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REVIEW ARTICLE

Biochar for simultaneous soil remediation and carbon sequestration: application, mechanism, and development prospect – a comprehensive review

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Abstract

Biochar, as a carbon-enriched porous material obtained via pyrolysis of biomass in anoxic environments, exhibits significant potential for application in soil remediation and carbon cycle management due to its unique physicochemical properties. This article reviews the application and action mechanism of biochar in the remediation of heavy metals and organic pollutants contaminated soils, and the effects of carbon sequestration. The remediation of heavy metals involves a complex interplay of physical adsorption, ion exchange, surface complexation, co-precipitation, and redox reactions. For organic pollutants, adsorption mechanisms such as pore filling, hydrophobic partitioning, and π-π interactions are paramount, alongside biochar-facilitated microbial degradation. Furthermore, the review details how biochar application promotes soil carbon sequestration by directly introducing stable carbon, influencing soil organic matter dynamics, fostering aggregate formation, and modulating microbial communities to reduce greenhouse gas emissions. Despite its potential, significant challenges persist, including the long-term stability of biochar, the risk of pollutant remobilization upon aging, and context-dependent performance influenced by soil properties. This review not only systematically explores its mechanism of action, but also aims to provide crucial theoretical support and forward-looking research directions for the design of multifunctional biochar materials and the realization of the synergistic effect of pollution control and carbon neutrality.

Keywords Biochar · Contaminated soil remediation · Heavy metals · New contaminants · Carbon sequestration

Introduction

As the global population grows and industrialization accelerates, environmental pollution has become a global challenge (Hassani et al. 2021). Soil is not only the basis of agricultural production, but also an important part of the carbon cycle (Machmuller et al. 2024). At present, soil pollution is mainly affected by several aspects, first of all, the pollutants produced by industrial activities, including manufacturing operations and mineral extraction practices, is one of the main sources of soil pollution. In agricultural production, the excessive use of chemical fertilizers and pesticides can also lead to soil contamination; the pollution of heavy metals(HMs) in the soil as well as the pollution of new pollutants has been more important in recent years, and then there is also the disposal of waste and soil degradation problems that need our attention. Therefore, it is particularly important to find a method that can both remediate polluted soils and enhance soil carbon sinks.

Biochar, a carbon-rich porous material produced from biomass pyrolysis under oxygen-limited conditions, possesses high porosity, extensive specific surface area, potent adsorption capacity, and beneficial effects on soil properties like nutrient availability, water-holding capacity, permeability, and pH regulation(Agyekum and Nutakor 2024). Its adsorption performance improves the soil water-holding capacity and porosity and affects the survival environment of soil microorganisms and metabolism, so it has been widely used in soil in recent years. Biochar's high specific surface area and rich pore structure enable it to adsorb and

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fix soil pollutants. Furthermore, being rich in organic carbon and resistant to biodegradation, biochar persists in the soil after application, which means it can increases soil organic matter content, thereby improving the soil's physicochemical and biological properties. (Kavitha et al. 2018). With the development of research, the application of modified biochar in the remediation of contaminated soil is also increasing (Jiao et al. 2021). Through various preparation techniques, including chemical treatment, physical modification, and biological modification, which can produce charcoal-based materials with enhanced adsorption capabilities for a wide range of substances. These improved materials can significantly boost their effectiveness in soil remediation efforts (Ravindiran et al. 2024). It has been proved that the modification treatment can increase the surface area and the abundance of oxygen-containing functional groups of biochar, thus improving its adsorption capacity for pollutants to increase cation adsorption (Wang et al. 2018). Biochar demonstrates effective remediation capabilities for co-contaminated soils by synergistically lowering pollutant bioavailability while facilitating stabilization and decomposition processes. Through multi-mechanism interactions, this carbon-based material effectively remediates both organic contaminants and heavy metals, with growing evidence supporting its efficacy against novel contaminants (Lalmalsawmdawngliani et al., 2024).

Beyond its effectiveness in soil remediation, biochar's long-term stability in soil also makes it an effective carbon sequestration strategy. It has been demonstrated that by spatially reorganizing carbon in the soil, as well as reducing soil respiration, it increases the humus-like fluorescent component of the soil, thus helping the environment to promote carbon storage in the soil (Hernandez-Soriano et al. 2016). It is also possible to improve soil structure and optimize microbial communities, reduce greenhouse gas emissions from soils, and promote sequestration of plant-sourced carbon, thereby contributing to carbon emission reduction as well as carbon fixation (Luo et al., 2023). Therefore, based on these points, this review aims to discuss the application and action mechanism of biochar in contaminated soil remediation and carbon sequestration, so as to provide a scientific basis for the rational application of biochar and environmental management.

Therefore, based on the above points, this review aims to explore the application and mechanism of biochar in the remediation of contaminated soil and carbon sequestration and constructs a comprehensive framework encompassing raw materials, preparation, properties, and applications (Fig. 1). More importantly, by clarifying how pollutant fixation and microbial regulation affect the carbon cycle, as well as how enhanced carbon sequestration and changed soil properties feedback to influence the long-term effectiveness and stability of the remediation. This perspective is expected to provide scientific basis for the rational application of biochar and environmental management, in order to achieve the dual goals of environmental health and climate change mitigation.

Remediation of heavy metal contaminated soil by biochar

Potentially toxic elements of soil are considered one of the most serious environmental threats (Bilias et al. 2021). There are many kinds of heavy metals in soil, of which mercury, cadmium, lead, arsenic, antimony, copper and so on are of high concern. Soil contamination by heavy metals poses significant threats to agricultural productivity, human health, and global food security. Elevated HMs concentrations exceeding critical thresholds not only impair crop

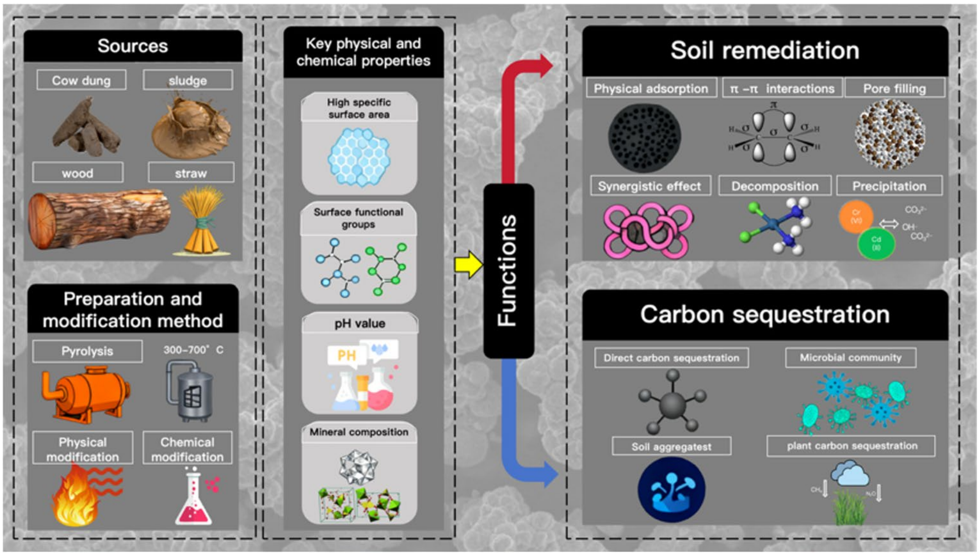

Fig. 1 Biochar for soil remediation and carbon sequestration

health and yield but also disrupt structural integrity and functional mechanisms of cellular components, thereby hindering essential metabolic pathways and developmental processes (Angon et al. 2024). Biochar has emerged as a promising sustainable alternative in environmental remediation, particularly for heavy metal (Tran et al. 2023).

Adding biochar to the soil may affect the soil pH value, thereby influencing the complexation between biochar and heavy metal functional groups. Studies have shown that the addition of biochar can increase the pH value of acidic soil by approximately 0.5 to 1 unit, which depends on the raw materials of biochar, pyrolysis temperature, initial pH value of the soil, and the amount of biochar added. For example, the pH was increased by adding hardwood biochar, thereby promoting the hydrolysis of heavy metal ions (Bakshi et al. 2014). And the content of soil organic matter, changing the redox state of the soil, as well as affecting the composition of microbial communities and the bioavailability of plants (Chen et al. 2023).

The mechanism of action of biochar on heavy metals mainly include adsorption, complexation, precipitation, ion exchange, redox and other mechanisms (Tang et al. 2022), thereby reducing the migration and bioavailability of heavy metals and reducing the damage caused by heavy metal pollution to soil (Pathak et al. 2024). Figure 2 shows how biochar removes heavy metals through multiple pathways working together. Biochar lowers the bioavailability and mobility of heavy metals by combining physical adsorption, chemical reduction and complex precipitation. For heavy metal cations like Pb^{2+} and Cd^{2+}, biochar mainly uses oxygen-containing functional groups for complexation and electrostatic adsorption. To enhance capturing these metals, modifiers are added to form insoluble precipitates. For example, phosphates form phosphate precipitates with HMs, like $Pb_3(PO_4)_2$, $Cd_3(PO_4)_2$, while iron-based compounds create stable complexes through redox reactions, chelation and co-precipitation. For common divalent metal ions, such as Ca^{2+}, Mg^{2+}, etc., their removal involves oxygen-containing group complexation, multi-ionic competitive adsorption equilibrium and metal salt precipitation with anions such as PO_4^{3-}, S^{2-}.

The mechanism of heavy metal removal by biochar usually also includes adsorption and precipitation, which can increase the binding sites for heavy metals by improving the soil colloidal surface area (Bashir et al. 2022), and the porous nature of biochar retains suspended soil particles, which enhances heavy metal immobilization (Bakshi et al. 2014). The enrichment of oxygen-containing moieties on biochar surfaces enhances redox transformations of metallic species through electron transfer mediation. Concurrently, mineral co-precipitation serves as a supplementary immobilization pathway, where metal-biochar complexes form stable crystalline phases via ligand-specific interactions (Kumar et al. 2020; Wang et al. 2022). Whereby heavy metal ions react with biochar indicating a complex porous structure to form organo-mineral complexes. In addition, its high specific surface area, porous structure and surface liquid film enrich heavy metal ions through physical trapping and adsorption and finally remove heavy metal ions.

Table 1 lists the removal effects of different types of biochar on heavy metals. The different types of biochar will have corresponding effects on heavy metals in soil by modifying the properties of the biochar when treating them. When unmodified biochar is added to the soil, the biochar may also retain suspended soil particles, which enhances the immobilization of Cu in the soil and reduces the loss of Cu in the leachate (Bakshi et al. 2014).

Meanwhile, there are some improved methods, for example, acid modification or the addition of magnetic substances will improve the heavy metal elimination effectiveness (Meng et al. 2017; Wu et al., 2024a). Some acid-modified or physically ball-milled modified biochar added to the soil will lower the pH of the soil, which will accelerate the reduction of some heavy metals, such as Cr, due to the complexation of the introduced carboxyl groups with oxygen-containing functional groups, thereby slightly decreasing the pH of the

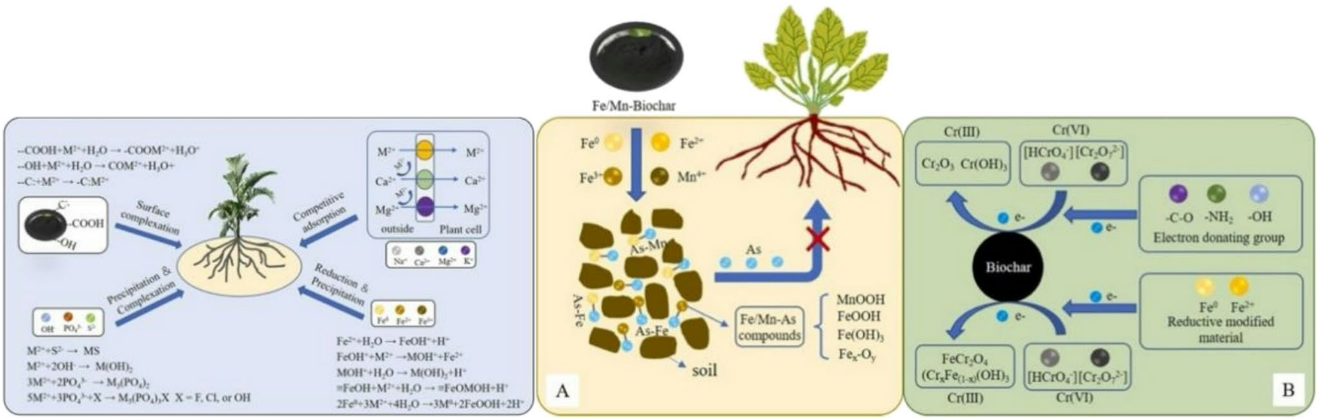

Fig. 2 Comprehensive mechanisms of biochar in remediating heavy metal contaminated soil (Gong et al. 2022)

Table 1 Remediation effects of different Biochar on heavy metal contaminated soil

Types of biochar	Type of pollutant	Application condition	Effect	Reference
Sesame straw biochar	Cu	Moisture Content: 70% Biochar dosage: 2%	Reduction in bioavailable Cu : 51%.	(Bashir et al. 2022)
Maple and oak wood biochar	Cu	Moisture Content: 70% Biochar dosage: 5%	Cu leaching loss from 48% to 9%	(Bakshi et al. 2014)
HCl-willow biochar	Cr	Moisture Content: 70% Biochar dosage:25 g Soil dosage:500 g	Cr^{6+} reduction rate: 97.26%.	(Meng et al. 2017)
Big biochar spheres (mass ratio of silicate, Fe_3O_4 and straw biochar 4:1:1)	Cd, Pb, As	Moisture Content: 100% Biochar dosage: 20%	Reduction in bioavailable Cd:30.6%, Pb:30.2%, As:41.0%	(Wu et al. 2024a)
Carboxylated rice husk biochar	Cd, Pb, Cu, Zn	Biochar dosage:1% Moisture Content: 30%	Reduction in bioavailable Cd :22.88%, Pb:99%, Cu:28.3%, Zn:34.7%	(Li et al. 2022)
PEI-methanol modified corn stalk biochar	Cd	Biochar dosage: 13,000 kg/ha	Reduction in bioavailable Cd: 40.54%.	(Tang et al. 2022)
Cattle manure biochar	Cr	Biochar dosage:50 g/kg	Significantly lower	(Kumar et al. 2020)
Peanut shell biochar (400 °C)	Cr	Biochar dosage: 0.10 g Soil dosage: 2 g	Cr^{6+} decreased by 46.2%.	(Ke et al. 2024)
Sludge biochar + ryegrass	Cr, Ni, Cu, Zn, As, Cd	Biochar dosage :5% Soil dosage: 100 g Moisture Content: 60%	Reduction in bioavailable of Cr:24.12%, Ni: 23.30%, Cu:22.01%, Zn:9.98%, As:14.83%, Cd:15.08%	(Li, X.N. et al., 2024)
Modified cornstalk biochar	Cu, Cd	Biochar dosage :10% Soil dosage: 20 g	The extractability of Cu^{2+} was reduced from 85% to 15.2%	(Zhang et al. 2020)
Rice straw biochar(700 °C)	Cd	Biochar dosage :3%	The availability of Cd reduced from 0.16 $mg \cdot kg^{-1}$ to nearly 0	(Zhao et al. 2025)

soil, and facilitating the dissociation and oxidation of phenolic hydroxyl groups, etc., which will increase the supply of protons for the reduction of metal ions (Lyu et al. 2018; Wang et al. 2015). However, for the removal of Cd from soil, alkaline biochar is often added, this is because biochar usually contains saline ions that directly reduce H^+ in soil, leading to an increase in pH (Wei et al. 2023), and changes in microbial abundance and community structure can also indirectly affect pH, but have inconsistent effects on pH (Xiao et al. 2020).

Furthermore, under multi-metallic coexistence conditions, there is competition between metal ions, for example, Pb^{2+} has a stronger affinity for most functional groups and has a lower zeta potential and hydration radius, leading to its binding to heavy metals through electrostatic interactions or chemical associations, which makes it more likely to bind to the adsorption sites of biochar (Li et al., 2022; Li, X.N. et al., 2024).

It is noteworthy that the role of soil pH changes induced by biochar in the heavy metal immobilization process remains an issue requiring further investigation (Hu et al. 2022). While most studies suggest that the alkalinity of most biochar increases soil pH, thereby promoting the precipitation and adsorption of cationic heavy metals, notable exceptions exist. For instance, using biochar in soils with high organic matter content or certain acid-modified biochar may result in negligible pH changes or even pH reduction. In such scenarios, mechanisms like surface complexation with functional groups and physical adsorption within the porous structure may outweigh precipitation effects. This phenomenon arises from the initial properties of biochar and soil composition. Following biochar application, regular monitoring of soil pH is essential to predict subsequent changes in metal speciation.

Some magnetic biochars demonstrate unique advantages in heavy metal remediation, but their practical application is still limited by the risk of metal leaching, high cost, and challenges in large-scale preparation (Wang et al. 2025).

Remediation of organic pollutants contaminated soil by biochar

In the soil, due to the application of pesticides, the burning of biomass and petroleum (Li et al. 2024b), there is a widespread problem of some difficult to degrade organic matter pollution soil, which has been the focus of environmental monitoring for decades, including well-known compounds, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), is the focus of environmental monitoring for decades. Some researchers are using brown seaweed biochar for remediation, for example, the condition at pH 3, biochar addition of 3.0 g/L and the mass ratio of peroxymonosulfate and polycyclic aromatic hydrocarbons was 1:1, PAHs removal rate was 77% (Hung et al. 2021). In addition, biochar combined with other methods has a better effect on removing organic pollutants. Some studies have shown that the addition of biochar can increase the removal rate of phenanthene in PAHs in soil by 75.7%, and the removal rate increased to 93.4% after combining with microorganisms (Wang et al. 2025a, b, c). In addition, several new pollutants have received attention in recent years, including persistent organic pollutants (POPs), endocrine disrupting chemicals (EDCs), antibiotics, and microplastics (Jiang et al. 2023; Liu et al., 2023a). Biochar have shown great promise for environmental remediation processes (Rajput et al. 2024). Long-term accumulation of low-cyclic PAHs may threaten ecosystems through food chain enrichment, the persistence and biotoxicity of PCBs may lead to long-term soil function degradation and affect crop safety, and long-term exposure to ng/g BPA may still affect reproductive health (Valizadeh et al. 2021). These contaminants are often associated with modern lifestyles, industrial practices, and their potentiality.

Effect of biochar on removing organic pollutants

Table 2 shows the remarkable effect of biochar in the remediation of conventional and emerging organic pollutants. For conventional pollutants such as polycyclic aromatic hydrocarbons (PAHs) and pentachlorophenol (PCP), adding 2% ~ 5% of rice husk, corn or wheat straw biochar, the PAHs removal rate can reach 19.78% ~ 62.5% (Guo et al. 2024; Shang et al. 2024; Zhao et al. 2022), PCP decreased by 67.2% (Zhu et al. 2020); When combined with plants such as ryegrass and alfalfa, the improvement of microbial activity further enhances the degradation efficiency (Shang et al. 2024; Zhao et al. 2022). Emerging pollutants include antibiotics, such as tetracycline, sulfonamides; endocrine disruptors, such as 4-tert-octylphenol; and organochlorine pesticides, such as hexachlorocyclohexane. For emerging pollutants, biochar is effectively removed by functional modification: The removal rate of sulfamethoxazole could reach 80.4% by adding 5% methanol activated walnut shell biochar (Keshiknevisrazavi et al. 2022). The removal rate of tetracycline from corn biochar modified with 2% phosphoric acid was almost 98% (Han et al. 2024). The degradation rates of α-HCH and γ-HCH were 55.2% and 85.4%, respectively, by 1% peanut shell supported nano-ferric zero-valent biochar (BC/nZVI) (Li et al., 2023b). Its strong polarity and resistance to degradation depend on the removal of biochar by porous adsorption (Zhang et al. 2021), π-π interaction (Tang et al. 2023), and combined techniques such as chemical oxidation and nanomaterials.

Biochar removal mechanism of organic pollutants

Figure 3 shows the mechanism by which biochar is used to remove heavy metals. The mechanism of biochar adsorption to remove organic micropollutants includes (a) pore filling, (b) cation-π interaction, (c) electrostatic interaction, (d) hydrophobic interaction, (e) hydrogen bonding. (f) π-π EDA interaction (Tran et al. 2023). Biochar plays an efficient adsorption role on organic pollutants through its unique physical and chemical properties, including its high specific surface area, porous structure and rich functional groups (Loffredo and Parlavecchia 2021). The physicochemical mechanism led by adsorption usually includes pore filling and hydrophobic action. The microporous structure immobilizes hydrophobic pollutants such as PAHs and PCBs through physical adsorption. The study found that the higher the content of organic matter in soil, the easier the retention of phenolic substances. Biochar can better reduce the residue of organic matter in soil due to its high SOM characteristics and strong pollutant entrapment efficiency (Ou et al. 2016). Some researchers found that adsorption efficiency was positively correlated with the specific surface area of biochar (Anae et al. 2021; Zhang et al. 2021). There are also surface functional groups: oxygen-containing functional groups (carboxyl, hydroxyl) bind to polar pollutants, such as antibiotics and EDCs, through hydrogen bonding and electrostatic attraction; Adsorption of phenyl-containing compounds by aromatic structures through π-π electron donor acceptor (EDA) interaction (Cwielag-Piasecka et al. 2023; Tang et al. 2023). When multiple contaminants coexist, such as sulfonamides and quinolones antibiotics, adsorption site competition may reduce efficiency (Wang et al. 2021).

Furthermore, biochar can indirectly facilitate the biotransformation of pollutants by regulating the soil microenvironment. Biochar can provide habitats and nutrients for microorganisms, and its porous structure can provide protection sites for degrading bacteria, such as Rhodococcus, a PA-degrading bacterium, while releasing soluble organic carbon to stimulate microbial activity (Zhao et al. 2022). Mineralization of PAHs and PCBs can also be accelerated by stimulating the abundance expression of organic degradation genes, such as PAH-RHDα and dehalogenase genes (Guo et al. 2024; Song et al. 2024). Ni et al. found that biochar promote the biodegradation of PAHs to reduce the risk of PAHs (Ni et al., 2021).The hierarchical porosity also acts as an electron transport mediator, facilitating microbial redox reactions such as Fe^{3+} reduction-coupled PCBs dechlorination (Zhu et al. 2020).

Conventional biochar properties can be optimized through physical or chemical modification. After modification, the pore structure of biochar can be regulated,

Table 2 Remediation efficiency and mechanisms of biochar-based technologies for organic pollutants in contaminated sites

Types of pollutant		Type of biochar	Application condition	Effect	Reference
Conventional organic pollutants	PAHs	Rice husk biochar + alfalfa	Biochar dosage:2% Moisture Content: 60%	The removal rate :65.26%	(Shang et al. 2024)
	PAHs	Straw biochar + ryegrass	Biochar dosage:2% Moisture Content: 60%	The removal rate :52.76%.	(Zhao et al. 2022)
	PAHs	Corn straw biochar	Biochar dosage:2% Moisture Content: 71%	The dissipation rate :32%.	(Ni et al., 2021)
	PAHs	Wheat straw biochar + ryegrass	Biochar dosage:2% Moisture Content: 60%	The removal rate:62.5%.	(Guo et al. 2024)
	Pentachlorophenol(PCP)	Maize straw biochar	Biochar dosage:5%	The removal rate: 67.2%	(Zhu et al. 2020)
Emerging organic pollutants	Endocrine disrupting chemicals	Grapevine pruning residues biochar	Biochar dosage : 1.2 g Soil dosage: 120 g Moisture Content:60%	4-tert-octylphenol : 80% bisphenol A: 62%	(Loffredo and Parlavecchia 2021)
	Tetracycline	Methanol-activated walnut shell biochar	Biochar dosage:5% Moisture content:70%	The removal rate: 80.4%	(Keshiknevisrazavi et al. 2022)
	Tetracycline	Phosphate-modified corn biochar	Biochar dosage:2% Moisture Content:40%	Tetracycline content decreased from 25 mg/kg to 0.51 mg/kg	(Han et al. 2024)
	Sulfonamides	Maize straw biochar + lettuce	Biochar dosage:0.5%	The largest dissipation rate:93.9%	(Ye et al., 2016)
	Alpha-hexachlorocyclohexane(α-HCH), gamma-hexachlorocyclohexane(γ-HCH)	Peanut shell biochar-loaded nano zero-valent iron (BC/nZVI)	Biochar dosage:1% moisture content 26.42%,	The degradation rates:α-HCH 55.2%;γ-HCH:85.4%	(Li et al., 2023b)

and the proportion of micropores can be increased during high-temperature pyrolysis (>500℃), thereby enhancing the sorption potential for non-polar contaminants (Zhang et al. 2024). After methanol modification, the increase of surface functional groups of biochar enhanced the adsorption capacity of tetracycline (Keshiknevisrazavi et al. 2022). Mineral modification is also a common method. Fe_3O_4 in load strengthens the π-π EDA effect (Zhao and Zhou 2019), facilitates recycling, and reduces the risk of secondary pollution (Ahmad et al. 2022). However, numerous studies have shown that long-term aging may release Nano plastics.

After numerous experiments, the experimenters found that the removal rate of organic matter by applying a single biochar needs to be improved, so they began to promote the combined technology. For example, rice husk biochar and alfalfa combined repair PAHs, biochar adsorbs pollutants and improves soil fertility, and plant root exudates promote desorption and microbial degradation (Shang et al. 2024). Due to its porous properties and abundant elements, biochar promotes the degradation of soil organic matter and plant growth, and also reduces the abundance of organic resistant endophytes, which is due to the acceleration of soil microbial degradation activities by plant root exudates (Ye et al., 2016). In addition to combining with plants, earthworms or plant rhizosphere growth-promoting bacteria can usually be combined to improve repair efficiency through bioturbation or metabolic enhancement (Hou et al. 2023; Lu et al., 2024). Loaded with nano-zero-valent iron or persulfates, which

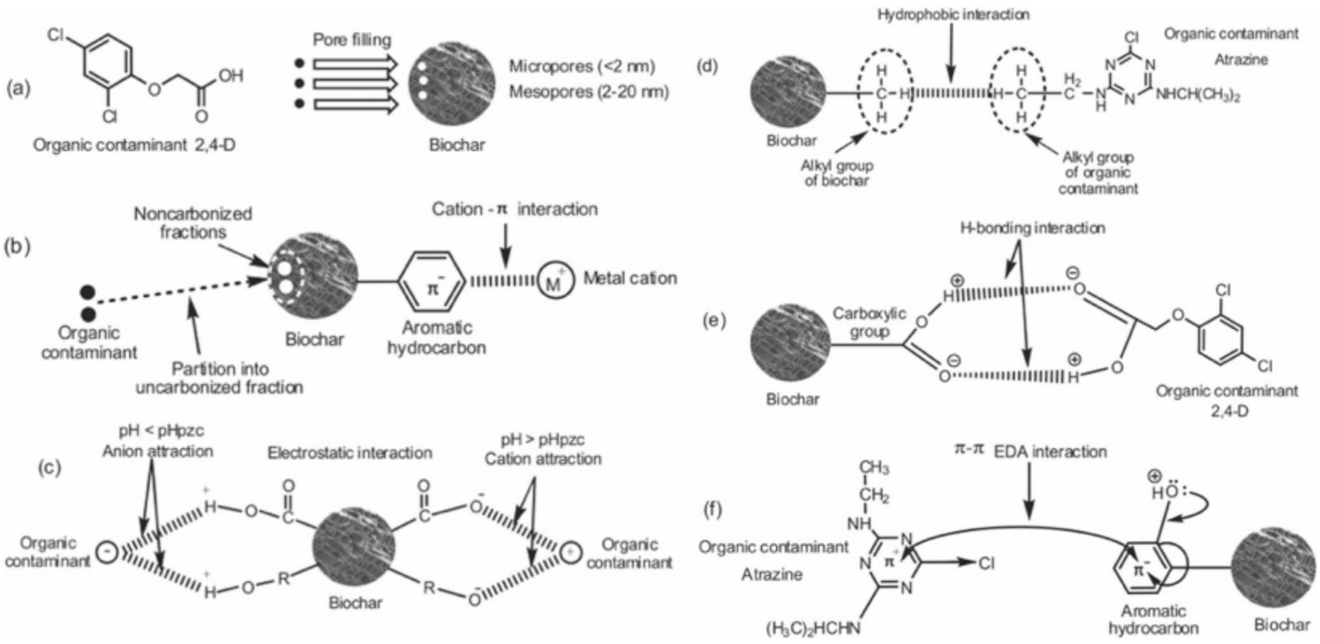

Fig. 3 Comprehensive mechanisms of biochar in remediating organic pollution contaminated soil (Tran et al. 2023)

resulted in reactive oxygen species, such as ·OH, and SO_4^- also achieved deep mineralization of contaminants (Ahmad et al. 2022).

In the complex pollution system, the interactions between different types of pollutants on the surface of biochar are highly diverse and not simply competitive inhibition. For example, the competitive sorption for active sites on biochar surfaces remains inadequately understood. Some researchers found that Cr(VI) competes with Congo red for protonation sites, inhibiting Congo red adsorption. However, adsorbed Congo red provides additional functional groups that promote Cr(VI) adsorption (Liu et al. 2025). In the practice of biocarbon remediation of multi-pollutant systems, the effect is not simply additive. A large number of studies have confirmed that different pollutants may exhibit either synergistic removal or antagonistic effects due to competition and other relationships (Fan et al. 2025). When biocarbon is combined with active components such as zero-valent iron, it not only acts as an adsorbent but also serves as a carrier and electron medium for catalytic reactions, forming a synergistic degradation system with the active components to achieve higher efficiency in the transformation and removal of pollutants (Chen et al. 2024). Moreover, biocarbon can also act as an electron shuttle, playing a crucial role in the collaborative driving of microbial degradation of organic matter during the process. It enhances the metabolic activity of microorganisms by accelerating extracellular electron transfer (Wang et al. 2025).

Whether it is synergy or antagonism, the direction is determined by the joint control of the physical and chemical properties of the pollutants, such as molecular size, charge characteristics and the surface properties of the biocarbon. Therefore, the key to future research lies in accurately revealing the priority order and relative contributions of these complex interface processes, so as to achieve rational design of biocarbon materials and accurate prediction of their behavior in complex systems.

Carbon sequestration in soil by biochar

In addition to its ability to adsorb pollutants in soil, biochar carbon storage capacity is receiving increasing research attention and is intrinsically linked to its remediation function. The processes involved in pollutant immobilization often directly contribute to carbon sequestration. For instance, the formation of stable complexes between biochar, heavy metals, and soil minerals not only reduces metal bioavailability but also protects biochar-derived carbon and native soil organic matter from decomposition. Thus, the stability of carbon is improved. It can influence the mineralization of soil organic carbon and interact with soil microbes (Yang et al. 2022), it can also improve soil physicochemical properties, such as moisture (Ernest et al. 2024), soil pH levels, as well as cation exchange capacity (Lu et al. 2021), affect microbial activity and community structure (Zhu et al. 2017), promote soil aggregate formation, adsorption or co-precipitation, and promote carbon uptake and storage by plants (Liu et al. 2023b). It promotes soil organic carbon cycling, enhances soil carbon sequestration, and helps reduce greenhouse gas emissions, thus playing an important role in carbon emission reduction. Biochar is usually alkaline, and after being added to the soil, it combines with H in the soil solution to increase the pH value of the soil and improve the weakly acidic environment of the soil (Zhang et al., 2023). By affecting soil organic carbon mineralization and greenhouse gas emissions, biochar promotes soil organic carbon cycling, enhances soil carbon sequestration, and helps reduce greenhouse gas emissions, thus playing an important role in carbon emission reduction.

Mitigation of greenhouse gas emissions

The presence of greenhouse gases within soil is predominantly attributed to microbial respiration activity and nitrification and denitrification. The change of soil physicochemical properties has an influence on soil microbial population and its physiological and biochemical processes. As well as respiration of plant roots and emissions caused by human activities. In terms of mitigating the effects of climate warming, biochar alone or in combination with other substances can reduce soil greenhouse gas emissions to varying degrees.

When biochar is applied to soil alone, its carbon sequestration effect is significantly different based on the type of raw material, pyrolysis temperature and modification method. For example, wood biochar has a better CO_2 adsorption capacity than straw biochar, because of its abundant aromatic structure and significant porosity (Yerli et al., 2022). Biochar made from animal manure is better at regulating soil pH and indirectly inhibiting N_2O emission due to its rich alkaline substances (Cai et al. 2017). In addition, pyrolysis temperature substantially influences biochar performance: biochar produced at lower temperatures (300–400 °C) exhibits a higher concentration of oxygen-containing functional groups on its surface, which enhances its capacity for greenhouse gas adsorption. High temperature (600–700 °C) biochar, on the other hand, has a more developed pore structure and can be used to fix gas through physical retention (Chatterjee et al. 2018; Ojeda et al. 2024). Modification methods such as metal loading or acidification can further optimize its adsorption capacity, such as iron-modified biochar which reduces CH_4 release by an enhanced redox reaction (Dong et al. 2024). In addition, soil physical and chemical properties, such as pH and organic matter content can also indirectly affect the carbon sequestration stability of biochar by changing the microbial community (Liu et al. 2024). The same source of biochar and soil is more beneficial to N_2O emission reduction (82%), which is due to biochar increases soil pH and the abundance of functional genes, such as *nosZ*, *nirK*, AOA, and AOB. (Fang et al. 2024; Liu et al. 2024).

When biochar is used in combination with other materials or bactericides, its carbon sequestration effect may change due to synergistic or antagonistic effects. For example, when combined with a bactericide, biochar can act as a microbial carrier, promote denitrifying bacteria activity, significantly reduce N_2O emissions (Yuan et al. 2024), and enhance microbially driven carbon fixation. For example, the addition of nitrogen-fixing fungicides can promote the development of sturdy organic-mineral interactions on the surface of biochar, thereby reducing CO_2 emissions (Dong et al. 2024); When the biochar mixed with straw biochar, it both improves soil acidification and inhibits CH_4 and N_2O release through a synergistic effect (Dai et al. 2024). However, the presence of complex pollutants in soil may interfere with the function of biochar. For example, microplastics can inhibit the expression of functional genes on the surface of biochar, leading to the increase of N_2O emission in the coexistence of straw biochar and microplastics (Li et al. 2022a, b; Wu et al., 2023). In addition, in soils polluted by high salt or heavy metals, biochar may indirectly reduce microbial activity and greenhouse gas generation by adsorbing pollutants. However, some metals such as Fe combined with biochar can enhance the reduction reaction through electron transfer, but improve the emission reduction effect (Wu et al., 2024b). In cases where pollutant concentrations are particularly elevated, it may disrupt the structural integrity of biochar and compromise its carbon sequestration efficiency (Wu et al., 2023).

Increasing soil carbon inputs

Biochar addition promotes soil organic carbon content

Biochar application in soil enhances soil organic carbon content through inhibitory effects and the development of organic-mineral complexes (Xu et al. 2018), increased carbon deposition in inter-root soils (Jin et al. 2024), increased the proportion of soil macroaggregates, and reduced loss of organic carbon. Biochar, as a carbon-rich material, can increase the nutrient content of soil and improve soil fertility when added to soil (Hua et al. 2013; Zhang et al. 2016). In the soil, straw biochar is most often used, which has a better effect on the total carbon content than the other biochar, and it can also enhance soil carbon storage and reduce the depletion of soil organic carbon, thereby boosting the soil's carbon sequestration capacity.

Biochar addition promotes plant photosynthetic carbon sequestration

When biochar was combined with nitrogen fertilizer, the cumulative assimilated C-13 content in the aboveground, rhizospheric and pedospheric carbon reservoirs rose by 23%, 14%, and 20%, respectively, over the whole reproductive period, and the nitrogen use efficiency was increased by about 23%, thus improving plant productivity and soil carbon sequestration potential (Liu et al. 2021). However, it was also found that excessive biochar application hindered the growth of photosynthetic microorganisms, thereby reducing the oxidation of Fe^{2+}, decreased chlorophyll-a by 4.74 ~ 15.78 mg/g, and promoted the reduction of Fe^{3+} (Jia et al. 2018). The soil amendment was prepared by combining the Miscanthus lutarioriparius biochar with passivating agent improved photosynthetic efficiency, Increased leaf stomatal conductance, intercellular CO_2 concentration, and transpiration rate, leading to an enhancement in net photosynthetic rate (22.8% ~62.4%), and the content of photosynthesis-related trace elements in leaves also increased significantly, with an increase in Mg content by 22.79% ~ 24.80%, and in Fe content by 82.2% ~ 89.8%.

Biochar addition to promote microbial carbon sequestration

Biochar creates a favorable habitat for microorganisms and improves soil nutrient content promotes microbial development, inhibits signaling between microorganisms and secretion of enzymes and molecules (Li et al., 2023a). Wheat biochar colonized by tufted arbuscular mycorrhizal fungi reached a colonization rate of 35.9%, produced more biomass, and substantially decreased soil carbon storage in the unaltered soil (Mason et al. 2024). Biochar enhances the sturdiness of soil clumps and elevates the expression of genes involved in carbon and nitrogen conversion provides a suitable environment for the growth of soil microorganisms, improves soil enzyme activity and nutrients, and promotes the recovery and management of degraded black soils (Zhang et al., 2023). After adding biochar, soil organic carbon, total nitrogen, microbial carbon and soil free carbon increased, and the mixed application of biochar and fertilizer can reduce soil metabolic quotient by 56%, which is conducive to the microbial use of organic carbon (Ferreira et al. 2025).

Figure 4 illustrates biochar facilitates soil carbon sequestration through synergistic pathways that integrate soil physicochemical and microbial processes. Derived from biomass pyrolysis, biochar enhances soil organic carbon accumulation by stabilizing labile carbon compounds within its porous structure while improving soil aggregation, thereby physically protecting carbon from microbial decomposition. Under low nitrogen input, biochar-mediated adsorption of CO_2, NO_3^-, and NH_4^+ creates a microenvironment conducive to denitrification and SOC preservation. In high N conditions, biochar stimulates microbial activity and nitrogen mineralization, accelerating organic matter turnover and carbon incorporation into stable aggregates. Due to

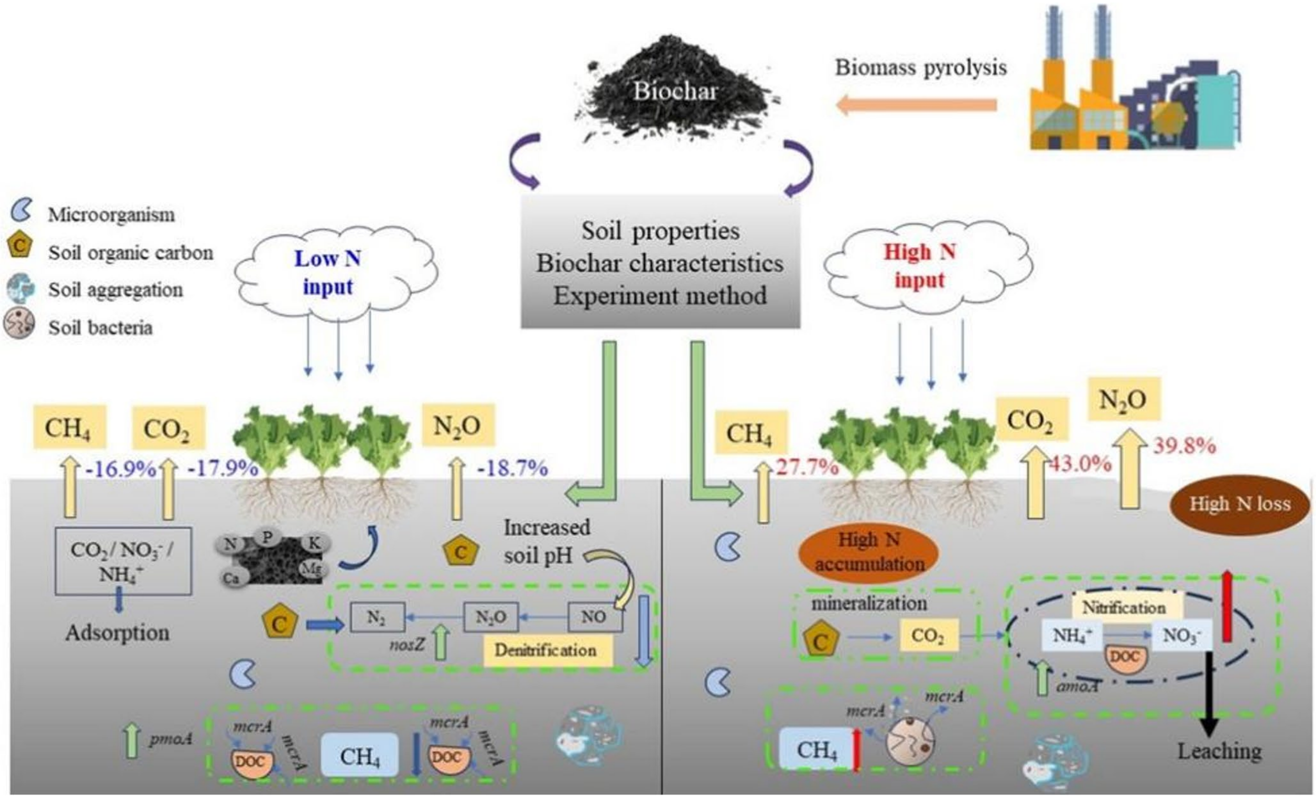

Fig. 4 Synergistic pathways of biochar promoting soil carbon input (Li et al. 2024a)

intensified nitrification, biochar concurrently mitigates CH_4 release and channels excess nitrogen into humus formation. The role of indirectly supporting long-term carbon storage direct carbon stabilization and indirect enhancement of soil-microbe interactions is emphasized biochar's potential as a tool for soil carbon management.

The efficacy of biochar in mitigating nitrous oxide (N_2O) emissions exhibits significant variability across studies. The prevailing hypothesis attributes this mitigation to a shift in the microbial community, particularly an enrichment of N_2O-reducing microorganisms carrying the nosZ gene, thereby promoting the complete denitrification of N_2O to N_2. However, a substantial knowledge gap persists in mechanistically linking specific biochar properties to this microbial regulation (Nguyen et al. 2023). Further research is needed to explore the relationship between biochar's impact on soil respiration and soil improvement, in order to determine the best soil improvement method for minimizing carbon dioxide emissions (Fekadu et al. 2024).

Biochar design for specific applications

The efficacy of biochar in environmental applications is fundamentally governed by the interplay between its intrinsic physicochemical properties and the specific target. As shown in Table 3, for the immobilization of cationic heavy metals, biochars derived from manure or lignocellulosic biomass pyrolyzed at moderate to high temperatures (500–700 °C) are most effective. Their high pH, significant ash content, and abundant oxygen-containing functional groups promote mechanisms such as precipitation, ion exchange, and surface complexation. Conversely, the removal of hydrophobic organic contaminants is maximized by biochars produced from woody biomass at higher temperatures (> 500 °C), which exhibit high specific surface area, developed microporosity, and a highly aromatic structure, facilitating dominant removal mechanisms like pore filling and π-π interactions. For the primary goal of carbon sequestration and greenhouse gas mitigation, biochar with high stability is paramount. This is best achieved using woody biomass pyrolyzed at high temperatures (> 600 °C), which yields a highly aromatic and recalcitrant carbon structure that directly enhances soil carbon storage and promotes physical protection within soil aggregates. In scenarios involving co-contamination, a balanced biochar design is required, often necessitating modified biochars with tailored surface functionality and mineral compositions to address multiple pollutants simultaneously. Therefore, the strategic selection of feedstock and pyrolysis conditions to engineer specific biochar properties is the key to unlocking its full potential for precision environmental management.

Table 3 Guiding principles for targeted Biochar design

Target application	Ingredients	Pyrolysis conditions	Key physical and chemical properties	Dominant mechanism
Heavy metal removal	Livestock poultry manure wood-based biomass sludge	500–700 °C	· High pH value · High ash content · Medium specific surface area · Abundant oxygen-containing functional groups	· Precipitation · Ion exchange · Surface complexation
Removal of organic pollutants	Wood-based biomass straw	> 500 °C	· High specific surface area · Well-developed microporous structure · High aromaticity · Hydrophobic surface	· Pore filling · π-π interaction · Hydrophobic distribution
Carbon sequestration and emission reduction	Wood-based biomass	> 500 °C	· High aromaticity · Low O/C and H/C ratio · Well-developed pore structure	· Direct carbon sequestration · Promote aggregate formation · Influence microbial communities · Reduce greenhouse gas emissions

Conclusions and future prospects

Biochar, as a porous carbon material prepared by pyrolysis of biomass, cannot only carry out pollution remediation through adsorption, catalytic degradation, and microbial regulation, but also carbon sequestration through carbon sequestration and emission reduction, promotion of plant photosynthesis carbon sequestration, and optimization of microbial carbon metabolism by virtue of its substantial and extensive surface area, robust carbon framework, and functional groups on its surface. The mechanisms through which biochar immobilizes heavy metals via precipitation, complexation, and adsorption, and removes organic pollutants through pore filling, interactions, and microbial degradation. In addition, biochar significantly improves soil carbon sink capacity by enhancing soil aggregate stability, inhibiting organic carbon mineralization, reducing greenhouse gas emissions, and enhancing plant photosynthetic efficiency. The efficacy of these processes is fundamentally governed by biochar's intrinsic physicochemical properties, such as specific surface area, surface functional groups, pH, and mineral content, which are in turn dictated by feedstock selection and pyrolysis conditions. While biochar exhibits potential in soil carbon sequestration and pollutant remediation, its practical deployment faces critical challenges. First, aging biochar may release adsorbent pollutants or undergo structural decomposition, thereby posing a risk of secondary carbon pollution in the short term. Secondly, future research should focus on elucidating the precise binding mechanisms and efficiency of biochar surface functional groups with specific heavy metals and organic pollutants. Additionally, the long-term stability of biochar in soil requires systematic monitoring through extended field trials to track changes in its carbon stability, pollutant fixation efficiency, and structural integrity during aging processes. Concurrently, the economic cost-effectiveness of biochar warrants in-depth investigation by researchers.

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Declarations

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