrolysis is not a one-size-fits-all process but can be tailored through feedstock selection and process parameters to produce BC with specific properties for environmental applications.

Beyond conventional pyrolysis, BC can be produced through alternative thermochemical conversion methods such as gasification, hydrothermal carbonization, and torrefaction, each yielding a material with distinct properties (Wang et al., 2017). For instance, gasification operates at high temperatures ($\geq$ 700 ℃) with a controlled supply of steam and oxygen, primarily aimed at producing syngas (hydrogen and carbon monoxide) (Cheah et al., 2014). Consequently, the resulting BC is typically a low-quality by-product with limited suitability for soil amendment (Ippolito et al., 2020). In contrast, torrefaction (often termed "mild pyrolysis") occurs at lower temperatures and produces a hydrophobic solid with a low O/C ratio (Pimchuai et al., 2010). However, its application can be limited by elevated levels of inorganic metallic compounds (Weber and Quicker, 2018). Hydrothermal carbonization processes biomass with water at elevated temperatures (up to 250 ℃) and pressure, making it ideal for wet feedstocks (Dai et al., 2017). This technique yields a carbon-rich “hydrochar” with enhanced carbon stability, making it a promising soil amendment for improving fertility and carbon sequestration (Weber and Quicker, 2018).

The conversion of agro-industrial wastes into BC not only creates a valuable soil amendment but also provides a sustainable approach for managing organic waste and enhances climate change resilience through carbon sequestration (Wang et al., 2015). However, BC derived from contaminated or hazardous recyclable materials may pose pollution risks to soils, plants, and humans by entering the food chain (Anyika et al., 2016). Subsequently, a thorough assessment of feedstock composition is essential to mitigate any potential ecological and health risks associated with BC production and application.

2.1. *Physical characteristics of biochar*

The functionality of BC is governed by its physical characteristics, which include bulk density, SSA, pore size distribution, and water holding capacity (WHC; Ippolito et al., 2020). Bulk density is a crucial characteristic to consider when dealing with BC (Haider et al., 2022). Biochar typically exhibits a low bulk density (< 0.6 g cm^{-3}), which results from its porous structure (Ippolito et al., 2020). This porosity arises from the thermal decomposition of biomass (Singh et al., 2025). Pyrolysis of agricultural biomass at low to moderate temperatures (200–500 ℃) transforms lignin, cellulose and hemicellulose into aliphatic carbon structures, while high-temperature ($>$ 500 ℃) converts them into aromatic carbon forms with more defined pore structure (Wang et al., 2015).

The pore structures, categorized into macropores ($>$ 50 nm), directly determines the SSA, which is a critical property for pollutant adsorption (Zhang et al., 2021). Generally, increasing pyrolysis temperature (e.g., from 500 to 900 ℃ with a 2-hour residence time) enhances SSA and total pore volume by removing volatile matter and creating new pores (Qian et al., 2016). For instance, wood BC porosity can increase from 50 % to 70 % as temperature rises from 300 ℃ to 850 ℃ (Somerville and Jahanshahi, 2015). The SSA of BC increases with pyrolysis temperature due to the development of a more complex pore structure (Table 1). Micropores often dominate this pore volume, comprising up to 80 % in activated BCs (Brewer et al., 2014). However, excessively long residence times can cause pore collapse, reducing SSA and pore volume (Haider et al., 2022). It is important to note that SSA varies significantly with feedstock; for example, sewage sludge-derived BC often has an SSA below 100 m^2 g^{-1} due to high ash and mineral content (Sarfraz et al.,

Table 1
Physical and chemical properties of biochar relevant to pyrolysis temperatures and biomass raw materials.

Temperature (°C)	Feedstock	pH	Surface Area (m^2 g^{-1})	Porosity Diameter (nm)	Elements (%)				Reference
					Nitrogen	Carbon	Potassium	Phosphorus	
300	Sewage sludge	6.8	4.5	-	4.11	30.72	-	-	Ahmad et al. (2014)
500	Sewage sludge	7.3	26.2	-	2.84	20.19	-	-	Ahmad et al. (2014)
400	Palm waste	9.25	-	-	0.45	66.87	2.17	-	Usman et al. (2015)
700	Tea waste	10.2	342.22	1.75	3.39	73.6	-	-	Vithanage et al. (2016)
600	Rice husk	-	168	-	0.56	51.8	-	-	Yi et al. (2016)
550	Wheat straw pellets	9.81	26.4	-	1.39	68.3	0.62	0.16	Shen et al. (2017)
300	Husk	6.3	1.99	-	0.11	48.3	-	-	Yavari et al. (2017)
500	Rice straw	10	36.7	-	16.6	50.6	-	-	Lu et al. (2017)
400–500	Rice straw	7.9	8.9	-	1.3	74.9	0.001	-	Han et al. (2018)
700	Corn straw	10.4	553.8	3.785	0.39	38.84	-	-	Jia et al. (2018)
700	Rice husk	9.42	406.2	3.82	0.31	45.9	-	-	Jia et al. (2018)
500	Barley grass	9.97	35.4	8.20	1.07	60.9	-	0.27	Zhao et al. (2019)
600	Rice straw	8.83	65.5	-	1.66	59.6	-	-	Zhang et al. (2019)
500	Wheat straw	-	7.42	-	0.93	59.3	-	-	Meng et al. (2019)
550	Rice straw	9.4	-	-	2.65	7.9	0.04	0.12	Kamran et al. (2019)
500	Rice hulls	6.96	95.67	5.88	0.31	33.6	-	-	Wu et al. (2019)
500	Corn straw	9.97	9.97	2.39	0.71	57.33	-	-	Tang et al. (2019)
500	Peanuts shell	-	2.49	10.1	-		-	4.03	Ibrahim et al. (2019)

2024).

The water interaction of biochar is a function of two distinct properties: WHC and surface hydrophobicity (Singh et al., 2025). The WHC is primarily dictated by the total pore volume, which generally increases with pyrolysis temperature. In contrast, surface hydrophobicity is controlled by the presence of polar functional groups, which diminish at higher temperatures (Sarfraz et al., 2024). This creates an apparent contradiction: high-temperature BCs possess greater pore volume for retaining water but exhibit lower affinity for initial water absorption due to a more hydrophobic surface, as described by Pimchuai et al. (2010). Therefore, the efficacy of BC for a specific application is ultimately defined by the interplay between its pore architecture, SSA, and surface chemistry, all of which can be meticulously engineered through pyrolysis conditions.

2.2. *Key chemical properties of biochar*

The chemical features of BC, which dictate its environmental behavior and agronomic utility, are primarily a function of feedstock biomass and the specific conditions under which it is pyrolyzed (Haider et al., 2022). The key chemical properties encompass its elemental composition, pH, CEC oxygen/carbon (O/C), and hydrogen/carbon (H/C) ratios (Zhang et al., 2023). Among these, pH is an important property that markedly influences the BC's interaction with the soil environment and its other chemical properties (Singh et al., 2025).

The pH of BC is generally alkaline, typically ranging from 7.0 to 11.7, due to the presence of alkaline functional groups, carbonates, and inorganic ash (Zhang et al., 2020). The specific pH value depends heavily on the feedstock. For instance, BC from agriculture and forestry residues often has a pH of 7.0–10.4, while BC from sludge or animal manure can exceed pH 11 due to higher mineral oxide and carbonate content (Ippolito et al., 2020; see Table 1). Pyrolysis temperature is another key factor influencing BC pH; with increasing temperature, the decomposition of acidic functional groups and the accumulation of ash contribute to elevated pH values (Ahmad et al., 2014; Chen et al., 2014).

The surface chemistry of BC is generally defined by functional groups such as carboxyl (-COOH), hydroxyl (-OH), and carbonyl ($-C{=}O$), which are influenced by biomass type and pyrolysis conditions (Zhang et al., 2023). BCs derived from herbaceous and woody biomass undergo enhanced volatilization of organic acids and decomposition of acidic functional groups, thereby reducing their abundance (Wang et al., 2015). These groups are crucial because they directly determine the CEC, which is the BC's ability to hold and exchange positively charged nutrients (Singh et al., 2025). At lower pyrolysis temperatures, the concentration of these oxygen-containing functional groups is higher, leading to a greater CEC (Yuan et al., 2013). The mechanism of CEC involves dissociation of these groups (e.g., $-COOH \rightarrow -COO^{-} + H^{+}$), which generates negative surface charge, enhancing the BC's ability to adsorb cations like ammonium and potassium (Ippolito et al., 2020). This loss of acidic protons at elevated temperatures also explains the observed increase in BC pH, thereby linking surface chemistry to its interactions with the soil environment.

The elemental composition and stability of BC are assessed using atomic ratios (Munera-Echeverri et al., 2018). A decrease in the H/C and O/C ratios with increasing pyrolysis temperature indicates greater carbonization and the formation of a stable, aromatic structure (Haider et al., 2022). This structural stability is a primary factor governing BC interaction with soil nutrients and their bioavailability (Cheah et al., 2014). Biochar produced at lower temperatures generally retains more volatile nutrients and has a higher abundance of functional groups, making nutrients like phosphorus and potassium more readily available to plants (Tian et al., 2018). For example, maize stalk BC pyrolyzed at 300–400 ℃ improved nutrient uptake more effectively than BC produced at > 500 ℃ (Naeem et al., 2016). Furthermore, pyrolysis can transform nutrient species; for instance, it can create organosulfur compounds or heteroaromatic nitrogen compounds, which influence the BC's value as a slow-release fertilizer (Chi et al., 2024).

Overall, the chemical properties of BC are not universal but can be strategically engineered through the selection of feedstock and pyrolysis conditions (Zhang et al., 2023). Understanding these relationships is essential for designing BC amendments to address specific soil limitations, such as acidity or low nutrient retention, thereby optimizing its agricultural benefits. Future research should focus on refining these thermal processes to maximize BC's effectiveness for targeted applications.

3. Effects of biochar on soil properties

Modern agricultural practices and various geographical factors have contributed to soil compaction stress, which deteriorates soil physical structure and ultimately hinders plant root development (Zhang et al., 2021). Because of its inherent porosity, SSA, and functional groups, BC has been widely adopted for usage in soil quality improvement, with carbon content classically ranging from 60 % to 80 % (Chi et al., 2024; Ippolito et al., 2020). The long-term efficacy of BC is evidenced by the deep black soils, also known as "terra preta," that were thoroughly constructed by ancient Amazonian civilisations a millennium ago (Jien and Wang. 2013). To evaluate soil quality and select appropriate indicators for assessment, it is important to choose parameters relevant to management practices (Schmidt et al., 2021). The following sections will discuss the effects of BC on key soil physicochemical properties, as well as on biological indicators such as microbial biomass, respiration, and enzymatic activities.

3.1. *Effects on soil physical properties*

The application of BC can significantly enhance soil physical properties, including structure, WHC, and porosity (Haider et al., 2022; Ali et al., 2020). The extent of these improvements is highly dependent on the specific properties of both the BC and the soil (Sarfraz et al., 2024). The primary mechanism is the introduction of a network of stable pores into the soil matrix, which alters its physical architecture (Ippolito et al., 2020). Consequently, BC amendment promotes soil aggregation and stability, improves water and nutrient retention, and reduces susceptibility to erosion and leaching. These combined effects contribute to improved soil quality and enhanced plant growth (Ali et al., 2019; Fig. 3).

3.1.1. *Soil porosity and bulk density*

Soil bulk density is a key factor influencing soil productivity, as it indicates soil compaction, impacts plants resistance to environmental stresses, and plays a role in supporting root growth (Chi et al., 2024). The utilization of BC enhanced the porosity of the soil, leading to a reduction in soil bulk density (Herath et al., 2013; Aslam et al., 2014). The soil's overall porosity increases in direct proportion to the increase in BC dosages (Liu et al., 2020). Masulili et al. (2010) demonstrated that the addition of rice husk BC markedly increased total pore volume and accessible water, and reduced penetration resistance. The application of BC markedly changed soil porosity ranging from 5 to 25 μm (Rasa et al., 2018). The soil bulk density of BC-amended soil markedly reduced from 1.42 g cm^{-3} to less than 1.15 g cm^{-3} over 105 days of incubation, with the reduction rate increasing as the BC application rate was raised (Jien and wang. 2013). Biochar amendment at a rate of 100 t ha^{-1} decreased soil bulk density by 32 % compared to the unamended control (Fang et al., 2016). The reduction in soil bulk density reflects an increase in total soil porosity, signifying enhanced soil aeration and improved moisture permeability (Rasa et al., 2018). The reduction in soil bulk density, coupled with the intrinsic porosity of BC, contributes to a higher WHC in amended soils, which promotes root growth and enhances soil microbial activity (Ameloot et al., 2013). The decrease in soil bulk density has a beneficial impact on various soil parameters including WHC, aggregation, texture, structure, as well as chemical and biological characteristics.

3.1.2. *Soil aggregation*

Soil aggregates are critical for soil health, preserving soil organic matter, improving soil structure, porosity, facilitating water infiltration, encouraging root growth, and promoting microbial activity (Zhang et al., 2021). Biochar amendment significantly influences soil aggregation (Peng et al., 2016). For instance, the application of peanut hull and maize straw BC (7.8 t ha^{-1}) markedly increased the proportion and average weight of macro-aggregates (Ma et al., 2016). The impact of BC on the stability of soil aggregates is highly dependent upon its texture, with a more pronounced effect typically observed in coarse-textured (sandy) soils compared to fine-textured soils (Rasa et al., 2018; Ouyang et al., 2013). The mechanism involves a complex interaction

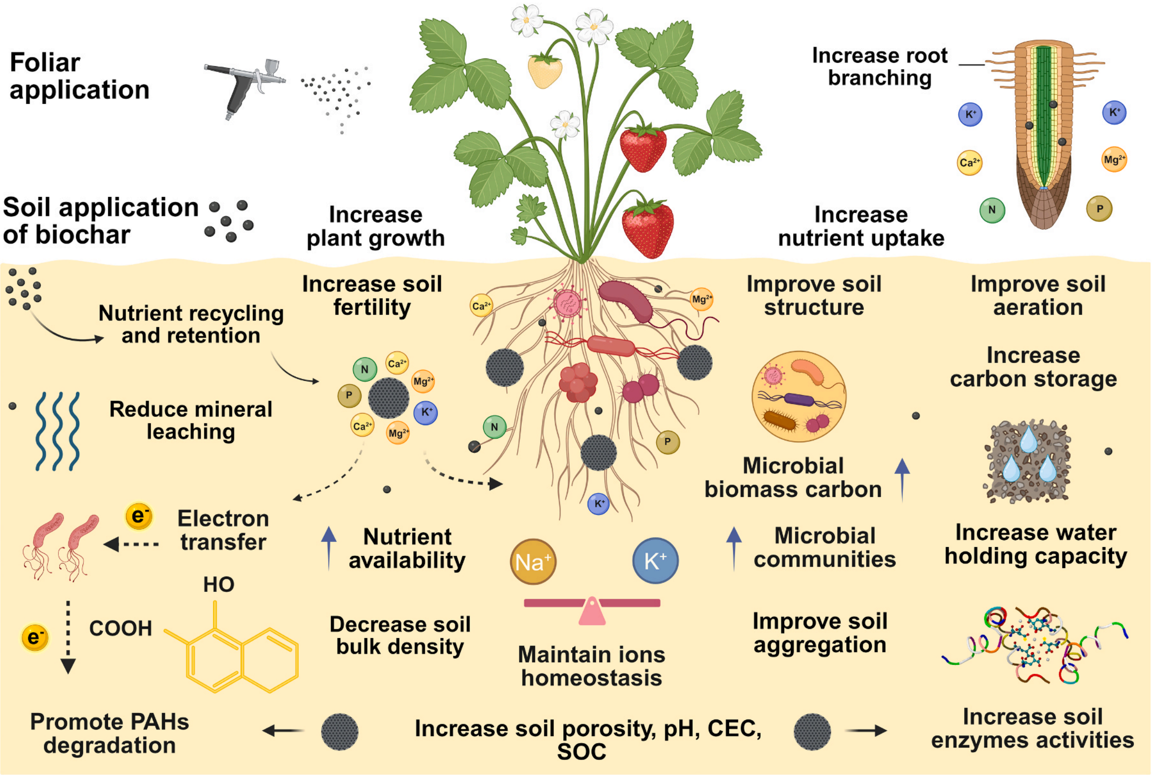

Fig. 3. A schematic illustration depicting the key mechanisms through which biochar amendment enhances soil physical, chemical and biological properties. (1) The porous nature of biochar increases soil pore space, enhancing aeration and facilitating root penetration. (2) Biochar can enhance soil infiltration rates, reduce surface runoff and promote groundwater recharge. (3) Biochar can raise soil pH which provides plausive environment for microbial activities. (4) By adsorbing enzyme molecules, biochar affects soil enzyme activities and nutrient cycling. (5) Electron transfer processes on the biochar surface can generate free radicals, which facilitate the degradation of organic contaminants and the transformation of heavy metals, thereby reducing their toxicity to microbes. Collectively, these mechanisms enhance soil fertility and ecosystem functioning by promoting a more active and diverse soil microbiome, which in turn supports plant growth and increases agricultural productivity.

among BC, soil organic matter, minerals, and microbial activity (Peng et al., 2016). Biochar can raise soil pH, stimulate soil microbial activity, and function, which contributes to the soil aggregate formation (Singh et al., 2025). Specifically, enhanced microbial activity leads to the production of binding agents like polysaccharides and glomalin, which adhere soil particles together (Aslam et al., 2014). Additionally, BC inputs can boost soil organic matter, helping to bind soil particles together and promote their aggregation, which in turn improves the stability of soil aggregates.

3.1.3. Soil Hydrological process

Biochar amendment significantly influences a suite of interconnected soil hydrological properties, including water retention, hydraulic conductivity, infiltration, runoff, and erosion resistance. The primary mechanism stems from BC's introduction of a persistent, porous network into the soil matrix, which directly enhances soil water storage and plant-available water (Hardie et al., 2014). For instance, incorporating 5 % and 25 % biochar into a sandy soil increased water retention by 260 % and 370 %, respectively (Brockhoff et al., 2010). Such improvements in soil moisture availability can directly translate to higher crop yields, as evidenced by a three-year field study where corn yields eventually increased by 28–140 % following biochar application (Vitkova et al., 2017).

The impact of BC on water movement is multifaceted. Its inherent porosity can alter soil hydraulic conductivity, but the promoting or inhibiting effect largely depends on the specific characteristics of both BC and soil (Zhang et al., 2023). For example, the addition of BC derived from *Robinia pseudoacacia* increased water-holding capacity by 97 % and saturated water content by 56%, while simultaneously decreasing the hydraulic conductivity of sandy soils (Uzoma et al., 2011). On the other hand, Barnes et al. (2014) demonstrated that *Prosopis sp.*—derived BC reduced hydraulic conductivity (67 %) in organic soil, and 92 % in sandy soil, but led to a 328 % increase in clay-rich soil. According to Major et al. (2010), the application of BC markedly increased the saturated hydraulic conductivity, rising from 2.60 to 13.3 cm h^{-1}. This duality underscores the importance of BC properties, indicating that variations in application rate, particle size, and soil characteristics can lead to highly variable effects on soil hydrological behavior.

These changes in water storage and movement collectively affect broader hydrological processes. By improving soil aggregation and porosity, BC generally enhances water infiltration, reduces surface runoff, and mitigates soil erosion (Sun et al., 2018). Applications of 2.5 % and 5 % (w/w) BC have been shown to reduce soil loss by 50 % and 60 %, respectively (Jien and Wang, 2013). However, the efficacy in erosion control is also contingent upon BC characteristics. In a silty loam soil, erosion increased with the application of fine BC particles but decreased with larger particles, indicating that particle size must be matched to soil texture for optimal performance (Li et al., 2019; Chi et al., 2024).

Biochar holds significant promise for managing the soil water balance and mitigating land degradation. However, predicting its hydrological outcomes requires a holistic understanding of the complex interactions between specific biochar properties (e.g., porosity, particle size, and hydrophobicity) and the inherent characteristics of the target soil.

3.2. Effects on soil chemical properties

3.2.1. Soil pH

Soil pH is a basic property governing soil chemical dynamics (Singh et al., 2025). The application of BC can markedly alter soil pH, and the direction and magnitude of these changes depend on the properties of BC and the prevailing soil conditions (Ippolito et al., 2020). In acidic soils, BC typically increases pH due to its inherent alkaline nature, which stems from the presence of carbonates, oxides, and hydroxides of alkali and alkaline earth metals (Dai et al., 2017). Moreover, negatively charged functional groups (e.g., hydroxyl, phenolic, carboxyl) on the BC surface can bind H^+ ions in the soil solution, reducing their activity and thereby raising the pH (Chintala et al., 2014).

On the contrary, in alkaline soils, BC can sometimes induce a slight pH decrease. This acidifying effect is attributed to the release of acidic compounds, either from the oxidation of BC's labile carbon fractions or from the decomposition of soil organic carbon (Zhang et al., 2019; Dias et al., 2010). In addition, BC can influence the speciation of carbonates; for instance, it can promote the conversion of sodium carbonate to calcium carbonate, which has a lower hydrolytic pH (Liu et al., 2020). Nevertheless, the high buffering capacity of calcareous soils often mitigates significant pH shifts, even at higher application rates (Ippolito et al., 2014). The net effect is complex, as demonstrated by the application of acidic, steam-activated BC, which successfully lowered pH in calcareous soils, while alkaline BC like those from poultry litter can raise pH beyond optimal levels, potentially reducing nutrient availability (Ippolito et al., 2016; Novak et al., 2014). These findings underscore that BC's efficiency as a soil amendment is context-specific, demanding further research into the long-term interactions between BC types, soil properties, and climate to guide tailored agricultural applications.

3.2.2. Soil cation exchange capacity

The soil's CEC is usually used to assess its ability to absorb, retain, and exchange cations, a critical factor for soil fertility (Munera-Echeverri et al., 2018). The SSA, surface functional groups (-OH, -COOH) and the number of cation exchange sites of BC can change soil CEC (Wang et al., 2017). A high CEC enables soils to adsorb and retain cationic nutrients (e.g., magnesium, potassium, ammonium, and calcium), thereby enhancing their availability for plant use and reducing leaching losses (Ippolito et al., 2014). The CEC of BC is not static. Fresh BC often has a limited CEC, but upon incorporation into the soil, it undergoes a process called "aging" or "weathering," where surface oxidation increases the number of carboxyl groups (Chintala et al., 2014). This aging process, however, is complex; for instance, a 4-month-aged wood BC showed a 10 % decrease in CEC after incubation, highlighting that changes are not always positive and depend on environmental conditions (Zhao et al., 2015). Moreover, some studies report no significant change in soil CEC following BC amendment, particularly in sandy soils. The laboratory incubation investigation conducted by Basso et al. (2013) found that the addition of 3 % and 6 % w/w hardwood BC did not change the CEC of the sandy soils, indicating that the effect is not universal.

The ultimate effect on CEC is governed by feedstock and pyrolysis conditions (Singh et al., 2025). Higher pyrolysis temperatures typically lead to the loss of functional groups, resulting in a lower CEC and a higher C/O ratio (Ippolito et al., 2020). Positive correlations have been observed between the CEC and C/O ratios of BC. The BC application produced at 450 ℃ to 700 ℃ temperatures decreased soil CEC from 26.34 cmol kg^{-1} to 10.27 cmol kg^{-1} (Fang et al., 2016). The CEC of BC prepared from sugarcane and straw at 750 °C were 13 cmol kg^{-1} and 48 cmol kg^{-1}, and the C/O ratios were 0.091 and 0.105, respectively, indicating that the CEC of BC is related to feedstock used and the C/O ratios (Jeong et al., 2016). Due to the partial decomposition of cellulose in various plants under lower-temperature conditions, many O-containing functional groups (-C=O, -OH, and -COOH) are preserved, leading to higher CEC and C/O ratios (Ouyang et al., 2013). Usually, the CEC remains lower until the pyrolysis temperature surpasses 420 ℃, as the nutrients in the biomass varied with pyrolysis temperature (Munera-Echeverri et al., 2018). Therefore, the key to using BC for CEC enhancement lies in selecting a low-temperature BC derived from a feedstock rich in oxygen-containing compounds.

3.2.3. Soil organic carbon

Biochar application directly enhances soil organic carbon stocks due to its high aromatic carbon content, which contributes to long-term carbon sequestration (Zhang et al., 2017). Generally, BC produced at lower temperatures contains more labile carbon than that generated at higher temperatures (Ippolito et al., 2020). This is evidenced by the higher accumulation of soil organic carbon observed with rice straw BC produced at lower temperature compared to higher temperature (Wang et al., 2014). Additionally, BCs generated at higher temperatures contain a significant amount of fixed aromatic carbon (C-C bonds), enhancing their stability, while low-temperature BC's possess many labile substrates (C-H bonds) (Ippolito et al., 2020). The net increase in soil organic carbon following BC amendment is not solely due to the direct input of stable carbon (Yuan et al., 2025). It is also a combined effect of interactions with the soil biota, including the promotion of microbial biomass, the physical protection of native soil organic carbon within newly formed aggregates, and the addition of carbon from root exudates in the rhizosphere (Pandian et al., 2016). Additionally, specific BC properties can suppress mineralization. For instance, corn stover BC with a higher ash concentration and lower volatile matter resulted in a reduction in carbon mineralization in mollisols (Chi et al., 2024). By mitigating the loss of native soil organic carbon and adding stable carbon, BC can increase soil organic carbon by up to 30–35 % (Jeong et al., 2016), which concomitantly enhances the soil's nutrient and water retention capacity.

3.2.4. *Soil nutrients availability and retention*

Biochar improves soil fertility by enhancing nutrient retention and availability, primarily through two mechanisms: its higher SSA and abundant surface functional groups (e.g., hydroxyl, carbonyl, carboxylic), which facilitate the adsorption and immobilization of nutrient cations (Hameed et al., 2024; Schmidt et al., 2021). This adsorption capacity significantly reduces nutrient leaching, thereby improving fertilizer use efficiency and mitigating the eutrophication of aquatic ecosystems (Natasha et al., 2022). By reducing fertilizer requirements, BC contributes to improved soil health and more sustainable nutrient management (Uzoma et al., 2011).

The nutrient retention efficacy of BC is well-documented (Singh et al., 2025). Numerous studies have demonstrated that the application of BC-based fertilizers in agricultural soils enhances nutrient use efficiency and retention (Ma et al., 2020; Dai et al., 2017). For example, BC derived from *Umbellularia californica* reduced the leaching of phosphate, nitrate, and ammonium by 20 %, 34 %, and 34 %, respectively (Agegnehu et al., 2017). Similarly, *Arachis hypogaea* BC decreased ammonium and nitrate leaching by 14 % and 34 % (Yao et al., 2012). Beyond retention, BC itself can act as a slow-release fertilizer, as it contains significant quantities of macro—and micronutrients essential for plant growth (Ippolito et al., 2020).

The overall impact of BC on nutrient dynamics is highly context dependent (Zhang et al., 2025). The magnitude of improvement in soil properties such as pH, available phosphorus, and nitrate levels varies with BC type, application rate, soil pH, and microbial interactions (Haider et al., 2022; Xu et al., 2014). Consequently, BC cannot be considered a universal amendment; its success hinges on matching its specific properties to the nutritional constraints and physicochemical characteristics of the target soil.

3.3. *Effects on soil biological properties*

Biochar application can significantly influence the soil biological properties by modifying the physical and chemical habitat for the microorganisms (Gul et al., 2015). These amendments can enhance microbial abundance, activity, and diversity, which in turn drive essential ecosystem functions such as nutrient recycling, organic matter decomposition, and overall soil structure formation (Dempster et al., 2012). A comprehensive understanding of these effects requires insight into how BC creates favorable microhabitats for the soil microbiome (Liao et al., 2022; Xu et al., 2014). Subsequently, BC is recognized as a promising tool for bioremediation and sustainable agriculture by strengthening soil biological health and long-term fertility (Gul et al., 2015). The overarching effects of BC on soil biological properties are summarized in Fig. 3.

3.3.1. *Soil microbiome*

Biochar functions as a critical microbial habitat in soil, with its colonization strongly influenced by specific properties such as porosity and surface hydrophobicity (Mitchell et al., 2015). Its highly porous structure offers microorganisms refuge from predation and desiccation, while its micro- and mesopores retain water and dissolved nutrients that support microbial metabolism (Gul et al., 2015; Jaafar et al., 2014). Macro-pores exceeding 200 nm in diameter provide ideal niches for bacterial colonization (Quilliam et al., 2013). Furthermore, BC's high SSA and dark color improve solar heat absorption, creating favorable microclimates that stimulate microbial growth and activity (Gul et al., 2015).

The interaction between BC and the soil microbiome has significant functional consequences. Co-application of BC with fertilizers often exhibits synergistic effects, enhancing microbial biomass and activity, which in turn accelerates nutrient mineralization and release (Gao et al., 2021). For example, BC inoculated with *Enterobacter cloacae* raised bacterial density by 16 % within four weeks (Hale et al., 2015). Biochar can also selectively enrich beneficial functional groups, such as potassium-solubilizing bacteria. In one study, corn stover biochar added to a nutrient solution increased K-solubilizing activity by 80 % and stimulated a fivefold growth increase in *Bacillus mucilaginosus* (Wang et al., 2018b).

The response of soil microbial communities to BC is highly context-dependent, varying with soil type, BC properties, and management practices (Zhang et al., 2023). A meta-analysis indicated that microbial biomass increases markedly in neutral and acidic soils but may remain unchanged in alkaline soils (Schmidt et al., 2021). By fostering more robust and functional microbial communities, BC supports key ecosystem processes such as ecosystem restoration, carbon sequestration, and sustainable crop production, thereby contributing to climate change mitigation.

3.3.2. *Soil extracellular enzymatic activities*

The soil microbiome, as described above, directly governs the production of extracellular enzymes, which are crucial biological catalysts for nutrient cycling (Liao et al., 2022). Biochar influences these enzymatic activities through its effects on the microbiome and by directly altering the soil microenvironment (Wang et al., 2019). The net effect on enzyme activity represents a balance between enhancement and inhibition, primarily dictated by BC pyrolysis temperature. Enhancement mechanisms include the provision of protected habitats that support microbial biomass, thereby increasing enzyme production. For example, applications of rice-husk and almond shell BC have been shown to significantly boost the activities of urease, phosphatase, and dehydrogenase (Huang et al., 2017; Sakin et al., 2021). Increased phosphatase activity often directly indicates a higher proportion of bioavailable phosphorus (Shahzad et al., 2014). Conversely, inhibition can occur when enzymes or their substrates are adsorbed onto the highly aromatic surfaces of high-temperature BC, rendering them inactive (Singh et al., 2025; Lammirato et al., 2011). This temperature-dependent duality is clearly demonstrated by Ameloot et al. (2013), where low-temperature biochar (350 °C) increased dehydrogenase activity by 73 %, while high-temperature BC (700 °C) suppressed it by 47 %. Therefore, the selection of BC, particularly its pyrolysis temperature, is critical for steering soil enzymatic functions toward desired nutrient cycling outcomes.

4. Remediation of heavy metal contaminated soils

Heavy metal(loid)s, including arsenic (As), cadmium (Cd), copper (Cu) chromium (Cr), lead (Pb), mercury (Hg) and zinc (Zn), in soils pose various environmental and public health threats due to their capability to be readily absorbed by plants (Crișan et al., 2024; Jiang et al., 2022). The presence of these HMs in soil disrupts microbial communities, degrade soil structure, reduce plant growth, ultimately jeopardizing agricultural productivity and ecosystem stability (Hameed et al., 2024). Biochar has emerged as a promising soil amendment for immobilizing HMs, thereby reducing their phytoavailability and mitigating adverse effects on plants and agricultural productivity (Chi et al., 2024).

The efficacy of BC stems from its multifunctional properties, which enable several concurrent immobilization mechanisms (Zhang et al., 2025). The primary mechanisms include (1) physical adsorption within its porous structure, (2) surface complexation, via functional groups (e.g., -COOH, -OH), (3) ion exchange, (4) electrostatic interaction, and (5) chemical precipitation, which result in the reduced bioavailability of HMs in soil (Natasha et al., 2022; Bian et al., 2014). These processes collectively transform bioavailable HMs into more stable, less soluble forms in the soil (He et al., 2025). For instance, the addition of *Saccharum officinarum* L. straw derived BC was observed to decrease the bioavailability of Cd, Zn, and Pb concentrations by 56 %, 54 %, and 50 %, respectively, primarily through adsorption (Puga et al., 2015). The porous structure of BC and its unique surface functional groups (e.g., -COOH, -OH, C═N, and -C═O-) provide extensive binding sites, facilitating the immobilization of HMs through adsorption and complexation (Natasha et al., 2022), hence reducing their bioavailability in soil.

BCs produced at low to moderate temperatures possess higher densities of functional groups that facilitate complexation with metal ions (Xiao et al., 2018). Furthermore, BC can significantly alter soil chemistry through several pathways: it can increase soil pH leading to hydroxide precipitation (e.g., $Cd^{2+} + 2OH^- \rightarrow Cd(OH)_2$), increase CEC, and through its mineral content, promote specific precipitation reactions (Singh et al., 2025). For instance, phosphorus-rich BCs can desorb phosphate to form stable insoluble minerals like pyromorphite in Pb-contaminated soils (Qin et al., 2018; Liang et al., 2014). Moreover, BC can influence redox processes, such as reducing mobile Cr(VI) to less toxic Cr(III), thereby reducing Cr mobility (Choppala et al., 2012). The adsorption mechanisms of BCs are described as follows; a) increase in soil pH, $CaO + H_2O \rightarrow Ca(OH)_2$; $Ca(OH)_2 \rightleftharpoons Ca^{2+} + 2OH^-$, b) cation exchange, $M\text{-}Ca^{2+} + Cd^{2+} \rightarrow M\text{-}Cd^{2+} + Ca^{2+}$, c) precipitation, $Cd^{2+} + 2OH^- \rightleftharpoons Cd(OH)_2$, and d) inhibition and competition, $M\text{-}Ca^{2+} + 2\,H^+ \rightarrow M\text{-}2H^+ + Ca^{2+}$ and $M\text{-}Cd^{2+} + 2\,H^+ \rightarrow M\text{-}2H^+ + Cd^{2+}$, where M represents the BC matrix (Haider et al., 2022).

Biochar amendment effectively reduces the uptake of HMs by plants by immobilizing them in the soil, thereby decreasing their phytoavailability (Zulfiqar et al., 2022). This reduction is well-documented, with numerous studies demonstrating a negative correlation between BC amendment and HM uptake by plant roots (Zhang et al., 2025; Chen

Table 2
Effect of biochar applications on HMs and PAHs induced changes in soil plant systems.

Biochar types	Temp. (°C)	Biochar application rate	Pollutants conc. in medium (mg kg^{-1})	Plant species	% increase / decrease	Reference
Miscanthus	500	5 %	Ni 50	*Spinacia olearacea*	Decreased Ni (79), MDA (66), increased CAT (163), and APX (204)	Khan et al. (2017)
Tobacco	500	1 %	Pb 9.8, Cu 1.1, Zn 527.2	*Brassica campestris*	Decreased Pb (40), Cu (33), and Zn (8) in edible parts and increased chlorophyll and plant biomass	Lahori et al. (2017)
Bamboo	500	15 %	Ni 57.6, Mn 764.4, Cu 138.5, Cd 30, Zn 99.8, Pb 4.7	*Glycine max*	Increased plant biomass and decreased Ni (10), Mn (14), Cu (15), Cd (33), Zn (18), and Pb (53)	Wang et al. (2018a)
Miscanthus	350	2 %	Ni 77	*Trifolium pratense* L.	Reduced Ni in shoot (47), root (45), decreased O_2^- (62.8) and H_2O_2 (24.2)	Shahbaz et al. (2018)
Pistachio shell		2 %	Ni 50	*Lactuca sativa*	Ni (50), MDA (53), H_2O_2 (47) $O_2^{\bullet-}$ (7), and increased SOD (89), POD (36), CAT (54), and APX (83)	Turan (2019)
Rice hulls	600	25 %	Cd 5	*Oryza sativa*	Decreased Cd concentration (73), MDA (35) and increased antioxidants	Yue et al. (2017)
Rice straw	550	5 %	Cd 20	*Brassica chinensis*	Decreased H_2O_2 (34), Cd (25), increased SOD (66), POD (37), CAT (123), and APX (116)	Kamran et al. (2019)
Beeswax	400	6 %	Cd 9	*Crocus sativus* L.	Decreased Cd contents in flower (162), leaf (43), MDA (34) and increased SOD (143), and CAT (24)	Moradi et al. (2019)
Quercus, Carpinus, Fagus hardwood	500	5 %	As 1.06, Fe 6.32, Pb 23.39	*Salix viminalis*	Reduced As (67), Fe (76), Pb (31), and improved photosynthesis and dry biomass	Lebrun et al. (2019)
Sewage Sludge	500	2–10 %	16 PAHs (20.2)	*Lactuca sativa* L.	Increased plant biomass up to (93) and concentrations in edible parts were decreased by 56–67	Khan et al. (2013)
Pine sawdust and corn straw	450	3 %	13 PAHs (3–6 ring) (68.6)	*Zea mays*	Concentrations in the soil pore water and edible parts were decreased by 6–44 and 31–68 respectively	Brennan et al. (2014)
Sludge	550	2–10 %	16 PAHs (9.9)	*Cucumis sativa* L.	Improve fruit yield (32–67) and concentrations in the soil and edible tissues were decreased by 31–43 and 44–57	Waqas et al. (2014)
Sludge	550	2–10 %	16 PAHs (9.9)	Tomato	Improved plant growth and concentrations in edible tissues were decreased by 3–84	Waqas et al. (2015)
Soybean, rice straw, peanut shell	500	2–5 %	16 PAHs (10.2)	*Brassica rapa* L.	Increased yield (49) and concentrations in edible part were decreased by 27–80	Khan et al. (2015)
Wheat straw	500	1 %	Hexachlorobenzene (3.8)	*Lolium perenne* L.	Concentrations in the root were reduced by 93 %	Song et al. (2016)
Wheat straw	600–700	2.5 %	10 PAHs (700 μg/kg)	*Salix viminalis*	Concentrations were reduced by 12–26 %	Oleszczuk et al. (2017)
Corn straw	300	2 %	16 PAHs (7.5)	*Oryza sativa* L.	The uptake of 2 (+ 3)-, 4-, and 5 (+ 6)-ring PAHs was reduced by 10 %, 40 %, and 40 % respectively	Ni et al. (2018)
Maize straw	300	2 %	2, 2′, 4, 4′-Tetrabrominated diphenyl ether (125 μg/kg)	*Daucus carota* L.	Concentrations in the roots were reduced by 77 %	Xiang et al. (2019)
-	-	5 %	PAHs (1200 μg/kg)	Hordeum Sativum	Concentrations in edible parts were reduced by 37–48 %	Sushkova et al. (2021)

et al., 2021). This reduction is primarily ascribed to the adsorption and surface complexation of HMs onto the surface of BC (Natasha et al., 2022). For instance, the application of pinewood BC (2 % w/w) decreased the uptake of Cd (80 %), Cr (76 %), Ni (68 %), and Pb (86 %) in *Triticum aestivum*, respectively (Yousaf et al., 2018). Similarly, the addition of *Casuarina* BC (4 %) reduced the concentrations of Zn, Cd, Cu, Co, and Pb by 25 %, 25 %, 32 %, 52 % and 85 % in the roots and 35 %, 37 %, 40 %, 66 % and 89 % in the shoot of summer squash plants (Ibrahim et al., 2022; Table 2). A meta-analysis demonstrated that BC amendments to soils resulted in average reductions of 17 %, 25 %, 39 %, and 38 % in plant tissue concentrations of Zn, Cu, Pb, and Cd, respectively (Chen et al., 2018).

The immobilization of HMs by BC directly mitigates their phytotoxic effects on crucial plant physiological processes (He et al., 2025). At elevated or toxic concentrations in plants, HMs can cause morpho-physiological, and biochemical alterations leading to plant death (Natasha et al., 2022). The primary target of HMs toxicity is photosynthesis (Nazir et al., 2024). HMs can selectively affect photosynthesis by disrupting photosystem II through interference at the donor site (the β-subunit of ATP synthase), and the O-evolving proteins within the chloroplast (Gao et al., 2021). BC can decrease the bioavailability of HMs via sorption reactions on its surface, which helps minimize chlorophyll degradation by restricting the movement of HMs from the soil to the plant leaves (Shahbaz et al., 2018). These protective effects of BC amendments are well documented (Singh et al., 2025). For instance, application of *Parthenium hysterophorus* L. BC (2 %) increased the photosynthetic rate (13 %), stomatal conductance (16 %), transpiration rate (15 %), chlorophyll a (14 %), chlorophyll *b* (12 %), total chlorophyll (13 %), and carotenoids (12 %) in Cd stressed *Oryza sativa* L. (Ahmad et al., 2024). The addition of BC at (2.5 % or 5 %) to Cd stressed *Brassica rapa*. increased intracellular CO_2 concentration (18 %, 67 %), stomatal activity (55 %, 17 %), transpiration rate (46 %, 161 %), and net photosynthetic rate (111 %, and 33 %), respectively (Kamran et al., 2019). The application of BC in field conditions significantly increased root area by (91 %), chlorophyll content (50 %), net photosynthetic rate (77 %) and total biomass (72 %) of tobacco plants (Ren et al., 2021). A meta-analysis study showed that BC amendments significantly increased average photosynthetic rate by 23 %, compared to control (Gao et al., 2021). However, this increase in photosynthetic rate was highly dependent on BC application rate. The application rates of (2–4 %) or (10–20 t ha^{-1}) were found best in the higher mean increase in photosynthetic rate by 25 % and 46 %, respectively. Therefore, by preventing metal-induced damage to the photosynthetic machinery, BC plays a vital role in maintaining plant productivity under HM stress.

Beyond protecting photosynthesis, BC amendment also plays a critical role in mitigating the oxidative stress induced by HM toxicity (He et al., 2025). Plants subjected to HM stress typically experience severe phytotoxicity, largely due to the increased production of ROS and active radicals (Hameed et al., 2024; Zulfiqar et al., 2022). These ROS lead to the disruption of chlorophyll biosynthesis, degradation of lipid membranes, and an imbalance in cellular redox homeostasis. For instance, Kamran et al. (2019) demonstrated that 2.5 % and 5 % BC applications decreased H_2O_2 contents (17–32 %) and MDA levels by (14–27 %) respectively, in Cd stressed *Brassica chinensis* (Table 2). Likewise, Naeem et al. (2020) reported that wheat-straw and acid-treated wheat-straw BC (2 %) decreased H_2O_2 content by 81 % in *Chenopodium quinoa* under Cd stress. Application of (2 % w/w) *Miscanthus* BC (produced at 350 °C) decreased O_2^- (62 %) and H_2O_2 (24 %) contents, respectively, in *Trifolium pratense* leaves grown on Ni-contaminated soil (Shahbaz et al., 2018; Table 2). This consistent reduction in oxidative damage markers underscores BC's efficacy in lowering the plant's oxidative burden, a key step in mitigating HM phytotoxicity.

A complementary mechanism by which BC mitigates oxidative stress is through the induction of the plant's innate antioxidant enzyme machinery (Nazir et al., 2024). BC applications can trigger antioxidative enzymes such as peroxidase (POD), superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) to reduce oxidative stress and maintain redox balance (Zulfiqar et al., 2022). For instance, the BC addition significantly increased antioxidant activities such as SOD (76 %), POD (29 %), CAT (123 %) and membrane stability index (45 %) respectively in Cd stressed spinach plants (Tanveer et al., 2022). In similar ways, Yue et al. (2017) demonstrated that rice hulls BC (25 %) markedly ameliorated Cd induced phytotoxicity as reflected by improved SOD (108 %), POD (50 %), CAT (85 %) and decreased oxidative stress in *Oryza sativa* plants, due to the high sorption affinity of BC for Cd. Application of BC (2 %) combined with microbes significantly boosted SOD (33 %), CAT (24 %), POD (51 %), and APX (19 %) activities respectively, while marked reduction was found in the H_2O_2 (16 %) and MDA (26 %) content in *Oryza sativa* L. plants under Cd stress (Ahmad et al., 2024). The application of 2 % pistachio shell BC (pyrolyzed at 300–350℃) increased SOD (89 %), POD (36 %), CAT (54 %), APX (83 %) and decreased H_2O_2 (47 %) and $O_2^{\bullet-}$ (47 %) contents in Ni stressed *Lactuca sativa* (Turan, 2019). Similarly, Khan et al. (2017) demonstrated that the addition of 5 % *miscanthus* BC produced at 350℃ increased CAT (163 %), APX (204 %) and decreased H_2O_2 (59 %) and $O_2^{\bullet-}$ (47 %) contents in Ni stressed *Spinacia olearacea.*

The protective effects of BC extend to the molecular level, where it modulates the expression of genes involved in the plant's stress response (Sun et al., 2023). Various BC soil amendments can effectively reduce HMs toxicity by regulating genes associated with stress tolerance (Xu et al., 2024; Sun et al., 2023). For instance, Mehmood et al. (2021) demonstrated that rice straw BC (3 %), significantly improved phytoremediation capacity and vanadium tolerance by influencing antioxidant activity and the expression of genes responsible for encoding antioxidant enzymes. Their findings showed that the utilization of BC increased antioxidant activities, with fold changes for *OsSOD* (5.57), *OsPOD* (5.04), *OsCAT* (4.97), *OsAPX* (5.25), respectively, as compared to their respective controls. The application of BC downregulated the expression of *MnSOD*, *CAT*, and *GR* genes, which was associated with reduced ROS and phytotoxicity of Cd (Kang et al., 2022). This ability to regulate stress-related genes provides a molecular basis for the observed physiological improvements and underscores BC's role as a potent elicitor of plant innate immunity.

Conclusively, BC primarily alleviates HMs stress by immobilizing HMs in soil through altering soil physiochemical properties such as pH, CEC, and mineral content (Fig. 4), which reduces their phytoavailability and uptake (Singh et al., 2025). It cannot be assumed that BC directly quenches ROS or interacts with oxidative pathways within the plant (Natasha et al., 2022). The direct effect of BC on plant intracellular ROS signaling independent of metal immobilization remains poorly understood and represents a critical area for future research. Elucidating these mechanisms will be essential for optimizing BC applications to enhance crop resilience in contaminated soils.

5. Polycyclic aromatic hydrocarbons

Soil contamination with persistent organic pollutants such as PAHs poses significant environmental and public health concerns due to their carcinogenic and mutagenic properties (Cao et al., 2024; Wang et al., 2023). Upon entering the soil ecosystem, PAHs can persist for decades, inhibiting microbial activity, disrupting soil functions, and posing risks of bioaccumulation in the food chain (Jiang et al., 2025). BC's application has emerged as a promising solution, primarily owing to its high SSA and porous structure (provide habitat for microbes), that make it an excellent adsorbent for PAHs (Ni et al., 2018). The efficacy of BC in PAH remediation is highly variable, being profoundly influenced by its properties, especially pyrolysis temperature, which dictates the dominant mechanism of action.

While the primary pathway for the ultimate mineralization and removal of PAHs in soil is microbial degradation, the strong sorption capacity of BC can have contrasting effects (Zhang et al., 2021). Specifically, high-temperature BC presents a trade-off between

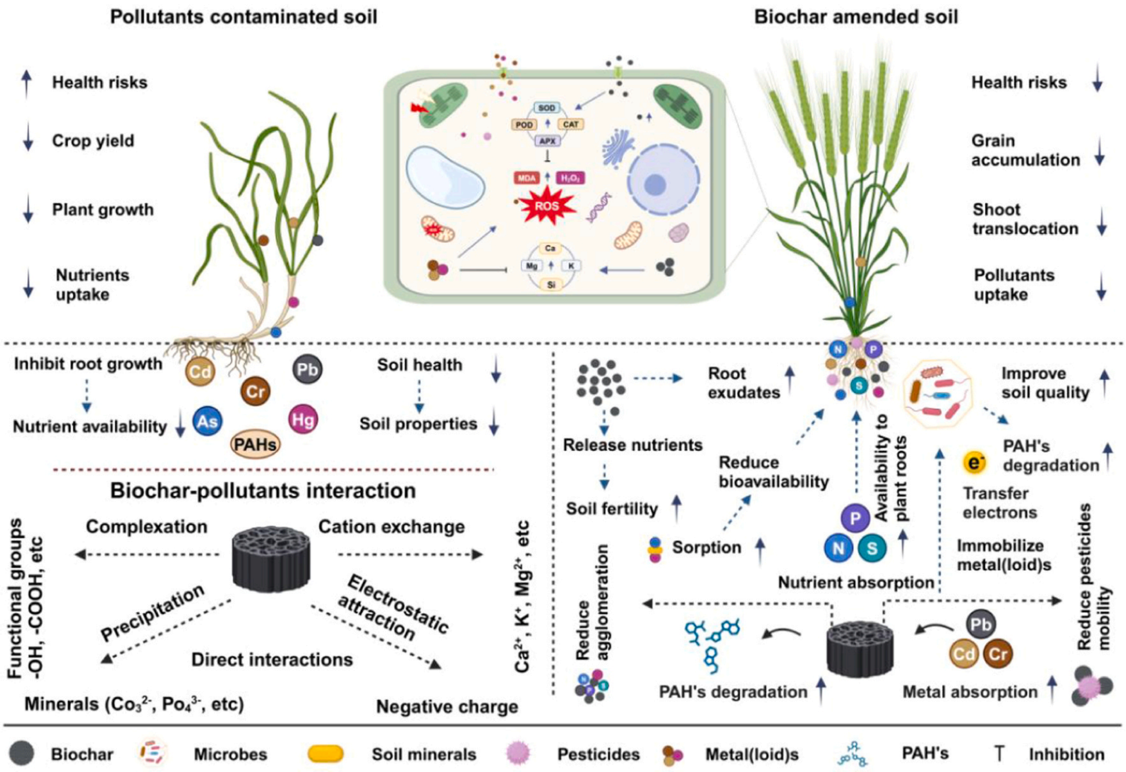

Fig. 4. A proposed mechanism of biochar amendment in the remediation of contaminated soils.

immobilization and degradation (Yaashikaa et al., 2024). On one hand, the strong sorption capacity of high-temperature BC can hinder the biodegradation of PAHs by reducing their bioavailability to microbial communities, which is a key limiting factor for their degradation (Anyika et al., 2015). For instance, the application of wood-derived BC produced at 800 °C decreased the availability of monoaromatic hydrocarbons (Bushnaf et al., 2011). Similarly, biogas residue–derived BC pyrolyzed at 700 °C markedly decreased bioavailable PAHs through immobilization, thereby reducing their uptake by basil roots (Li et al., 2023). Although this strong sorption capacity can potentially reduce the immediate bioavailability of PAHs to soil microorganisms, it effectively immobilizes the contaminants in the soil matrix, which is a key mechanism for reducing plant uptake and bioaccumulation (Zhang et al., 2021). Brennan et al. (2014) demonstrated that the application of pine sawdust and corn straw BC (3 %) produced at 450 ℃ immobilized 13 PAHs (3–6 ring) in soil and decreased their concentrations in *Zea mays* L. shoots by 31–68 %. However, in heavily contaminated soils, the inorganic mineral (ash) content of BC plays a positive role in stimulating microbial abundance and diversity, thereby contributing to enhanced PAH biodegradation (Zhang et al., 2020).

In contrast to high-temperature BC, low-temperature BC primarily enhances the degradation of PAHs by actively promoting microbial activity (Song et al., 2016). The porous structure of BC is optimal for microbial colonization at lower pyrolysis temperatures (Cheng et al., 2025). The total pore volume of BC typically increases as pyrolysis temperature rises from 250 ℃ to 500 ℃ but decreases when the temperature increases further from 550 ℃ to 750 ℃ (Ma et al., 2017). Consequently, the rich pore volume and unique porous structure of BC produced at low temperatures offer an appropriate habitat for the microbial growth that degrades PAHs (Ni et al., 2018). This is evidenced by the finding that wheat-straw BC produced at 500 ℃ was more effective at removing PAH content than BC from the same residue produced at 700 ℃, likely due to its higher pore volume which positively influenced soil microbes (Kong et al., 2018). Beyond providing a habitat, low-temperature BC serves as a nutrient source, further stimulating microbial degradation (Yaashikaa et al., 2024). As pyrolysis temperature increases, the carbon content of BC increases, while nitrogen, phosphorus, and other essential nutrient elements decrease (Bruun et al., 2011). Therefore, incorporating low-temperature, nutrient-rich BC into soil ensures a greater nutrient supply for PAH-degrading microbes, improving soil carbon storage, enhancing nutrient retention, and increasing nutrient availability (Ennis et al., 2012). The quantity of biodegraded PAHs in soil increased by approximately 20 % following the addition of wheat straw or wood chip BC produced at 300 ℃ (Kong et al., 2018). This combination of habitat and nutrients creates a synergistic effect, significantly enhancing the dissipation of PAHs.

The most effective remediation often occurs in the rhizosphere, where a complex interaction between BC, plants, and microbes takes place. Wang et al. (2023) demonstrated that application of bamboo and maize straw BC significantly decreased the concentrations of PAHs in the rhizosphere soil by 15 %-33 % and reduced their uptake in winter wheat root by 26 %-21 %, stem by 12 %-19 %, and grain by 15 %-26 %, respectively, thereby decreasing the incremental lifetime cancer risk values by 11 % and 22 %. The biodegradation of accessible PAHs is enhanced by a higher abundance of soil bacteria, functional gene expression, and methanogens associated with PAH degradation (Song et al., 2016). This enhancement is stimulated by the addition of low-temperature BC that is nutrient-enriched and possesses a favorable physical structure (Ni et al., 2018). For example, application of 5 % BC decreased PAH concentrations in soil by 47 % and in the edible parts of *Hordeum Sativum* by 37–48 % (Sushkova et al., 2021). Oleszczuk et al. (2017) observed that the addition of wheat straw BC (2.5 %) immobilized PAHs in soil and reduced their accumulation in *Salix viminalis* plants by 12–26 %. While root exudates like oxalic acid can facilitate the desorption of PAHs from BC-amended soil, their bioavailability often remains low in the rhizosphere due to concurrent microbial activity (Oleszczuk et al., 2017). Furthermore, high-throughput sequencing has revealed that the enhanced relative abundances of specific genera (e.g., *Azohydromonas, Sporocytophaga*, *Fluviicola*, and *Pseudomonas*) following BC amendments are directly correlated with the dissipation of PAHs in the rhizosphere soil (Song et al., 2016). Consequently, the interactive relationship between BC, root exudates, and microorganisms plays a crucial role in reducing PAH bioavailability and limiting their transfer into plants (Zhang et al., 2025). This is strongly demonstrated by the addition of 1 % wheat straw BC, which decreased root uptake by 93 %, increased the biomass of *Lolium perenne* L., and enhanced the activity and diversity of PAH-metabolizing microorganisms, along with related gene expression (Song et al., 2016).

Beyond reducing PAH transfer into plants through rhizosphere interactions, BC directly enhances plant physiological health by mitigating PAHs toxicity through multiple mechanisms (Cheng et al., 2025; Yaashikaa et al., 2024). The primary mechanism involves reducing contaminant phytoavailability. For instance, Cui et al. (2023) reported that 1 % BC (500 ℃) amendment to phenanthrene contaminated soil significantly enhanced *Suaeda salsa* L. growth, increasing plant height by 22 %, fresh weight by 92 %, and elevating chlorophyll and carotenoid content by 46 % and 28 %, respectively. This protective effect shows enhanced efficacy in nano-formulations. Cui et al. (2025) demonstrated that nano-BC reduced PHE accumulation in wheat seedlings by up to 1.77-fold through high adsorption capacity. Beyond pollutant immobilization, nano-BC treatment actively enhanced photosynthetic performance under phenanthrene stress, increasing chlorophyll content by 14 % and improving photosynthetic efficiency. Kaur and Sharma, (2019) demonstrated that application of 5 % *Prosopis juliflora* BC (pyrolyzed at 450 ℃) increased plant biomass, increased micronutrient concentrations in tissues, and reduced PAH uptake and accumulation in *Trifolium alexandrinum* L. grown in contaminated soil. Biochar further fortifies plant defense mechanisms against oxidative stress. Wang et al. (2024) reported that BC application alleviated oxidative stress in *Buchloe dactyloides* roots under PAH contamination by boosting key antioxidant enzyme activities (POD, CAT, GR, and APX). While these findings demonstrate BC's multifunctional protective role, research gaps remain in understanding the molecular mechanisms across diverse plant species and environmental conditions, warranting further investigation.

Despite its significant promise, the potential of BC to enhance the biodegradation of PAHs and reduce their bioavailability can be inconsistent (Zhang et al., 2021). This variability is primarily context-dependent, as outcomes are influenced by a complex interplay of factors (Yaashikaa et al., 2024). Firstly, the efficacy is governed by BC-specific properties, such as feedstock type, pyrolysis temperature, surface area, porosity, and the presence of functional groups, all of which determine its sorption capacity and interaction with pollutants and microbes (Zhang et al., 2021). For instance, BCs produced at lower temperatures (e.g., 400 ℃) may have a higher affinity for PAH sorption due to a larger surface area, while those produced at higher temperatures might promote electron-transfer reactions that aid degradation (Lan et al., 2022). Secondly, the soil physicochemical properties, including pH, and organic matter content can alter the binding affinity of PAHs to BC and influence the overall remediation process (Haider et al., 2022). Thirdly, the native microbial community's composition and activity are crucial; while BC can generally enhance microbial density and function by improving soil aeration, water retention, and nutrient availability, its impact is highly taxa-specific. The porous structure of BC can provide a habitat for microbes, but if the sorption of PAHs is too strong, it may reduce their bioavailability to degrading microorganisms, thus limiting biodegradation (Anyika et al., 2015). This context-dependent nature, where success is contingent on the specific combination of BC properties, soil type, and microbial ecology, currently limits the predictable, large-scale application of BC for remediating PAH-contaminated soils (Yaashikaa et al., 2024). Therefore, a tailored approach, involving advanced characterization of both the contaminant matrix and the BC, is essential to optimize remediation strategies and move toward more reliable field-scale outcomes.

6. Conclusions and perspectives

6.1. Conclusion

Biochar plays a critical role in managing soil pollution, preserving ecosystem balance, and fostering a sustainable agricultural environment owing to its unique physical, chemical and biological properties. Its incorporation into soils can significantly lower bulk density, increase porosity, WHC, fertility, adsorption capacity, organic matter content, and microbial activity, thereby reducing the mobility and phytoavailability of HMs and PAHs. BC's high CEC, zeta potential, and specific functional groups enable it to adsorb HMs through multiple mechanisms, including ion exchange, electrostatic attraction, co-precipitation, and complexation, thereby reducing their phytoavailability in soils. BC provides suitable habitat for microbes, acts as an electron shuttle, enhances surface redox reactions, stimulates microbial degradation processes and adsorbs PAHs to reduce their bioavailability. Moreover, BC reduces the uptake of pollutants (HMs and PAHs), improves photosynthesis and plant growth, and activates antioxidative enzymes (SOD, POD, CAT) to relieve plants of oxidative stress, thereby promoting plant vigor and higher crop yields under challenging environmental conditions. BC-mediated variations in pollutant toxicity and stress resilience in plants are plausibly due to BC-pollutants interactions in soil leading to decreased soil-plant transfer.

While BC plays a pivotal role in controlling the fate and behavior of HMs and PAHs at the soil–plant interface, its application may also lead to several potential adverse effects. Significant amounts of HMs and PAHs may reside on the BC surface, which could contaminate BC-amended soils. Additionally, BC influences the persistence, bioactivity, and biodegradability of agrochemicals essential for plant growth, development and yield, potentially leading to the dire need for higher application rates. Thus, BC composition, soil, and BC physico-chemical properties, application rates, and agroecological conditions must be carefully considered before applying BC to soils contaminated with HMs and PAHs.

6.2. Perspective

The agricultural waste across the world is a valuable resource for the BC industry. There is no uncertainty that BC helps soil thrive (Demichelis et al., 2025). As emphasized by Xiao et al. (2018), future research should focus on tailoring BC to the specific requirements of different soils, including the selection of appropriate feedstocks and production methods. It is also crucial to understand how biomass can be modified or engineered to suit diverse soil types.

Establishing unified standards and policy frameworks is necessary for BC production, as some production processes remain economically prohibitive. Different biomass, pyrolysis temperatures, times, and preparation methods markedly influence the physico-chemical properties of BC. Therefore, to maximize BC utilization, its combined application with other soil amendments represents an important future direction for sustainable soil management and provides a scientific foundation for its broader agricultural applications.

Despite the robust scientific evidence and the growing number of studies (Fig. 1), the commercial BC market remains underdeveloped. This gap between research and widespread adoption stems from three primary barriers: (1) the high variability in BC properties and performance, which creates uncertainty for end-users; (2) economic constraints, including production costs and a lack of clear return-on-investment data from long-term field studies; and (3) the absence of standardized quality controls and regulatory frameworks. Overcoming this bottleneck requires future research to validate BC's long-term field efficacy, develop cost-effective production technologies, and establish clear product standards and certification systems to build market confidence and facilitate large-scale adoption.

Future research and directions should focus on:

- Developing new cost-effective production and application methods to enhance BC's efficiency and its interaction with fundamental physicochemical and biological processes in soil environments. Greater improvements in soil properties and crop yields may also be achieved by combining BC with various materials, such as zeolite, mineral amendments, organic residues, natural or slow-release fertilizers, and beneficial soil microorganisms.
- More research is needed to see if BC can keep reducing the availability of HMs and PAHs in the long term, or if it breaks down over time, depending on how it was produced and releases these elements back into the soil. Studies should also look at BC's stability in ways beyond just using H/C and O/C ratios to estimate its half-life.
- Biochar may contain toxic elements, such as metal ions, dioxins, and PAHs, which cannot be removed once introduced into the soil. Therefore, it is essential to assess the toxicity of BC before its application as a soil amendment.
- Incorporating specialized microbial consortia capable of degrading pollutants such as PAHs into BC-amended soils can enhance degradation efficiency. Bioaugmentation using engineered strains that utilize BC as an electron acceptor/donor may accelerate pollutant breakdown and leveraging BC–microbe interactions offer great potential for effective remediation, sustainable agriculture, and environmental restoration.

CRediT authorship contribution statement

Muhammad Mudassir Nazir: Conceptualization, Methodology, Investigation, Writing - Original Draft, Visualization, Funding acquisition; **Guanlin Li:** Conceptualization, Writing - Review & Editing, Funding acquisition, Supervision; **Mohsin Nawaz:** Writing - Review & Editing; **Rashida Hameed:** Writing - Review & Editing; **Faisal Zulfiqar:** Writing - Review & Editing; **Sanaullah Jalil:** Writing - Review & Editing; **Jian Li:** Writing - Review & Editing; **Xiaojun Zheng:** Writing - Review & Editing, Visualization; **Xin Zhao:** Investigation, Writing - Review & Editing, Project administration; **Daolin Du:** Writing - Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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