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Enhanced Biochar as a Game-Changer in Heavy Metal and Organic Pollutant Remediation

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Abstract

Soil pollution represents a significant global environmental challenge driven by industrial activities, agricultural practices, and urban development, which collectively contribute to the accumulation of heavy metals and organic contaminants. Current estimates indicate that approximately 52 million hectares of land worldwide are affected by heavy metal contamination, resulting in decreased agricultural productivity and posing serious risks to human health. Traditional methods for soil treatment often incur high costs and pose the risk of secondary pollution, underscoring the necessity for sustainable and efficient remediation technologies. This review examines recent advancements in biochar-based remediation of soil pollution, emphasizing biochar preparation, modification techniques, pollutant removal mechanisms, and the impacts on soil properties and microbial communities. Biochar has shown significant potential in immobilizing heavy metals through various processes, including adsorption, ion exchange, and precipitation. Modified biochar enhances adsorption efficiency. Research has demonstrated that alkali-modified biochar significantly reduces cadmium bioavailability by more than 50%, while nano-enhanced biochar demonstrates high efficiency in degrading organic pollutants such as PNP and OTC. Future research should prioritize large-scale implementation, advanced modification strategies, and comprehensive risk assessments to optimize biochar applications in sustainable soil remediation efforts.

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1. Introduction

Industrialization, agricultural fertilization, and other anthropogenic activities have resulted in the accumulation of substantial heavy metals and organic pollutants within the soil, causing irreversible disruption to the ecological balance.[1-3] Soil pollution has emerged as a critical issue of global concern.[4,5] The discharge of industrial wastewater, extensive use of pesticides, and incineration of municipal solid waste have resulted in the buildup of PTEs, posing critical environmental challenges to soil ecosystems.[6] Additionally, oil extraction and its associated organic pollution have significantly impacted grassland ecosystems, resulting in vegetation degradation and soil salinization, further undermining the stability and functionality of these ecosystems.[7,8]

Green remediation technologies have emerged as a key research frontier in addressing urgent global environmental challenges, including water pollution, soil system degradation, and climate change.[9-11] The development and application of advanced materials play a crucial role in pollution control and carbon sequestration, providing technological support for sustainable development goals.[9,12] In recent years, research on biochar composites has developed rapidly. As a sustainable adsorbent, biochar has gained significant attention for its eco-friendly nature, renewability, and economic viability.[13,14] Biochar, a stable carbonaceous material produced through low-oxygen thermochemical conversion of biomass, has garnered significant research interest due to its demonstrated efficacy in soil restoration, nutrient enhancement, and crop yield improvement.[15,16] In addition, biochar possesses alkalinity, high specific surface area, porous structure, abundant surface functional groups, negatively charged surface sites, as well as high CEC, carbon content, and ash content, making it a promising material for reducing the

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bioavailability and toxicity of heavy metals (*e.g.*, As and Sb) in agricultural soils.[17-21] The highly porous structure of advanced biochar materials can exhibit specific surface areas approaching 1500 m²/g, as demonstrated by recent characterization studies.[22] Applying biochar typically results in a significant increase in soil pH, with a mean increase of 5.59%; however, when initial soil pH or CEC is low , it may conversely decrease pH.[23] Additionally, modified biochar can effectively enhance the soil's CEC, with an increase ranging from 19.7% to 54.5%.[24]

In recent years, researchers have made significant efforts in developing innovative modification methods to enhance the remediation performance of biochar. These advancements include the integration of nanomaterials, clay minerals, and metal oxides, which markedly improve biochar's physical and chemical characteristics, including its adsorption ability, catalytic efficiency, as well as electrochemical potential, resulting in the expansion of biochar's potential applications beyond environmental pollution control to include energy storage solutions.[9,25] In addition, modified biochar demonstrates stronger pollutant adsorption and fixation capabilities by improving its structure and surface properties, making it a prominent research focus in soil remediation.[4,26] Biochar and its modified materials, with their environmentally friendly and cost-effective characteristics, have found widespread application in the restoration of polluted soils and have been proven to be practical tools for addressing soil pollution issues.[27,28] However, optimizing the performance and application effectiveness of biochar remains a key focus for future research. This ongoing investigation is crucial to realizing the full potential of biochar in various applications.

The sustainable utilization of biomass waste is vital for environmental protection. Global agriculture produces ~200 million tons of lignin waste annually, whose incineration releases toxic gases , exacerbating air pollution.[29] Converting agricultural residues into biochar addresses waste disposal while improving soil quality.[30,31] Similarly, valorizing ~1.3 billion tons of annual food waste through biochar production offers a dual waste-management and soil-enhancement solution.[32]

The growing volume of municipal solid waste threatens human health and ecosystems.[33,34] Pyrolysis technology presents an effective means of reducing waste volume while simultaneously converting it into high-value biochar products.[35] Sludge, which constitutes a significant category of waste, harbors substantial quantities of heavy metals, pathogens, and toxic substances. The untreated discharge of sludge poses a risk of environmental contamination, particularly to water bodies and soil ecosystems.[36,37] Nevertheless, the rich organic content inherent in sludge positions it as a viable candidate for transformation into porous biochar, which is increasingly utilized in soil remediation efforts.[37] Additionally, biological invasion is a pressing global concern.[38] The conversion of invasive plant species into biochar not only aids in the management of these species but also generates a valuable resource for soil remediation applications.[30] Collectively, agricultural/forestry residues, sludge, municipal waste, and invasive species represent abundant biochar feedstocks with dual environmental and economic benefits.[39,40]

This review summarizes and analyzes recent research on the use of biochar for soil pollutant remediation, including the preparation of biochar, its mechanisms in soil remediation, and the factors influencing its remediation effectiveness. By synthesizing relevant research, this paper provides a more systematic insight regarding biochar's role in contaminated soil remediation, as well as offering theoretical support for future research and practical applications.

The selected articles are all obtained from the Web of Science database, covering a five-year period up to March 11, 2025. As of that date, there are a total of 3,883 results. The search criteria used were the combination of "Biochar" (in the title) and "contamination" (in the title). Utilizing the keyword analysis feature of VOS viewer, a threshold was set for the past five years, including only keywords that appeared more than 20 times among the 10,993 keywords considered, ultimately identifying 313 keywords. The connection strength between these 313 keywords was calculated to determine their interconnections. The size of each keyword reflects the number of related documents, while the line thickness represents their association strength.[41]

As shown in Fig. 1, the 10 most frequently occurring keywords are: "biochar", "adsorption", "removal", "remediation", "heavy-metals", "cadmium", "water", "sorption", "aqueous-solution", and " immobilization ".

2. Production and characteristics of biochar

Biochar is typically produced by pyrolyzing organic materials under oxygen-limited or low-oxygen conditions, including agricultural and forestry waste, animal manure, and sludge (Fig. 2).[42-44] The diversity of biomass components directly affects the potential for producing biofuels or biochar from biomass.[45] The carbon content of biochar is typically about 85% higher than that of the original biomass, primarily due to the combined effects of lignocellulosic structure decomposition and aromatic structure formation during pyrolysis, which collectively promote carbonization.[46,47] Studies have found that biochar can be prepared through various thermochemical processes, including slow pyrolysis, fast pyrolysis, flash carbonization, and roasting.[48,49] The pyrolysis temperature is decisive in influencing the physicochemical properties of biochar, which in turn affects its effectiveness in remediating soil pollution (Table 1).[23,50] Research indicates that variations in temperature significantly affect the surface morphology, functionality, and porosity of

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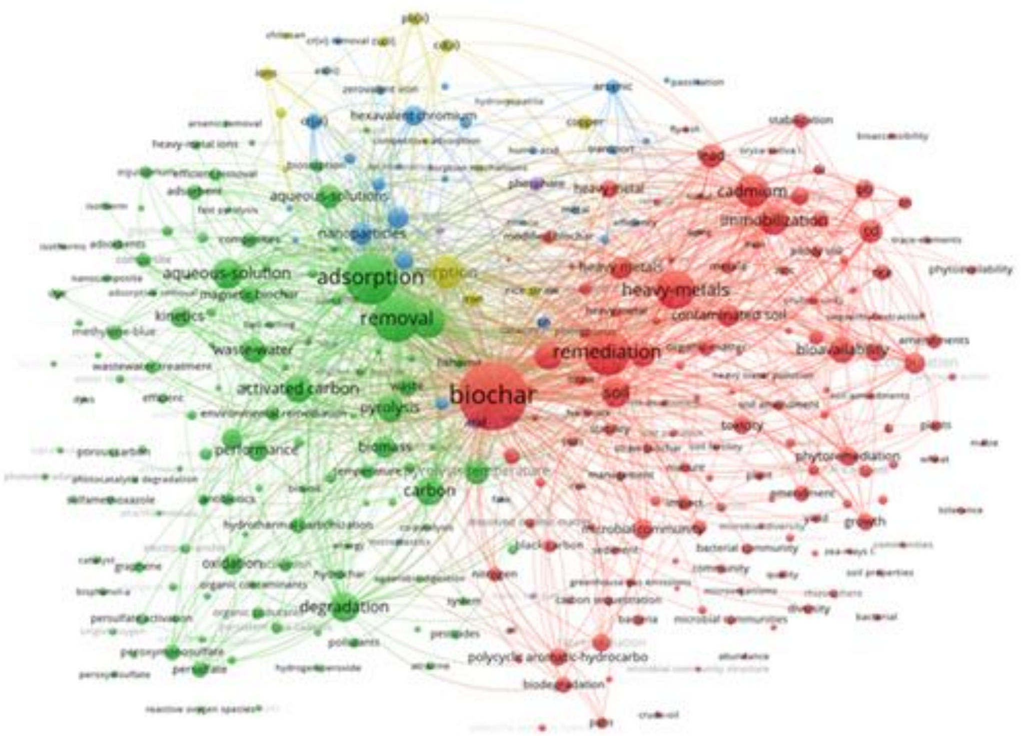

Fig. 1: The figure shows the key keywords and their relationships in biochar-based soil contamination remediation research from 2020 to 2025, with keyword size representing frequency and line thickness reflecting the strength of their connections.

biochar, highlighting its importance in environmental applications.[51] Low-temperature biochar (≤ 450 °C) is characterized by a higher concentration of surface functional groups and nutrients, resulting in strong hydrophilicity that supports microbial growth and enhances hydrocarbon degradation.[52,53] In contrast, high-temperature biochar, although excelling in physical adsorption, displays less reactive surface chemistry and has a diminished influence on microbial activity relative to its low-temperature counterpart.[53] Biochar properties are determined by pyrolysis parameters (temperature, duration, feedstock, residence time, and heating rate), which collectively govern its surface morphology, porosity, particle size, and ash content, ultimately defining its application potential.[54-57]

3. Modification strategies for enhancing biochar performance

In some cases, the adsorption capacity of conventional biochar is limited, resulting in suboptimal performance in remediating contaminated soils.[27] The modification of biochar through alterations in its surface properties and structure has emerged as a cutting-edge research field, primarily due to its enhanced adsorption capacity for heavy metals.[58] Modified biochar demonstrates superior adsorption capacity and stability, a finding supported by various studies.[59] Research indicates that modified biochar not only enhances adsorption capabilities but also contributes to an increased surface area, thereby providing additional adsorption sites for heavy metals.[3] Both biochar and its modified forms are recognized as environmentally friendly and cost-effective materials commonly employed in the remediation of contaminated soils.[27]

Biochar has attracted attention due to its excellent adsorption properties.[59,60] However, studies have shown that unmodified biochar may be insufficient to completely prevent the migration from heavy metals (for example, Cd) or salts (for example, Na) within plants and to maintain healthy plant growth.[59] As such, modifying biochar with organic amendments such as PSM, compost, and SMB could significantly improve its adsorption capacity and stability.[59,61] The integration of nanotechnology with biochar systems presents a dual-benefit solution, simultaneously mitigating heavy metal contamination and salinity stress in soils while boosting crop yields, thereby broadening its environmental remediation applications.[60]

Recent advances in biochar activation employ multidisciplinary methods (physical/chemical/biological) to engineer materials with superior stability and tailored functionalities.[24] The primary techniques of biochar modification encompass physical modification (*e.g.*, gas activation, secondary pyrolysis and microwave modification), chemical modification (*e.g.*, acid-base treatment and Fe modification), and biological modification.[58,67] In Fe-modified biochar, the iron phase is governed by temperature-dependent carbothermal reduction, facilitating redox remediation processes; although some micropores may be obstructed, the diffusion of fine iron particles onto the surface markedly enhances roughness and surface area, nearly doubling that of the original biochar.[54] The study found that Fe- and Zn-modified biochar significantly enhanced the removal capacity for Pb(II) from wastewater.[68] Fe-modified biochar significantly inhibited rice Cd uptake and reduced Cd accumulation in grains.[63] Fig. 3 demonstrates that biochars produced from different feedstocks through various

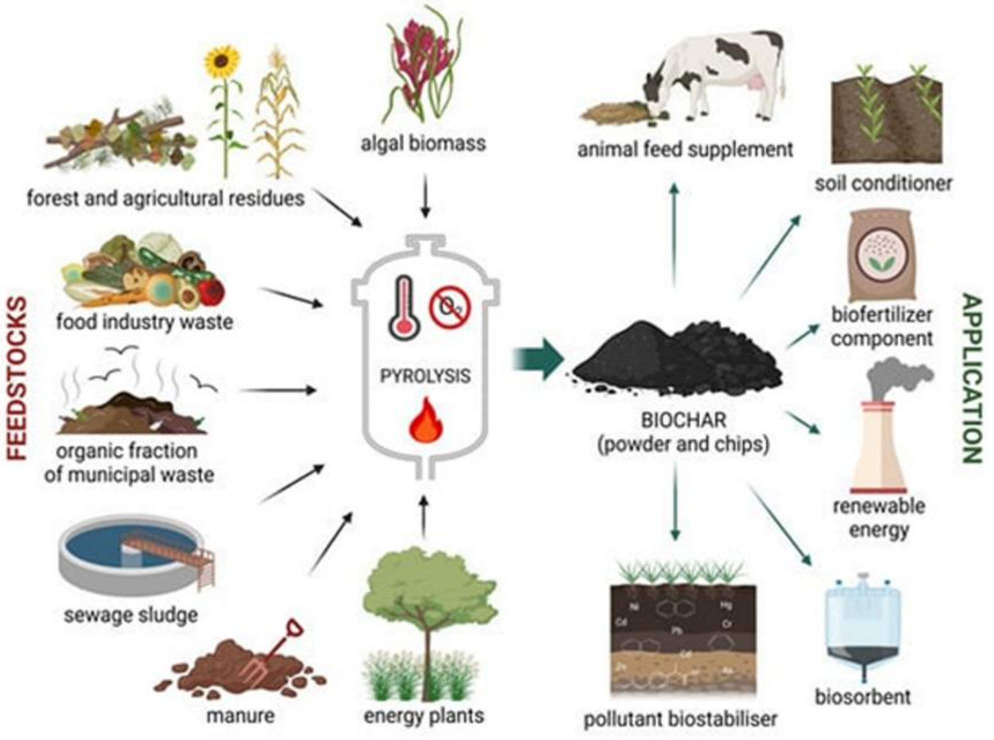

Fig. 2: Preparation of biochar Reproduced from.[62]

Table 1: Physicochemical properties of different biochar

Raw material	Pyrolysis conditions	Average pore diameter (nm)	Specific surface area (m^2/g)	Total Pore Volume	Ref.
Rice straw and rice husk	500 °C, 80 min	113.4	4.6	0.0132	[63]
Sugarcane bagasse	300/600 °C, 1 h	-	50.01/50.97	-	[26]
Rice straw	500 °C, 3 h	7.70	8.61	0.017	[64]
Fe-BBC	-	4.28	148	0.159	[64]
Conyza canadensis	450 °C, heating rate of 10 °C/min for 2 h	-	3.919	2.731 mm^3/g	[30]
Solidago canadensis	450 °C, heating rate of 10 °C/min for 2 h	-	4.971	7.480 mm^3/g	[30]
Tobacco stem	500 °C, 2 h	4.19	26.83	0.03 cm^3/g	[65]
Rice husk	500 °C, 2 h	5.29	7.85	0.01	[65]
Rubber wood	500 °C, 2 h	1.80	408.02	0.18	[65]
Rice husk	500 °C	1.83	251.79	0.12	[66]
Cellulose	500 °C	3.73	44.06	0.04	[66]

modification methods and pyrolysis temperatures exhibit distinct characteristics, with modified biochars showing significantly increased specific surface area that likely enhances their heavy metal remediation capacity in contaminated soils compared to unmodified counterparts.[16,24,69-71]

4. Applications of biochar in soil pollution remediation

The growing global challenge of water and soil pollution, intensified by rapid industrialization and heightened human activities such as fertilization and wastewater irrigation, has led to the release of significant quantities of bio-waste, organic pollutants, and heavy metals into ecosystems.[61,72] This situation results in considerable environmental harm, disrupting ecological balance and diminishing soil quality. It is imperative to prioritize the implementation of advanced remediation methods to address this urgent issue.[1,49,72]

Hence, the pursuit of a sustainable and high-efficiency soil remediation technology, with biochar gaining recognition for its beneficial impacts on soil quality and plant health, has attracted significant attention in recent studies.[24] Biochar, a carbon-rich material characterized by a large specific surface area, elevated carbon content, porous morphology, and other properties, can immobilize heavy metals through physical and chemical adsorption, reducing their activity and bioavailability while simultaneously optimizing soil structure and regulating soil pH, thereby improving soil quality, promoting plant growth, and enhancing soil microbial community functions.[44,58,72-74] Meanwhile, biochar demonstrates immense potential in carbon sequestration and environmental remediation.[31]

4.1 Immobilization of heavy metals in soil

Heavy metal pollution has emerged as a major environmental issue, largely attributable to industrial activities, excessive use of fertilizers, and wastewater irrigation practices. Toxic elements, including cadmium, lead, and arsenic, present significant risks to soil quality, plant health, and human safety. In this context, biochar has garnered significant attention as an effective remediation agent, attributed to its ability to immobilize heavy metals via mechanisms such as adsorption, cation exchange, and precipitation. This process effectively lowers the mobility and uptake potential of these toxic elements in soil, contributing to enhanced environmental safety.

The study found that biochar can effectively immobilize soil heavy metals through diverse mechanisms, including cation exchange, metal substitution (where metals replace surface cations on biochar), and surface complexation forming insoluble compounds, which can both prevent metal leaching and reduce their toxicity, thereby improving soil fertility and promoting plant health.[75-77] The combined effects of Geogenic

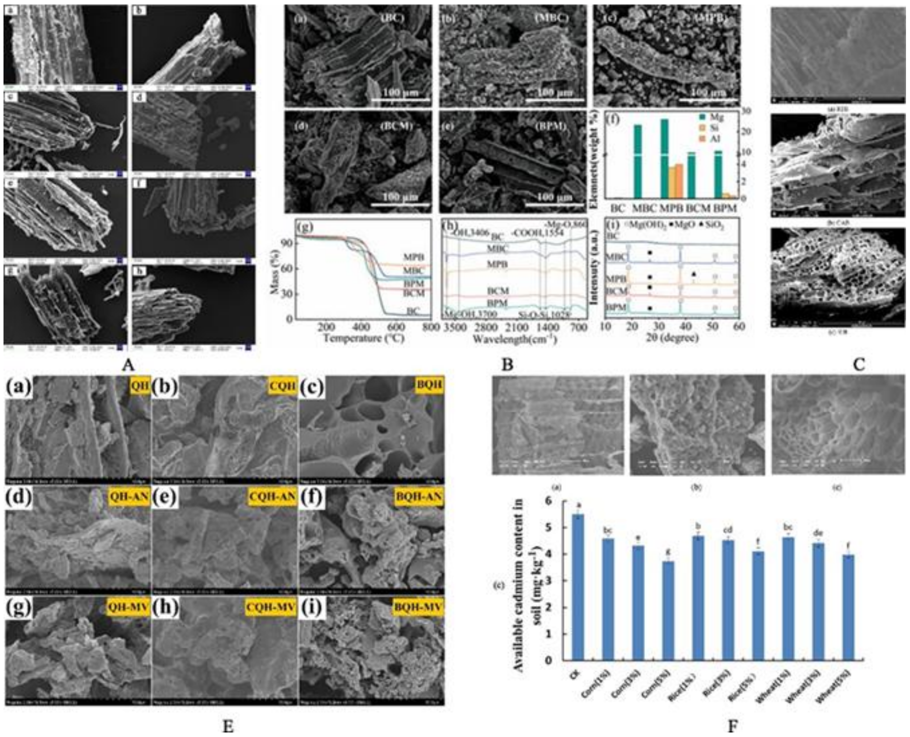

Fig. 3: Compared to unmodified biochar, the specific surface area of modified biochar is significantly larger. A: Surface characteristics of unmodified and Si-modified biochar at varying temperatures. Reproduced from.[24] B: SEM images of biochar (a), differently modified raw materials (b, c), and distinct modification methods (d, e), along with surface elemental composition (f), thermogravimetric analysis (g), FTIR spectra (h), and XRD patterns (i). Reproduced from.[69] C: SEM images of biochars prepared from different raw materials. Reproduced from.[70] D: SEM images of differently modified biochars. Reproduced from.[71] E: Biochars prepared from different raw materials (a-c) and their Cd remediation performance at varying doses (d). Reproduced from.[16]

sources result in widespread contamination of soils by heavy metals (Pb, Cd, As, Sb, Ni), posing a significant threat to the global soil environment.[76,78]

Cadmium (Cd) pollution has been a widespread environmental issue, posing serious threats to plants, animals, and human health due to its high mobility, bioaccumulation, non-degradability, and strong toxicity.[65,79-82] Over the past few years, biochar has demonstrated remarkable efficacy in co-remediating saline and cadmium-contaminated soils through three synergistic mechanisms: (i) cationic exchange reactions, (ii) ligand coordination, and (iii) π-electron-mediated precipitation.[79] Modified biochar is recognized for its efficacy in remediating cadmium-contaminated soil.[58] It has demonstrated a significant ability to reduce cadmium content, with enhanced effectiveness observed as application rates increase.[3,58] Compared to raw biochar, alkali-modified biochar exhibits superior performance by effectively altering cadmium distribution within the soil, leading to a reduction in its bioavailability.[58] Additionally, it has been shown to enhance urease activity, which also increases with greater application quantities.[58]

Recent research has demonstrated that zinc oxide nanoparticle (ZnONP)-modified biochar exhibits remarkable efficacy in immobilizing soil contaminants, specifically targeting toxic metals including nickel (Ni) and cadmium (Cd).[60,83] This modification not only enhances soil organic matter and nutrient availability but also influences cadmium accumulation in wheat tissues, leading to reduced BCF, TF, and BAC[60,84] Furthermore, ZnO NPs-modified biochar effectively alleviates membrane leakage and proline accumulation while enhancing leaf chlorophyll content, photosynthetic efficiency, and stomatal conductance.[60,85] These effects are particularly pronounced in saline-alkali soil conditions.[60] The reduction in Cd bioavailability is likely attributed to biochar's intrinsic properties, such as its highly porous structure, high pH value, CEC, and the abundance of chemical functional groups, particularly the elevation of soil pH, as well as its capacity to decrease Cd bioavailability by increasing SOC levels, which promotes Cd immobilization in soil.[30] The incorporation of biochar plays a crucial role in modifying soil properties by increasing pH levels and enhancing the interaction between its mineral components and cadmium ions (Cd^{2+}), thereby promoting the formation of salt precipitates that regulate the solubility and retention of heavy metals in the soil, ultimately influencing their migration and distribution and underscoring the significance of biochar in soil management and environmental remediation.[65]

Lead (Pb) is a major, widespread, and highly toxic persistent contaminant in soil, affecting plants, soil systems, and human beings.[86] Research has found that the composite material formed by integrating nano-zero-valent iron (nZVI) with biochar, referred to as nZVI-loaded biochar composite (nZVI-BC), exhibits significantly enhanced heavy metal removal efficiency compared to using nZVI or biochar alone, with the highest removal capacity for Pb^{2+}.[87] Arsenic(As), a highly toxic and carcinogenic element widely present in the environment, poses significant health risks, particularly in arsenic-contaminated soil and water.[88,89] This concern has elevated the importance of biochar as a high-quality remediation material, which is extensively employed as an adsorbent for the removal of arsenic from these mediums.[90-93] Recent studies have indicated that iron-modified biochar demonstrates exceptional adsorption capacity, particularly for Arsenite (As(III)).[90,94] Furthermore, research has shown that treating biochar with $ZnCl_2$ and $FeCl_3$ considerably boosts its surface area and porosity, enhances its adsorption capacity, and promotes the formation of oxygen-containing functional groups and π-π interactions, thereby improving its ability to efficiently adsorb As(III).[95]

Significant amounts of antimony (Sb) are released into the environment from various sources, such as mining, smelting, and fossil fuel power generation.[96,97] Given its similarities to arsenic (As) in physicochemical and toxicological characteristics, along with its classification as a carcinogenic heavy metal, elevated levels of antimony pose serious health risks when present in excess.[97,98] Research indicates that biochar can initially increase Sb levels in the soil and has the potential to mitigate Sb contamination by reducing plant absorption.[97,99] However, it is essential to consider the associated risks, as biochar may also promote Sb oxidation, leading to increased availability of Sb through modifications in soil properties.[97] Furthermore, studies demonstrate that zero-valent iron (ZVI) contributes significantly to enhancing soil and plant root structures by facilitating the creation of iron oxides, while also increasing the sulfide content, which is crucial for reducing the mobility of Sb by promoting the conversion of Sb^{5+} to the less harmful Sb^{3+}.[98,100] The combination of ZVI and biochar has been shown to significantly decrease redox potential and assist in managing pH fluctuations.[98,101] While initial interactions between these materials may present challenges, there is potential for synergistic effects to emerge over time, offering promising avenues for addressing antimony contamination in environmental contexts.[98]

4.2 Removal of organic pollutants from contaminated soil

Organic pollutants, including pesticides, antibiotics, petroleum hydrocarbons, and plastic additives, play an important part in long-term soil degradation and the disruption of microbial ecosystems. These contaminants can persist in both soil and groundwater, resulting in considerable environmental and agricultural challenges. It was found that biochar can effectively adsorb and facilitate the degradation of organic pollutants. This process minimizes their movement and harmfulness while simultaneously enhancing soil quality.

The contamination of soil ecosystems by PTEs has become a significant environmental concern, primarily due to excessive human activities, including the extensive application of pesticides, industrial wastewater discharge, and the incineration of urban solid waste.[17,102] In response to this issue, various remediation strategies have been implemented including excavation, soil washing, immobilization, and bioremediation, to address PTE-contaminated soils effectively.[6] While agricultural fertilizers have dramatically enhanced crop productivity and nutritional value, their overuse results in problematic nitrate (NO_3^-) and phosphate (PO_4^{3-}) deposition in ecosystems.[103]

The persistent presence of PE in terrestrial environments poses significant ecological risks, as its chemical stability leads to the accumulation of microplastic contaminants over extended periods.[104,105] Biochar, as a commonly applied soil improver, has recently been found to mitigate crop damage by adsorbing soil contaminants, thereby enhancing crop productivity and altering soil microbial communities.[57,105] Research indicates that biochar has the ability to lessen the toxicity of PE contamination to broad beans and influence soil bacteria, affecting the growth of Chinese cabbage.[105]

DBP, a widely applied plasticizer in agricultural films, easily leaches from agricultural waste, leading to prolonged soil ecosystem pollution lasting 200 to 400 years.[106,107] Earlier research has found that while the use of DBP-degrading bacteria alone can degrade pollutants, the effect is limited; however, biochar, used as a strain immobilization material, can significantly enhance microbial degradation capacity, and Fe-modified biochar, due to its larger specific surface area and porosity, provides a more suitable habitat for microorganisms, facilitating their colonization and reproduction, while the optimized preparation of $KPSB_3O_4$-modified biochar can simultaneously achieve DBP degradation and enhance soil potassium nutrient levels, providing a new approach for soil pollution remediation.[107]

Oil pollution forms hydrocarbon films that impair soil-water interactions and exacerbate salinization, degrading grassland ecosystems, while the mechanisms of its impacts on microbial communities remain unclear.[7,53,66,108] Studies have shown that modified biochar combined with specific functional bacteria can significantly enhance oil degradation efficiency, as the synergistic effect of sulfonate ($-SO_3H$) modified biochar and isolated bacteria achieves the highest degradation rate of 39.4%, providing a new approach for the comprehensive restoration of oil-contaminated and saline-alkali soils, while modified biochar further promotes the transition of saline-alkali soils to healthy soils; moreover, the combination of acid-modified biochar and a specific strain (Y-1) is instrumental in shaping soil microbial communities and supports the cycling of nitrogen and phosphorus nutrients, thereby further enhancing the restoration effect of degraded grasslands.[7] Research has shown that incorporating biochar can improve the removal efficiency of petroleum hydrocarbons from polluted soil.[108] Research has found that combining biochar addition with Biostimulation can effectively regulate soil pH and moisture levels, support microbial proliferation, and boost petroleum hydrocarbon degradation.[53] Petroleum leakage is a persistent planetary-scale problem mainly resulting from various industrial activities, including crude oil extraction, refining, processing, usage, and associated operations.[66] Biochar effectively degrades PNP in soil through adsorption (via rapid/slow stages) and reductive degradation (positively correlated with EDC), while oxidative degradation plays a secondary role.[72]

OTC is extensively used in the medical field and livestock farming; however, due to its widespread use and improper disposal, environmental pollution has become a serious issue, as antibiotics, while playing a crucial role in treating infections and improving public health, have led to severe pollution problems when used excessively; therefore, with the overuse of OTC, its contamination in vegetables has become a global concern, threatening food safety and human health.[2,95] Some research indicates biochar application can reduce the availability of OTC.[2] Additionally, research has shown that bimetal-modified biochar exhibits significant adsorption effects on OTC.[95]

4.3 Combined remediation techniques using biochar

Since biochar derived from different materials influences soil properties in distinct ways, the interplay between various biochar types can generate synergistic effects, thereby enhancing its effectiveness in remediating contaminated soil, as studies have shown that mixing four types of biochar into soil achieves better cadmium (Cd) remediation than using one or two types; moreover, soil amended with multiple types of biochar reduces the proportion of biomass allocated to sprouting in communities with lower diversity, while in more diverse communities, significantly reducing Cd concentrations can improve soil conditions and enhance root absorption capacity, indicating that biochar, as a soil amendment, plays a crucial role in regulating plant biomass allocation.[1]

Research has shown that applying biochar, particularly in combination with molybdenum nanoparticles (MoNPs), significantly reduces the negative effects of cadmium (Cd) on plants while enhancing both the length and dry weight of plant roots and shoots.[109] Additionally, studies indicate that using biochar alongside wood vinegar has a greater impact on phosphorus absorption in soil than using each one individually, as this combination not only raises soil pH but also lowers EC and CEC, while at higher doses, it notably affects the sorption of phosphorus in the soil.[18]

The combined application of PGPR and biochar significantly enhanced plant growth, reduced antioxidant enzyme activities and membrane lipid peroxidation, and effectively decreased lead (Pb) and cadmium (Cd) concentrations in plants by 58.3% and 86.3%, respectively, in highly contaminated soil.[75]

Studies show that the combined application of AMF and biochar is more effective than using either alone, as it enhances photosynthetic capacity, increases total dry weight, and reduces Cd accumulation in plant tissues.[110] Finally, some studies have also found that the combined application of bentonite and biochar is more effective in mitigating the harmful effects of cadmium (Cd) than using either material alone.[111]

4.4 Influence of biochar on soil physicochemical properties

Soil pollution substantially impacts essential physicochemical properties, leading to detrimental effects on soil fertility, water retention, and microbial balance. The incorporation of biochar helps to enhance soil structure through greater porosity, stabilizing pH levels, and improving CEC, all of which contribute to more robust plant growth. In addition, biochar helps to reduce the bioavailability of toxic metals and promote greater microbial diversity, making it a valuable amendment for improving polluted soils (Fig. 4).

Pollutants can indirectly influence nutrient dynamics, plant development, and agricultural productivity by affecting soil enzyme activities, whereas biochar and its modified forms have been shown to boost the functions of urease, ALP, and dehydrogenase in contaminated soils.[2] Owing to its distinct characteristics, biochar has attracted interest in its ability to significantly improve soil quality, promote plant growth, enhance nutrient retention, and foster a conducive environment for soil microorganisms.[112]

The incorporation of biochar can inhibit disease and promote plant growth, but its effectiveness varies depending on the materials used and pyrolysis temperature[24,49,113].Some studies have found that the yield of biochar decreases as temperature increases, possibly due to the increased breakdown of biomass at elevated temperatures, while silicon-modified biochar improves soil properties by increasing surface area, adsorbing silicon, and raising pH and EC; moreover, it promotes plant growth, enhances resistance to pests and diseases, boosts nutrient availability, and inhibits pathogenic microorganisms, thereby contributing to overall soil health and plant development.[24,114]

Studies have found that the pyrolysis of *Typha angustifolia* biochar at 600°C significantly enhances soil quality and boosts crop productivity.[51] Modified biochar significantly increases soil pH and nutrient content, reduces the bioavailability of cadmium (Cd) in soil, stimulates plant growth, and improves nutrient content and accumulation in plants to varying degrees.[115] It has been observed that biochar enhances soil characteristics, including EC, pH, organic matter content, and nutrient exchange capacity, all of which contribute to improved plant growth and the maintenance of soil fertility.[114] Biochar substantially decreases the bioavailability and leaching of cationic metals and metalloids in soil, while improving soil structure, enhancing physical and chemical characteristics, increasing fertility, and facilitating vegetation restoration, thereby affecting the mobility of elements.[116] The porous structure of biochar contributes to improved water-holding capacity of the soil, enhanced nutrient availability, and elevated microbial activity, thereby having a vital impact on the long-term fertility and productivity of the soil.[117]

Soil contamination and nutrient imbalances significantly impact crop yields and threaten food security, highlighting the need for sustainable soil management strategies. The application of biochar has demonstrated positive effects on soil nutrient availability, water retention, and microbial activity, thereby fostering conditions conducive to plant growth. Furthermore, biochar has the potential to diminish the uptake of toxic elements by crops, alleviate stress conditions, and enhance agricultural productivity in polluted or degraded soils. These benefits highlight its role as a valuable tool in promoting sustainable agricultural practices.

The application of biochar and biochar-based fertilizers can increase rice plant height and biomass during the tillering and booting stages, while also reducing cadmium accumulation in the roots and rice grains and potentially decreasing the transfer of cadmium from roots to stems; however, at the maturity stage, treatment with biochar or biochar-based fertilizers does not result in a significant increase in biomass.[120,121]

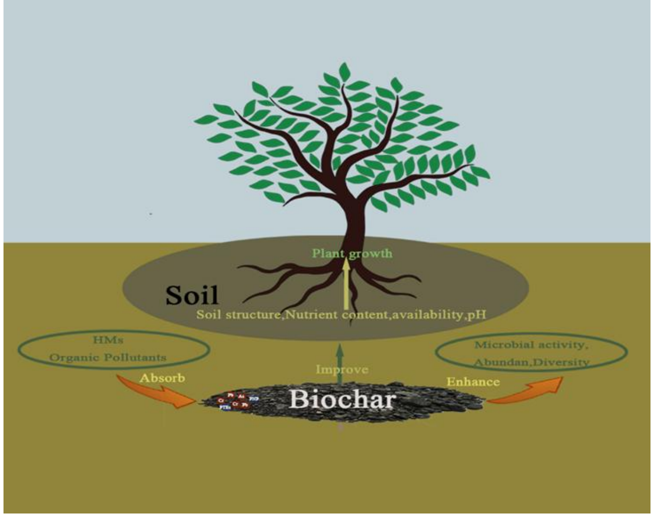

Fig. 4: Biochar for soil remediation Reproduced from. [62,118,119]

5. Limitations and challenges in the application of biochar

Biochar presents a promising opportunity for the remediation of soil pollution. However, its long-term stability and efficiency are significant areas of concern. Over time, biochar undergoes physicochemical transformations as a result of weathering, microbial activity, and interactions within the soil. These changes can affect its adsorption capacity and its effectiveness in immobilizing contaminants. The aging process affects various properties, including pH, surface area, and functional groups, and may either enhance or weaken remediation capabilities under different soil conditions. The performance of biochar exhibits considerable variation across different soil types influenced by factors like pH, organic matter content, and the concentration of competing ions. To address challenges related to durability and adaptability in diverse environments, researchers are investigating modifications to biochar, including mineral doping and the integration of nanomaterials.

It is essential to consider the environmental and ecological risks related to the application of biochar. There is potential in the release of PAHs during pyrolysis, which raises concerns regarding soil contamination and possible human health risks if not carefully managed. Additionally, changes in microbial communities can be beneficial; however, they may also disrupt soil biodiversity in unforeseen ways. Implementing strict controls over pyrolysis conditions and conducting comprehensive risk assessments are crucial to mitigating these concerns.

The lack of well-defined regulatory frameworks in many regions further complicates the widespread adoption of biochar, as uncertainties remain regarding its long-term environmental impact. Economic constraints and implementation challenges also pose significant barriers to large-scale applications. The high production costs associated with raw material collection, pyrolysis, and modification render widespread use financially challenging.

To enhance efficiency while minimizing costs, integrating biochar with other remediation technologies including phytoremediation, microbial bioremediation, and chemical amendments has proven effective. Ongoing research endeavors are dedicated to developing cost-effective production methods, advocating for policy incentives, and exploring hybrid remediation approaches, ultimately aiming to maximize biochar's capacity to serve as a sustainable remedy for soil pollution.

6. Conclusion

This review offers a comprehensive examination of recent advancements in biochar research related to soil pollution remediation, with a specific focus on its preparation, modification, and application for the mitigation of heavy metal and organic contaminants. Biochar is recognized for its exceptional adsorption properties, surface functionalization, and ability to enhance soil health, positioning it as a promising solution to combat soil degradation resulting from industrial and agricultural practices.

The evolution of modified biochar, which includes the integration of nanomaterials and chemical alterations, has further augmented its efficacy in pollutant immobilization. This enhancement provides a cost-effective and sustainable alternative to conventional soil remediation approaches. On a global scale, the application of biochar aligns with sustainable development objectives by fostering waste valorization, facilitating carbon sequestration, and mitigating pollution. However, the implementation of biochar is not without its challenges, including uncertainties regarding its long-term stability in diverse soil environments, potential ecological risks linked to its use, and considerations surrounding the economic feasibility of large-scale application. Addressing these challenges is crucial for promoting the extensive use of biochar-based remediation strategies.

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Conflict of 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.

Supporting Information

Not applicable.

Nomenclatures

ALP	Alkaline Phosphatase
AMF	Arbuscular Mycorrhizal Fungi
BAC	Biota Accumulation Coefficient
BCF	Bioconcentration Factor
CEC	Cation Exchange Capacity
DBP	Dibutyl Phthalate
EC	Electrical Conductivity
EDC	Electron Donor Capacity
OTC	Oxytetracycline
PAHs	Polycyclic Aromatic Hydrocarbons
PE	Polyethylene
PGPR	Plant Growth-Promoting Rhizobacteria
PNP	*p*-nitrophenol
PSM	Phyllosilicate Minerals
PTEs	Potentially Toxic Elements
SMB	Sulfur-Modified Biochar
TF	Translocation Factor

CRediT Statement

Tao Hu: Writing – original draft, Investigation, Formal analysis, Data curation. **Haiping Gu:** Writing – review & editing, Validation, Investigation, Conceptualization. **Su Shiung Lam:** Writing – review & editing, Validation, Investigation. **Wanxi Peng:** Validation, Investigation. **Hanyin Li:** Validation, Investigation. **Lijun Yan:** Writing – review & editing, Methodology, Supervision, Project administration.

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