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REVIEW

Biochar for the removal of contaminants from soil and water: a review

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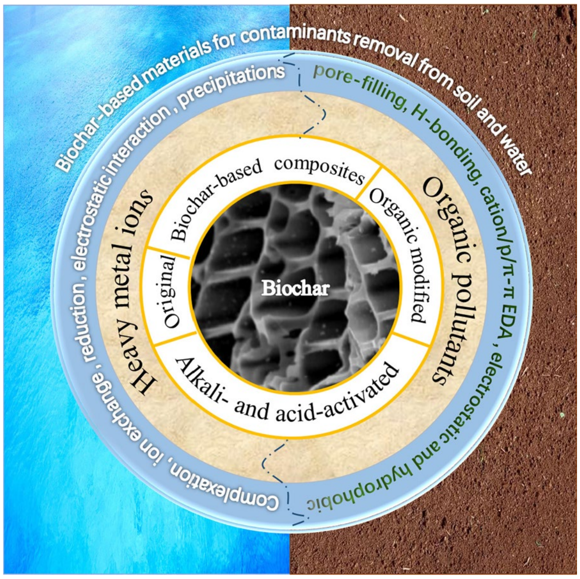
Abstract

Biochar shows significant potential to serve as a globally applicable material to remediate water and soil owing to the extensive availability of feedstocks and conducive physio-chemical surface characteristics. This review aims to highlight biochar production technologies, characteristics of biochar, and the latest advancements in immobilizing and eliminating heavy metal ions and organic pollutants in soil and water. Pyrolysis temperature, heat transfer rate, residence time, and type of feedstock are critical influential parameters. Biochar's efficacy in managing contaminants relies on the pore size distribution, surface groups, and ion-exchange capacity. The molecular composition and physical architecture of biochar may be crucial when practically applied to water and soil. In general, biochar produced at relatively high pyrolysis temperatures can effectively manage organic pollutants via increasing surface area, hydrophobicity and microporosity. Biochar generated at lower temperatures is deemed to be more suitable for removing polar organic and inorganic pollutants through oxygen-containing functional groups, precipitation and electrostatic attraction. This review also presents the existing obstacles and future research direction related to biochar-based materials in immobilizing organic contaminants and heavy metal ions in effluents and soil.

Graphical Abstract



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Highlights

1. The synthesis strategies and characteristics of biochar are introduced.
2. The removal of contaminants from soil and water is explicated emphatically.
3. The removal behaviors of heavy metal ions and organics are determined.
4. Mechanisms and influencing factors of pollutant removal by biochar are discussed.
5. Prospects of biochar-based materials for contaminant removal are proposed.

Keywords Biochar · Heavy metal ions · Organic pollutants · Water · Soil

1 Introduction

Biochar refers to a material abundant in carbon. Biochar is typically collected via thermal treatment of biomass including wood, manure, or leaves under an oxygen free environment. Biochar has gained increasing attention owing to its distinct physio-chemical characteristics and diverse applications in multiple fields, such as climate change mitigation, agriculture, environmental remediation, and energy production (Premarathna et al. 2019). Biochar exhibits potential as a sustainable, carbon–neutral material, primarily owing to biomass emissions, which amount to an equal quantity of CO_2 emissions during conversion and utilization as the quantity used up in photosynthesis (Yuan et al. 2019). The physio-chemical characteristics of biochar, such as three-dimensional reticulated and porous structure, could serve as a lasting storage solution for carbon while adsorbing and degrading pollutants.

Biochar can be formed using a variety of carbonaceous feedstocks, most of which are regarded as organic wastes, which supports waste management indirectly. Owing to its cost-effective production and feasibility in numerous contexts, biochar has been employed in water and soil treatment as a low-cost material alternative to activated carbon for removing variety of contaminants such as volatile organic compounds, heavy metal ions, pesticides, pharmaceuticals, dyes, and polycyclic aromatic hydrocarbons (El-Naggar et al. 2021; Zhao et al. 2021c, f). Unlike activated carbon, the pristine biochar has not shown potential in the sorption and eradication of contaminants, mainly due to its relatively low surface area and the effect of abiotic and/or biotic processes on the properties and elimination capacity for pollutants. Thus, there has been increasing attention on improving the surface area and mechanical characteristics of biochar via numerous modification techniques, including amination, surfactant modification, base treatment, acid treatment, magnetic modification, and composite with other materials (Arif et al. 2021; Cheng et al. 2021b; Li et al. 2021b). In recent years, numerous biochar-based materials have been adopted as eco-friendly adsorbents to remove organic/inorganic contaminants from water and soil.

Over the years, there have beenmore and more soil environmental degradation phenomena such as soil nutrient loss, soil degradation and soil contamination. These phenomena create numerous secondary environmental issues, such as decline of land productivity, water scarcity, food security, and changes in the climate (Yuan et al. 2019; Zou et al. 2022). Globally, soil contamination is a prevalent issue, and both inorganic and organic pollutants can cause significant environmental issues. Therefore, sustainable remediation methods are needed to address these environmental issues. Biochar has shown potential as a suitable amendment in that biochar exhibits several benefits in raising soil pH value and the content of organic carbon, elevating the water-holding capacity of soil, lessening the number of contaminants, higher yields from agricultural crops, and impeding the uptake and accumulation of pollutants (Cheng et al. 2020). Several pivotal factors govern the characteristics of biochar, including heating rate, temperature of the pyrolysis process, biomass type, and residence duration. Under the influence of the pH value, dissolved organic carbon, and the content of ash in biochar, the interaction processes between heavy metal ions and biochar primarily involve the reduction, electrostatic attraction, complexation, precipitation, and cation exchange. The interaction processes between organic pollutants and biochar primarily include hydrophobic interaction, π–π interaction, and hydrogen-bond interaction (Khalid et al. 2020).

Globally, efforts have been directed at addressing the increasing water scarcity, reducing pollution of water bodies, and water-related issues resulting in innovations in technologies related to water treatment (Tang et al. 2021a; Tian et al. 2021; Yu et al. 2022). Preparation of suitable materials to achieve or maintain adequate elimination effect on a variety of water-based refractory chemicals is a feasible way to solve the above problems. The latest research indicates the potential of biochar in wastewater treatment applications, such as catalysis, adsorption, redox, or biocidal, all of which involve various reaction mechanisms (Kamali et al. 2021; Zhao et al.

2021b; Zhou et al. 2021). The main benefits of biochar-based materials lie in their highly porous, large surface area, better ion exchange capacity, and plentiful functional groups. Attempts have been made to remove pollutants from aqueous solutions using different types of biochar material, including wheat straw biochar (Cui et al. 2021), raw jujube seed biochar (Gayathri et al. 2021), Douglas fir biochar (Herath et al. 2021), pulp mill sludge biochar (Islam et al. 2021a), pinewood biochar (Zhao et al. 2021a), poplar sawdust biochar (Cheng et al. 2021c), coconut shell biochar (Wu et al. 2021c), and softwood biochar (Peter et al. 2021). Research has attempted to elevate the removal capacity of biochar-based materials to remove pollutants via surface modification and impregnation through the use of various media, such as iron-based materials (Liu et al. 2021b; Xu et al. 2021a; Yu et al. 2021c), oxide materials (Chen et al. 2021a; Rahman et al. 2021), organic functional groups (Liu et al. 2022; Wu et al. 2021a), and inorganic compounds (Herath et al. 2021; Zhong et al. 2021).

Several reviews have presented systematic discussions on the physicochemical features of biochar and its potential applications to improve the environment. Yuan et al. (2019) summarized how feedstock and preparation conditions affect the characteristics of biochar and the potential to apply biochar to remediate the soil. Liang et al. (2021) reviewed the preparation methods and physicochemical properties of biochar/biochar-based composites and the performance associated with the removal of contaminants from wastewater. Hu et al. (2020) described the degradation/transformation of organic contaminants and sorption processes of heavy metal ions/radionuclides using biochar and biochar-based materials. These reviews mentioned above were not comprehensive in providing explicit and in-depth discussions for remediating contaminants in water bodies and soil. Thus, the present review has three objectives: (1) to analyze the characteristics of numerous biochar; (2) to outline the existing trends in biochar to elevate the quality of contaminated water and soil; and (3) to acknowledge research gaps and limitations in current investigation and suggest potential research directions for future studies.

2 Biochar-based materials

Since the introduction of biochar to the environmental management field, scholars have attempted numerous methods to increase the removal efficiency. This part will discuss various types of materials based on biochar applied to remove contaminants from water and soil. Chemical activation, compositing and doping with different materials are the commonly applied methods to enhance the removal efficiency of biochar.

2.1 Pristine biochar

Biochar is usually made from biomass that is collected at a low cost (Shakoor et al. 2021). Biomass can include a multitude of different organic materials, such as forest residue, agricultural residue, food waste, manure, and sludge. They are readily accessible and abundant around the world. At the same time, there are disposal problems associated with such biowaste. Hence, converting the waste into biochar will be a considerably sustainable strategy.

Pyrolysis and hydrothermal carbonization have been adopted as popular methods to create biochar from carbonaceous materials. The biochar yield obtained from these methods are mainly dependent on the type of biomass, operational conditions, and reaction media. Pyrolysis is the most commonly employed method. Based on the pyrolysis temperature, residence time employed, and heating rate, the process can be categorized into slow and fast pyrolysis. The operation parameters of each method impart distinct characteristics of the final biochar products (Premarathna et al. 2019). Fast pyrolysis is a process involving swift thermal treatment of biomass having a low moisture content less than 10%, over an extremely limited period, generally lasting seconds. The process is carried out at temperatures in the range of 850–1250 °C. Slow pyrolysis is a process that takes place at temperatures in the range of 450–500 °C when the biomass is treated thermally over a period more than a few minutes. It is characterized by the slow effervescence of gaseous vapor from the biomass during conventional pyrolysis (Amusat et al. 2021). The process generates a higher biochar yield. Slow pyrolysis is more eco-friendly because it releases fewer toxic gases into the atmosphere. Owing to such characteristics, biochar production through slow pyrolysis is considered sustainable. Biochar produced via slow pyrolysis is reported to be useful in remediating the soil and is suitable for the sorption of numerous contaminants from wastewater (Zhang et al. 2017).

2.2 Alkali- and acid-activated biochar

The surface characteristics of the adsorbent have been changed by adopting acid or alkali modification. The process involves expanding the specific area and pore structure of the biochar, which has an impact on the physical adsorption of contaminants (Cheng et al. 2021b). C–OH and C–H functional groups created by acid–base activization also play an important role in the chemical removal process, thus changing the elimination capacity of biochar.

In acidic modification, acidic solutions include hydrochloric acid (Hemavathy et al. 2020), phosphoric acid (Yang et al. 2021a), oxalic acid (Lonappan et al. 2020), nitric acid (Li and Li 2019), and citric acid (Liu et al. 2021a) are used to treat biochar after pyrolysis. Acidic modification alters the physicochemical properties of biochar to aid the sorption abilities of biochar in removing organic and inorganic contaminants from wastewater and soil. The pickling process lessened the sludge-based biochar's micropore volume and increased the mesoporous volume, thereby enhancing the adsorbent's removal capacity of tetracycline (Liu et al. 2020). Compared to pure biochar, phosphoric acid activated eucalyptus biochar showed superior removal performance of Cr(VI) (Zeng et al. 2021). Nazari et al. (2019) found that the citric acid activated biochar presented the maximum adsorption capacity of 2475.7 mg/kg and 12,109.4 mg/kg for Cd and Pb in soil, respectively, higher than control soil and soil remediated with simple biochar.

Alkaline modification is a process involving the use of a basic solution to alter the structure of biochar post-or-pre pyrolysis (Amusat et al. 2021). Sodium hydroxide (NaOH) and potassium hydroxide (KOH) solutions have been used widely for this modification. For example, adding NaOH to the pyrolysis of swine manure raised the pH, ash content, yield rate, hydrophily, and aromaticity (Xu et al. 2020). The addition of NaOH advanced the transformation of the mobile fraction of Cu, Zn, and Cd into the oxidizable fraction. Ma et al. (2021a) demonstrated that the surface area of the bagasse biochar expanded significantly from 4.68 to 455 m^2/g following treatment with KOH, and correspondingly, the maximum elimination capacity of imidacloprid enhanced from 53.9 to 123 mg/g.

2.3 Organic modified biochar

It is possible to elevate the quality and functional group types in biochar by combining biochar with organic matter comprising high numbers of functional groups (Qiu et al. 2021a, b). The elimination capacity can also be enhanced by raising the number of adsorption sites. Out of different such materials, chitosan has been the focus of many studies. Chitosan is a polymer macromolecule that is obtained from crustacean shells and abundant in $-NH_2$, –OH, and –O– groups. The elimination performance of pollutants can be elevated by integrating chitosan onto the biochar surface. Zubair et al. (2021) investigated how the sole application of textile waste biochar (TWB), chitosan (CH), their combination (TWB + CH), and TWB coated with CH (TBC) influenced Cd-polluted soil on Cd distribution in moringa (*Moringa oleifera* L.) roots and shoots and plant-available Cd in soil. The TBC exhibited the best response in minimizing Cd concentrations in roots, soil, and shoots by 54%, 58%, and 73%, respectively, compared to the control. Zhang et al. (2020c) reported that poly (acrylic acid)-grafted chitosan and biochar composite (PAA/CTS/BC) exhibited high elimination capacity of ammonium, with the highest value of 149.25 mg/g at temperature of 25 °C, relatively greater than most reported the biochar-based materials. In addition, it has also been reported that the number of surface functional groups can be increased by modifying biochar by macromolecules, such as polyethyleneimine (Wang et al. 2020), cyclodextrin (Qu et al. 2020), humic acid (Zhao et al. 2019), and lignin (Wu et al. 2021b). These lead to better removal capacity for pollutants. Figure 1A shows how β-cyclodextrin (β-CD) functionalized rice husk-derived biochar (BC) was synthesized expediently and rapidly using a microwave (MW)-assisted one pot process. BCMW-β-CD was utilized for simultaneously eliminating bisphenol A (BPA) and Pb(II) (Qu et al. 2020). Microwave irradiation could realize surface modification in 15 min and the created BCMW-β-CD exhibited superior removal performance with a theoretic monolayer uptake of 240.13 mg/g for Pb(II) and a heterogeneous elimination capacity of 209.20 mg/g for BPA in the mono-component system.

2.4 Biochar-based composites

Engineering of biochar with various nanomaterials is likely to pave the way for the production of outstanding biochar-based nanocomposites which generally have combined benefits of both materials (Amusat et al. 2021). Biochar-based nanocomposite properties can be improved by incorporating the benefits of nanomaterials with the presence of abundant functional groups in pyrolyzed biochar, such as carboxyl (COOH), hydroxyl (OH) groups, and amino acids. These functional groups are instrumental in applying biochar, particularly to clean the environment by removing contaminants. Besides, nanocomposites are more efficient due to the inherent sizable specific surface area gained through characteristics of biochar and the nanomaterial.

Clays are classified as hydrous aluminosilicate minerals, which comprise different mixtures of fine-grained clay minerals and clay-sized crystals of other minerals such as carbonates, quartz, and metal oxides. Clays have been employed as the natural materials to remove toxic contaminants in polluted aqueous systems and soil (Arif et al. 2021). Clay minerals can be mined easily, non-toxic, lamellar structures, relatively low cost, and comparatively high surface area. In general, mineral modification encompasses impregnation of biochar with different minerals, such as birnessite (Wang et al. 2019), montmorillonite (Song et al. 2020), kaolinite (Xu et al. 2021b), hematite (Zhu et al. 2020b), ferrihydrite (Huang et al. 2020), and goethite (Zhu et al. 2020c). Kashif Irshad et al. (2020) investigated how different biochar (BC) and goethite-modified biochar (GB) modifications affect the mobility of Cd and transfer in the soil-rice structure. GB remarkably improved the conversion of Fe–Mn oxide fractions, exchangeable Cd fractions to residual, and elevated Cd

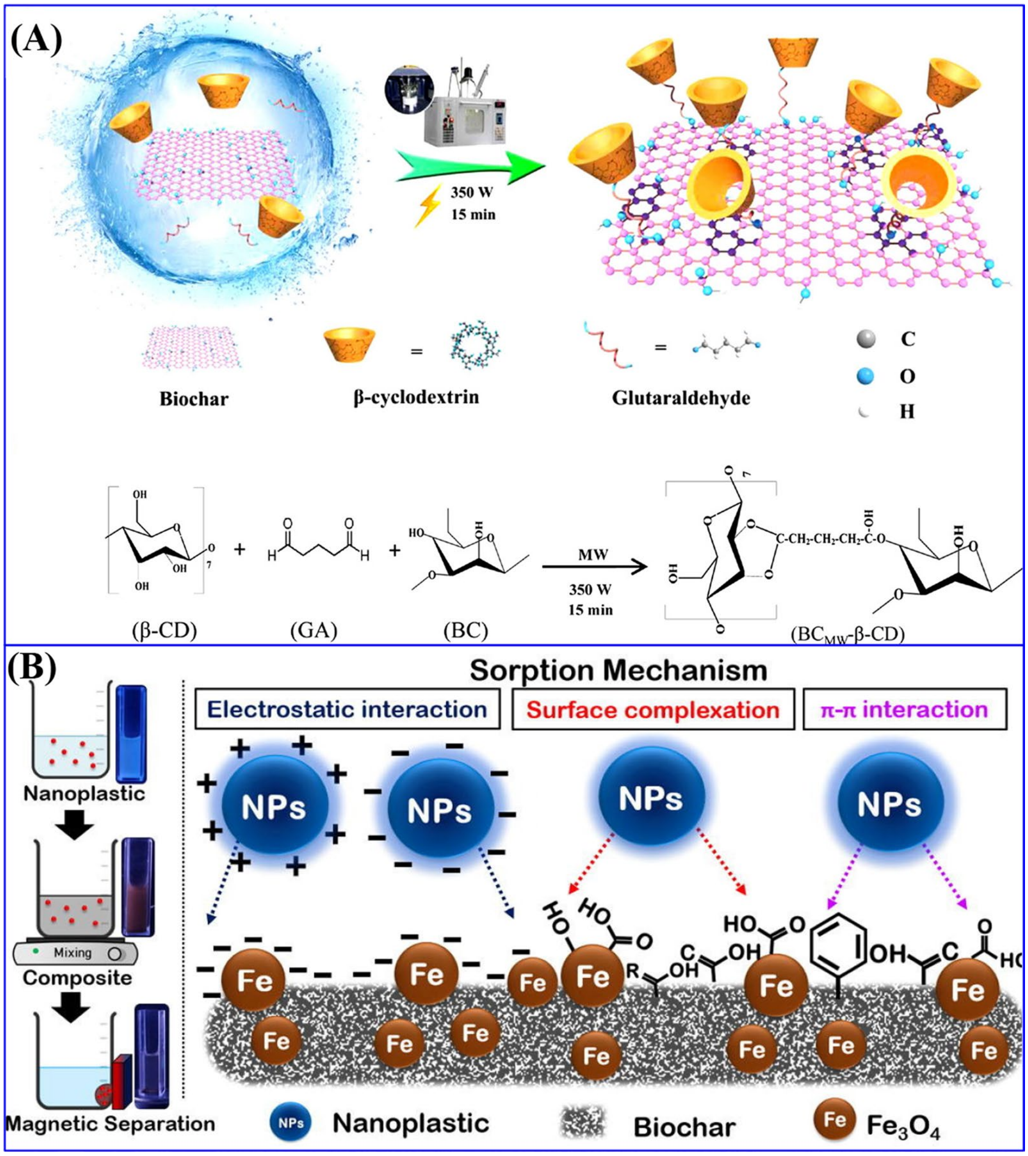

Fig. 1 **A** Schematic illustration and chemical reactions of microwave-assisted one-pot synthesis of β-cyclodextrin functionalized biochar (Qu et al. 2020). **B** The interaction mechanism between magnetic biochar and nanoplastics (Singh et al. 2021)

elimination by Fe oxide and Fe-OH. As a result, there was a significant reduction in the mobility of Cd in the soil and accumulation of Cd in the rice tissues. A sustainable biochar based on corncob and montmorillonite composite (Cc-Mt) was produced for the single elimination and co-elimination of Pb(II) and Atenolol (ATE) (Fu et al. 2020). In the single removal system, the highest adsorption capacities of Cc-Mt for ATE and Pb(II) were 86.86 mg/g and 139.78 mg/g, respectively. However, the elimination capacities for montmorillonite were only 69.68 mg/g and 98.69 mg/g, and for the corncob biochar only 47.29 mg/g and 117.54 mg/g. In summary, biochar and montmorillonite composite exhibits significant potential as a green adsorption material to treat numerous contaminants.

Nano-metal oxides comprise high surface energy in a sizable specific surface area. Nevertheless, nano-metal oxides have a tendency to aggregate and passivate owing to their finely-grained nature. Nano-metal oxide-biochar compounds combine the distinct advantages of biochar and nano-metal oxides and exhibit significant potential as a novel adsorbent (Zhao et al. 2021c). Iron (Chen et al. 2021b; Qiu et al. 2020), aluminium (Cui et al. 2020), magnesium (Zhu et al. 2020a), and manganese (Zhang et al. 2021d) are the most commonly used metals in metal oxide-biochar composites. Singh et al. (2021) examined the behaviors of iron-functionalized biochar with magnetic extractability for the prompt and easy elimination of nano/microplastics. As illustrated in Fig. 1B, surface complexation, electrostatic attraction, and ion-exchange played an important role in the removal of nano/microplastics. Wan et al. (2020) developed a hybrid material (namely MO-L-BC) via the dispersion of manganese oxide (MO) within the biochar that comprised an expanded pore structure (denoted as L-BC). The extensive pore structure of MO-L-BC significantly diminished the diffusion resistance of Cu(II) and Sb(III) in the pore region, having D values 1.5×10^{-7} and 8.6×10^{-8} cm^2/s for Cu(II) and Sb(III), respectively. Besides exhibiting superior performance in the removal of different pollutants, metal oxide-biochar composites are cost-effective to fabricate on a large scale and can also be recycled.

Biochar is compatible to be used in combination with carbonaceous adsorbents containing functional groups that can create strong bonds with the surface of biochar and the contaminants in an aqueous medium (Premarathna et al. 2019). Carbonaceous adsorbents such as carbon nanotube (CNT) and graphene, exhibit remarkable physicochemical features, including extensive surface area, superior π-π interactions, enhanced mechanical strength, high electron mobility, and excellent thermal conductivity. These features are conducive for the adsorption of numerous pollutants and act as an ideal catalytic supplement for the degradation of pollutants. Therefore, carbonaceous materials exhibit a significant potential to be used in remediation processes (Fang et al. 2020). Ma et al. (2020) prepared sludge biochar (SBC) and CNT composite (CNT-SBC) to eliminate sulfamethoxazole (SMX) with low concentrations. In contrast with SBC, CNT-SBC showed a higher S_{BET} (49.3–119 m^2/g), V_{mes} (0.219–0.807 cm^3/g), V_{tot} (0.230–0.836 cm^3/g), and D_p (18.6–28.0 nm) with an increment of CNT fraction in the composite. Unique graphene oxide-based magnetic sludge biochar composite ($GO/CoFe_2O_4$-SBC) was synthesized for the first time and evaluated for the elimination of imidacloprid at environmental concentration level (Ma et al. 2021b). $GO/CoFe_2O_4$-SBC had a maximum adsorption capacity of 8.64 mg/g for imidacloprid. The analysis of physicochemical properties, isotherms, kinetics, thermodynamics, and environmental factors indicated that its excellent removal performance was primarily attributable to π-π conjugation, pore filling, and the interaction of functional groups.

3 Remediation of contaminants in soil

Soil pollution by inorganic and organic contaminants is one of the significant environmental challenges faced by the world. Widespread industrial activities, elevated use of insecticides, herbicides, pesticides, agricultural fertilizers, antibiotics, and fossil fuel consumption are primary activities that seep organic and inorganic contaminants into the soil, which poses high health risks to humans. Attempts have been made by researchers and policymakers to find novel methods to manage soil contamination due to organic and inorganic compounds (Zama et al. 2018). As a soil remediation material, biochar has exhibited decent performance in elevating the quality of soil, promoting plant growth, relieving drought and salinity stresses, interacting with organic pollutants and heavy metals to prevent plants from absorbing such contaminants from the soil (Guo et al. 2020). Table 1 summarizes the removal of organic pollutants and heavy metal ions in soil by biochar-based materials. Adsorption is the primary underlying process in soil remediation via biochar. The adsorption mechanism encompasses hydrogen binding, surface complexation, electrostatic attractions, π–π interactions, and acid–base interaction.

3.1 Organic pollutants

At present, there is increasing attention on the use of biochar to remediate soils polluted with organic contaminates (Wang and Wang 2019). The elimination of organic contaminants by biochar-based materials are influenced by many factors, including pyrolysis temperature, types of feedstocks, the applied dosages, soil organic matters, and the targeted pollutants.

The extensive and inefficient use of pesticides to control crop diseases and pests result in the pollution of agricultural soils and related ecosystems (Khalid et al. 2020). As a cost-effective and sustainable adsorbent, biochar shows significant potential to reduce health risks due to pesticide contamination. Adding biochar to the soil is an effective means to have a significant impact on the behavior of pesticides in soil. Specifically, biochar affects the bioavailability processes of soil pollutants such as adsorption, desorption, degradation and leaching. Compared with unamended soil, the concentrations of two metalaxyl (MET) enantiomers (*R*-MET and *S*-MET) reduced considerably after wood waste-derived biochar (WBC) was added to amend the soil (You et al. 2021). The reduced MET uptake was primarily because of the reduced bioavailability of *R*- and *S*-MET in the WBC amended soils, due to the excellent elimination capacity of WBC to R-/S-MET and a shift in the soil bacterial community, particularly the enhanced abundance of degrading bacteria, such as *Hydrogenophaga*, *Methylophilus,* and *Luteimonas* (Fig. 2A). The remaining quantity of conazole fungicides reduced as the biochar concentration in the soil increased from 0.2 to 2% (Boskovic et al. 2021). The effect of wood-derived biochar prepared at 450 °C (BC450) on the thiamethoxam (THI) uptake by Chinese chive (*Allium tuberosum*) and its dissipation in soil was examined through a 42-day pot experiment (You et al. 2020). The addition of BC450 reduced the THI uptake and its metabolite clothianidin (CLO) by 22.8% and 37.6%, respectively. However, the

Table 1 Remediation of contaminants in soil by biochar

Materials	Feedstock	Pyrolysis temperature (°C)	Pollutants	Initial concentration (mg/kg)	Applied dose (%)	Removal efficiency (%)	Interaction mechanism	References
BC450	Wood	450	Thiamethoxam	6.0	1.5	22.8	Oxygen-containing groups, reactive oxygen species, persistent free radicals	You et al. (2020)
WBC	Wood	450	Metalaxyl	5.0	5	70.1	Hydrogen bond, pore filling, π-π interactions	You et al. (2021)
Biochar	Pig manure	700	Clothianidin Imidacloprid	4.95	2	90.5 81.4	Hydrophobic interaction, H-bonding, p/π–π interactions	Zhang et al. (2020d)
Biochar	Sewage sludge	700	PAHs	0.04	2	74.0	Pore filling, hydrophobic interaction, π–π interactions	Godlewska and Oleszczuk (2022)
Biochar	Rice straw	600	PAHs	857	2	58.8	–	Zhang et al. (2020a)
MagLsBC	Loofah sponges	900	PAHs	-	-	31.9	Hydrophobic interaction	Hao et al. (2021)
Biochar	Rice husk	700	Pcbs	0.08	4	91.0	Hydrophobic interaction	Silvani et al. (2019)
Biochar	Pig carcass	650	Zn	48.21	2	76.4	Inner complexation	Nie et al. (2021)
KRBC	Rice straw	500	Zn	37.98	5	36.9	Hydroxide precipitation, cation-π interaction	Liu et al. (2021d)
Biochar	Rice husk	500	Cd	6.10	5	25.0	Surface complexation	Islam et al. (2021b)
SBH_{10}	Sheep bone	800	Zn Cd	265 5.83	10	57.0 60.0	Precipitation, ion exchange, surface complexation	Azeem et al. (2021a)
Fe-PB	Pig carcass	650	As	141.3	3	35.9	Precipitation, surface complexation	Pan et al. (2021)
GWB	Green waste	650	Pb	736.2	3	92.9		
Biochar	Swine manure	450	Pb	228	5	97.0	Precipitation, ion exchange, π bond action	Yang et al. (2021b)
TMB	Carrot pulp	550	Cu	29.32	8	47.4	Electrostatic forces, covalent bonding	Gholami and Rahimi (2021a)
BC-nZVI	Kenaf bar	600	Cd	9.86	-	90.1	Electrostatic attraction, precipitation	Qian et al. (2022)

half-life of THI in the soil increased from 89.4 to 120 days, suggesting that BC450 elevated the persistence of soil THI. Zhang et al. (2020d) examined the adsorption and degradation of two representative neonicotinoid insecticides in typical Chinese paddy soil and red soil by six types of biochars. The results indicated that the pH value, total organic carbon, dissolved organic carbon, and surface area of each soil type exhibited an increase following biochar amendment, while H/C reduced. When the pyrolyzing temperature of biochar increased from 300 °C to 700 °C, the adsorption of the two pesticides on biochar-soil mixed systems improved by over 4.3 times, because of the higher surface area and lower H/C. In brief, the influence of biochar on the behavior of pesticides in soil is a complicated process and comprehensive research considering the type of biochar and property of soil is required to optimize biochar technology.

Polycyclic Aromatic Hydrocarbons (PAHs) are the most widespread organic contaminants, which pose a significant risk to humans via the food chain. PAHs are not easily degraded in soils because of their high hydrophobicity, low water solubility, and being readily uptake by soil particles (Bao et al. 2020). Thus, a feasible remedial method is

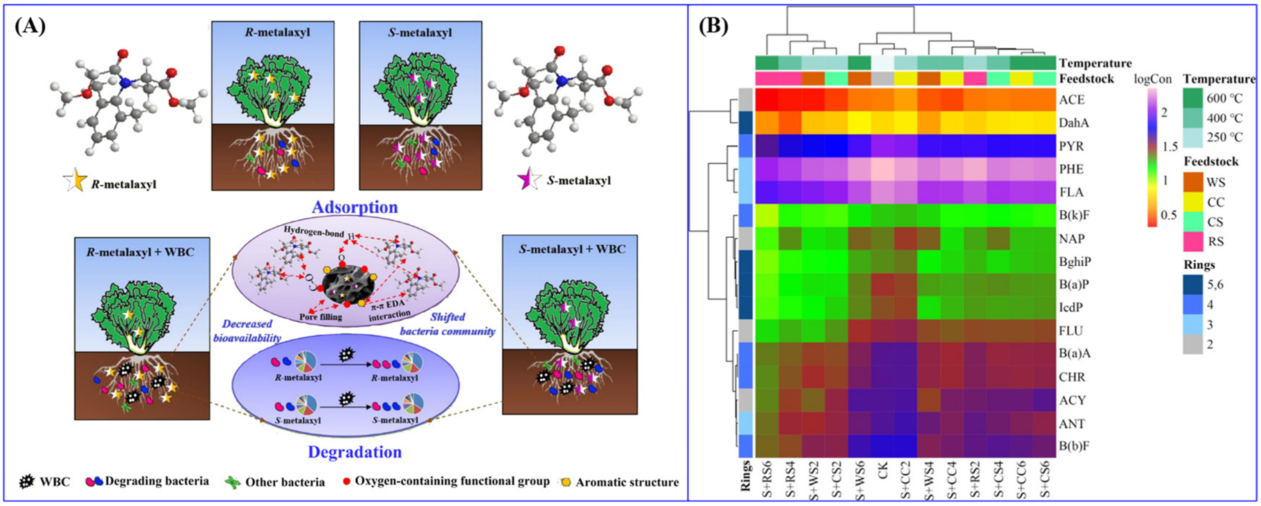

Fig. 2 **A** The proposed mechanisms underlying the decreased uptake and accumulation of the two MET enantiomers by the lettuce cultivated in the soil amended with WBC (You et al. 2021). **B** Heatmap with clustering analysis of biodegradation of PAHs in the control and biochar-treated soils using the pheatmap package in R 3.5.1 (logCon: log of the residual PAH concentrations in different treatments) (Zhang et al. 2020a)

required to alleviate the probable environmental risks that PAHs pose when present in soil. Biochar has been applied in the reconstruction of PAHs polluted soils owing to the superior adsorptive capacity of biochar, and it can advance the biodegradation of PAHs via microbial stimulation. As illustrated in Fig. 2B, Zhang et al. (2020a) examined how the feedstock of biochar and the temperature of the pyrolysis process affect PAHs biodegradation in coking plant soil. According to the results, significant negative correlations were found between the residual PAHs concentrations in soils and the content of ash in biochar ($p < 0.05$ for PAHs with 3–6 rings). Biochar derived from rice straw pyrolyzed at 600 °C (RS6) was effective in degrading PAHs, with higher percentages of biodegradation in individual PAHs (40.00–58.84%). Godlewska and Oleszczuk (2022) reported an amendment in the persistence of PAHs in the soil using biochar produced from sewage sludge (SL). The addition of biomass (BCSLW) improved the quality compared to the soil amended with the biochar derived solely from SL (BCSL). For BCSL, the pore-filling was the predominant adsorption mechanism, whereas adsorption based on the chemical (hydrophobic and π–π EDA) interactions was associated with BCSLW. Bao et al. (2020) examined whether the collective alteration of compost (CP), biochar (B), corn straw (Y), and mushroom residue (M) could advance PAHs degrading in polluted soils. Following an incubation period of 77 days, both B + M and B + Y significantly ($p < 0.01$) elevated the elimination rate of PAHs relative to amendment solely by biochar. Remarkably, B + CP resulted in significantly ($p < 0.01$) reducing the elimination of PAHs. Hao et al. (2021) implemented a unique three-dimensional mesh magnetic loofah sponge biochar (MagLsBC) produced from natural agricultural products, to remediate sediment contaminated by PAHs. MagLsBC exhibited a high removal of PAHs and bioavailability in sediment of 31.9% and 38.1%, respectively.

Polychlorinated biphenyls (PCBs) are xenobiotic chlorinated aromatic components, which can easily enter the ambient systems when several environmental matrices interact closely, including soils, sediments, surface water, groundwater, and food chain (Gopinath et al. 2021). In general, biochar can remove the PCBs in soil by two ways. In the first way, the chemical adsorption occurred via hydrogen bonds, dipole, coordination bonds, and π-π bonds created via chemical interactions between PCBs and biochar, whereas physical adsorption was primarily governed by intermolecular forces and electrostatic interactions. It should be mentioned that the energy of Van der Waals forces in physical interaction is relatively lower than chemical interaction. In the second way, a micropore-filling mechanism can be utilized to make PCBs bond onto biochar. Each likely mechanism of PCBs elimination by the biochar-based materials was dependenton the properties, structures and types of biochar and soil (Fang et al. 2021). Silvani et al. (2019) discovered that rice husk-based biochar decreased the accumulation of PCBs to an extent greater than mixed wood biochar for all phases. However, the dosage had no effect on either type of biochar. An experiment to amend biochar was conducted over a 120-day period to examine the dynamic effects of soil organic carbon (SOC) on the degrading process of PCBs in soil and adsorption to biochar (Huang et al. 2018). In low-SOC (LSOC) soils, biochar removed a considerably greater quantity of PCBs than it did in high-SOC (HSOC) soils. The degradation of di- and tri-chlorobiphenyls (CBs) was considerably increased in the LSOC soils than in the HSOC soils, while the biochar tended to remove a considerably greater quantity of tetra- and penta-CBs in LSOC soils.

3.2 Heavy metal ions

Different from organic pollutants, heavy metal ions cannot be degraded by organic activity, and the soil contaminated by heavy metal ions has severe health implications for humans and animals via the food chain and direct exposure (Yuan et al. 2019). Until now, several scholars have promoted the use of biochar as an efficient material to alter the solubility of heavy metals via the conversion of soluble metals into insoluble forms binding with oxides, organic matter, or carbonates and then fixed in the fields. Moreover, intensive investigations have been done in small and pilot-scale trails using biochar, and there have been beneficial results with several effects.

Common metal pollutants in soil are Zn, Cu, Cd, and Pb, which generally exist as divalent ions or compounds, so they have similar characteristics and behaviors. Therefore, it can be reasonably suggested that heavy metal ions exhibit similar properties when biochar is present, despite some differences (Wang et al. 2018). Previous research investigated how different types of biochar materials (husk-based, wood-based, bone-based, sewage sludge, and yard wastes) at different pyrolysis temperatures (in the range of 300–700 °C) affect heavy metal ions elimination in soil. Results indicated that animal-derived biochar exhibited the greatest efficacy in elevating the properties of the soil and improving the soil adsorption capacity for pollutants than plant-derived biochar, primarily owing to its relatively high ash content, surface alkalinity, pH, and plentiful oxygen groups (such as C–O, C=O) (Nie et al. 2021). Unlike pristine biochar, alkali-activated biochar had richer pore structure and larger surface area, which could bind more heavy metal pollutants. In addition, alkali-activated biochar had more π-conjugated aromatic structures, higher aromaticity, stronger cation-π interaction, which made more heavy metal ions became stabilized structure under the action of multiple interactions (Liu et al. 2021d).

The process underlying the use of biochar to immobilize heavy metal ions is not similar to the soil incubation owing to the organic acids with low molecular weight in the rhizosphere. Islam et al. (2021b) reported that low level exposure of tartaric acid increased the immobilization of Pb, Cd, and Zn, while the higher concentration of tartaric acid and all levels of oxalic acid improved the mobilization. Moreover, biochar-tartaric acid (2 mmol/kg soil) treatment was the superior modifier in Pb, Cd, and Zn redistribution and immobilization in distinct geochemical fractions during a 60-day incubation. In addition, the biochar's pyrolysis temperature can have an impact on the adsorption capacity of biochar. Azeem et al. (2021a, b) showed that bone biochar especially obtained at low-temperature pyrolysis could efficiently act as an immobilizing agent for Zn and Cd in polluted soils owing to the abundant surface functional groups. As shown in Fig. 3A, representative plant- and animal-derived biochars created from green waste (GWB) and pig carcass (PB) and their iron-engineered products (Fe-GWB and Fe-PB) were introduced to acidic soil and incubated to examine the capacity in removing Pb (736.2 mg/kg) and As (141.3 mg/kg). After applying Fe-PB and Fe-GWB, the concentration of As decreased by 35.9% and 32.8%, respectively, which exhibited greater efficacy than adding GWB and PB. However, PB and GWB proved to be have a higher efficacy than Fe-PB and Fe-GWB in immobilizing Pb (Pan et al. 2021). The bioavailability of heavy metal ions was significantly correlated with physicochemical characteristics of soil, such as organic matter, pH, redox conditions, etc. The mobility of Zn, Cd, and Pb was notably negatively correlated with the pH values. As illustrated in Fig. 3B, the underlying mechanisms primarily included precipitation, ion exchange, π bond action, and complexation on the swine manure biochar (Yang et al. 2021b).

Additional functional groups are usually formed on the surface of biochar samples by sulfuration, nitrogenation, oxidation and composite materials. The multiple modification method elevated thiol groups (-SH) and oxygen groups (–OH, –COOH, etc.) on the biochar surface. Besides, the total pore volume and the surface area also improved considerably (Wang et al. 2021b). Gholami and Rahimi (2021a, b) produced thiourea functionalized biochar obtained from potato peel (MPPB) and used it to eliminate Zn, Cu, and Cd in polluted acidic soils. The highest adsorption capacity of Zn, Cu, and Cd in the soil remediated with 8% MPPB were 3508.44, 4993.12, and 5142.63 mg/kg, respectively. Nanoscale zero-valent iron modified porous biochar (BC-nZVI) was used for the simultaneous remediation of Pb and Cd spiked soil. Figure 3C shows the immobilizing of Pb or Cd via the BC-nZVI method produced superior outcomes than that of BC or nZVI process, and nearly 80% of heavy metal ions was immobilized by the BC-nZVI (Qian et al. 2022). Stable Cd species such as $CdCO_3$, $Cd(OH)_2$, and CdO were created, meanwhile, stable Pb species including PbO, $Pb(OH)_2$, and $PbCO_3$ were produced via the BC-nZVI process. Cd^{2+} and Pb^{2+} can be eradicated up to 92.87% and 86.19% from soil using β-CD/hydrothermal biochar (Li et al. 2022). Pristine phosphorus functionalized biochar materials were created via the pyrolysis of biomass feedstocks (bamboo, wood, rice husk, and cornstalk) pre-processed with potassium phosphate (K_3PO_4). The P composition in the bamboo, wood, rice husk, and cornstalk modified biochar was 1.39%, 2.14%, 3.36%, 3.80%, respectively. The impregnation of P reduced the extractability of Cd(II) and Cu(II)

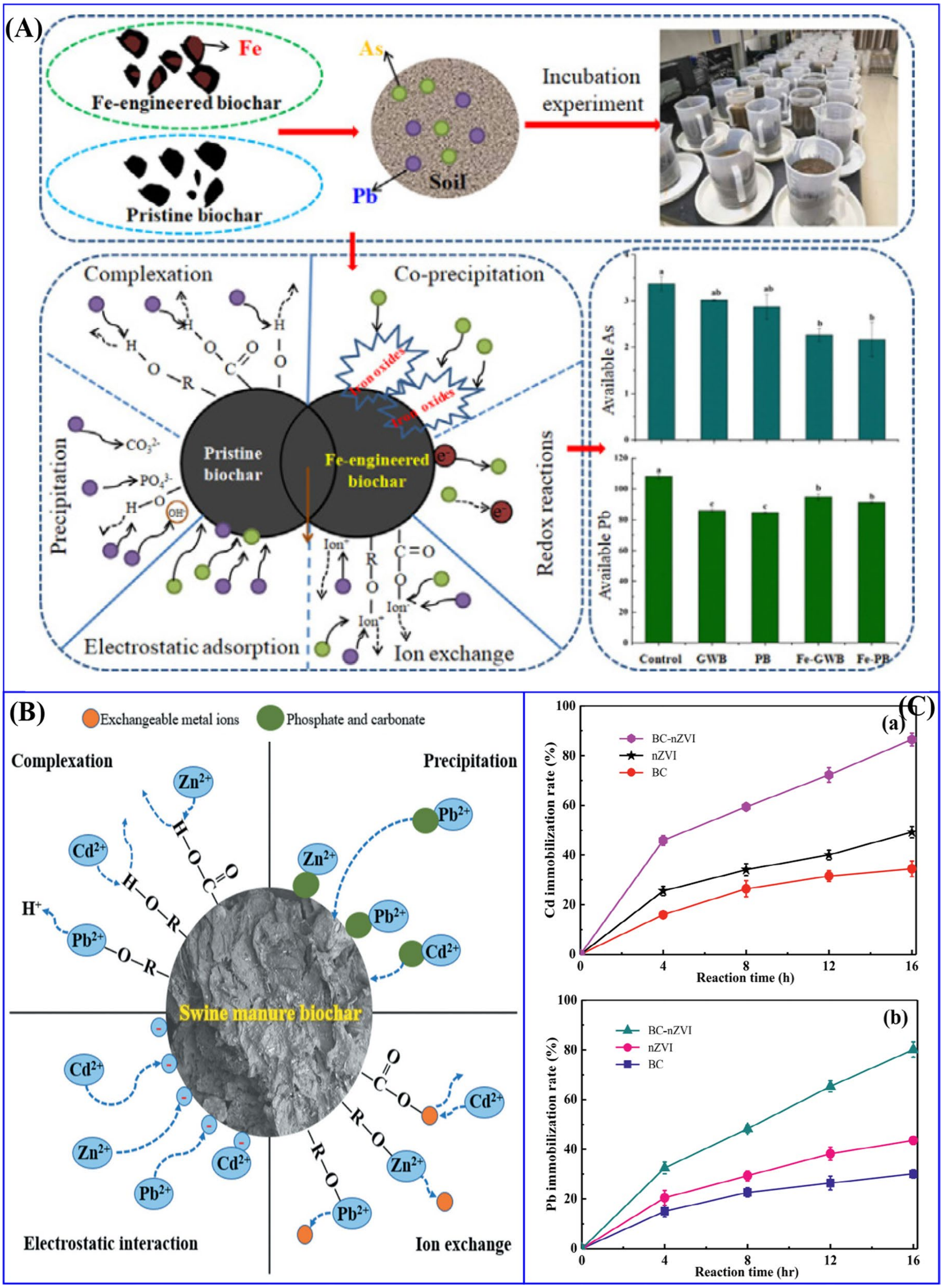

Fig. 3 **A** Pristine and iron-engineered animal- and plant-derived biochars enhanced bacterial abundance and immobilized arsenic and lead in a contaminated soil (Pan et al. 2021). **B** Immobilization mechanisms of heavy metals (Cd, Pb, and Zn) in soil by swine manure biochar (Yang et al. 2021b). **C** Immobilization efficiency of Cd (a) and Pb (b) by different amendments (Qian et al. 2022)

by 2 ~ 3 times through the creation of metal phosphate complex compounds and precipitates (Zhang et al. 2020b).

In summary, biochar-based materials could effectively remove organic pollutants in soil, as well as pore filling, hydrophobic interactions, π-π interactions were dominant removal mechanisms. The biochar-based materials adsorb and bind heavy metal ions in soil mainly through co-precipitation, ion exchange, electrostatic interaction, and the complexation of π-electrons and oxygen functional groups. The pollutants remaining in soil would go through a sequence of procedures including plant uptake, leaching, redox, volatilization, as well as methylation/demethylation. In addition, it will be challenging to speciate contaminants in the soil solution and solid soils modified by different biochar materials under dynamic redox settings. Extensive research is also needed to comprehend how biochar affects the dynamics of pollutants in polluted soil.

4 Remediation of contaminants in water

Pristine biochar has limited potential to selectively eliminate pollutants from water, which can be enhanced by modifying biochar to enrich surface active sites and improve elimination capacity. Attempts are continually made to modify biochar to enhance their pore structure, surface area, and surface groups which exhibit better potential to remove pollutants. Table 2 summarizes the removal of organic pollutants and heavy metal ions in water by biochar-based materials. Engineered biochar eradicates contaminants from water by combining numerous mechanisms, including precipitations, pore-filling, hydrogen binding, ion exchange, and electrostatic reactions.

4.1 Organic pollutants

Aromatic hydrocarbons (PAHs) are usually persistent organic contaminants that cause specific problems in rainwater runoff owing to their toxicity, prevalence, adverse health impacts, and high bioaccumulation (Wang et al. 2022a). Three raw products from different waste sources such as waste tire crumb rubber (WTCR), blast furnace slag (BFS), and coconut coir fiber (CCF), and two functionalized samples including biochar (BC) and iron modified biochar (FeBC) were employed as adsorbents to remove PAHs from rainwater (Esfandiar et al. 2021). The partition coefficients of PAHs were as follows: BC > FeBC > WTCR > CCF > > BFS, in the range of 80–390,000 L/kg. The primary elimination mechanism was hydrophobic π-π interactions. Lawal et al. (2021) studied the elimination mechanism and removal efficiency of phenol and tannic acid by biochar created from palm oil frond through steam pyrolysis. When 3 g/L biochar was used after 8 h reaction at solution pH of 6.5 and 45 °C temperature, the elimination capacities of tannic acid and phenol were 67.41 and 62.89 mg/g, respectively. A novel iron oxide and biochar composite (FeYBC) was prepared from ferric chloride and pomelo peel solution using a one-step method at suitable temperature (Dong et al. 2021). The pseudo-second order and Langmuir adsorption isotherm models could define the phenol removal behaviors over FeYBC. Han et al. (2021) showed that the addition of Fe(III) ions considerably increased the removal efficacy of biochar for bisphenol A and phenanthrene as well as increased the stability of biochar. Figure 4A shows the underlying process of biochar pore graded-modified structure for phenol adsorption (Feng et al. 2021). The hierarchical-modified structure of functionalized biochar significantly promoted the removal of phenol, and the oxygen and nitrogen functional groups contributed to biochar's chemical elimination of phenol.

Pharmaceuticals are pollutants of increasingly concern for water environment, because it has been reported that pharmaceuticals cause adverse effects in aquatic systems (Li et al. 2021c; Yu et al. 2021b). Modified biochar from organic waste was employed for adsorbing naproxen, diclofenac, and triclosan from wastewater (Czech et al. 2021). The elimination capacity of naproxen (127 mg/g) was higher than triclosan (113 mg/g) and diclofenac (92.7 mg/g), which could be attributed to its higher hydrophobicity. Elimination of sulfamethazine (SMT) on the magnetite modified biochar (MBC) is a promising method for the remediation of sulfonamides, primarily owing to its excellent removal efficiency and irreversibility (Bai et al. 2021). In contrast with pristine BCs, the fluctuation in the pH-dependent removal properties of SMT on MBC stems from the interaction of proton configuration and p-bonding. Zhao et al. (2021d) examined the adsorption characteristics of tetracycline by bovine manure biochar at various temperatures of 500 °C (BC-500) and 700 °C (BC-700). Owing to the influences of π-π interactions and hydrophobic effects, BC-700 (99.70% in 4 h) exhibited a higher elimination capacity than BC-500 (95.31% in 12 h). Wang et al. (2021a) applied the biochar from the residues of antibiotic fermentation (AFRB) and sludge (AFSB) to eliminate penicillin. Quantum chemical methods (Fig. 4B) confirmed that the interactions between penicillin and AFRB were H···π, H···O=C, π–π interactions, the processes for AFSB were chemisorption (–C=O–Fe–, –C = OO–Fe–). Wu et al. (2022) reported that the ampicillin resistance genes (ARG_{Amp}) were removed by Ce modified biochar through adsorption, persistent free radicals (PFRs), and ·OH oxidation. The possible action sites of PFRs were the phosphate bond in the nucleotide as well as the phosphodiester bond in the base stacking structure. When the initial concentration of ARG_{Amp} was 41.43 mg/L,

Table 2 Remediation of contaminants in water by biochar

Materials	Feedstock	Pyrolysis temperature (C)	Pollutants	Initial concentration (mg/L)	m/V (g/L)	pH	Adsorption capacity (mg/g)	Interaction mechanism	References
FeYBC	Pomelo peel	600	Phenol	40	2	5.8	39.3	π–π interactions, electron donor–acceptor complex	Dong et al. (2021)
BC-700	Bovine manure	700	Tetracycline	10	4	7.0	5.8	Hydrophobic interactions, π–π interactions	Zhao et al. (2021d)
AFRB	Antibiotic	800	Penicillin	10	1.6	5.0	44.1	H···π, H···O=C, π–π interactions	Wang et al. (2021a)
AFSB	Sludge	600					23.3	Chemisorption (–C=O–Fe–, –C=OO–Fe–)	
Biochar	Oil palm frond	500	Phenol Tannic acid	140	3	6.5	62.9 67.4	Van der Waals forces, π–π interactions, hydrogen bonding	Lawal et al. (2021)
GP-BC	Grape pomace	350	Cymoxanil	100	0.25	7.0	161.0	Hydrophilic interactions	Yoon et al. (2021)
Biochar	Sewage sludge	700	Diclofenac Triclosan Naproxen	10	1.25	3.0 3.0 4.0	92.7 113.0 127.0	π–π interactions, hydrogen bonding	Czech et al. (2021)
Biochar	Sugar cane	380	Thiamethoxam	10	1	6.2	10.2	π–π interactions, hydrogen bonding, dipole–dipole interactions	Fernandes et al. (2021)
Biochar	Lignin	400	Methylene blue	50	–	–	234.7	Chemisorption	Liu et al. (2021e)
LBC-800	Lotus root	800	Methyl orange	300	1	–	320.0	Physisorption	Hou et al. (2021)
HMB	Wheat straw	600 700 800	Cd	200	0.8	5.0	70.9 80.0 61.1	Precipitation, surface complexation, ion exchange, physical adsorption	Fu et al. (2021)
BC600	Blue algae	600	Cd	200	–	7.0	135.7	Ion exchange, surface complexation, precipitation	Liu et al. (2021c)
Biochar	Canola straw	500	Pb	100	1	–	165.1	Precipitation, surface complexation, ion exchange, cation-π interaction	Nzediegwu et al. (2021)

Table 2 (continued)

Materials	Feedstock	Pyrolysis temperature (C)	Pollutants	Initial concentration (mg/L)	m/V (g/L)	pH	Adsorption capacity (mg/g)	Interaction mechanism	References
ALB	Alkali lignin	400	Pb	100	0.4	–	1003.7	Precipitation, ion exchange, surface complexation	Wu et al. (2021b)
FeYBC	Pomelo peel	600	Cr	40	2	4.72	39.3	Ion exchange, surface complexation, reduction	Dong et al. (2021)
PBC_{KOH}	Corn straw	500	Cr	100	0.5	–	117.0	Electrostatic attraction, complexation, ion exchange, reduction	Qu et al. (2021)
BC	Tribulus terrestris	500	U	50	0.5	6.0	49.6	Surface complexation	Ahmed et al. (2021b)
PBC@LDH	Bamboo	700	U	–	1	4.0	274.2	Complexation, reduction, precipitation	Lyu et al. (2021)

the removal efficiency of adsorption, ·OH and PFRs was 28.37%, 27.56%, and 8.26%, respectively.

Pesticide-related health risks and toxic outcomes have been widely acknowledged. A study assessed the adsorptive performance and processes of biochar derived from grape pomace (GP-BC) in the eradication of cymoxanil (CM) (Yoon et al. 2021). The biochar created at a low temperature (350 °C) revealed smaller surface area (0.25 m^2/g), higher H/C (0.905) and K (1.94%) content, as well as the maximum elimination capacity (161 mg/g). Biochar obtained from sugarcane in the agro-industry by low-temperature pyrolysis exhibited approximately 70% removal efficiency of thiamethoxam in 60 min (Fernandes et al. 2021). In addition, biochar synthesized from phosphoric acid-treated rice straw (T-RSBC) was used for the removal of atrazine (ATZ), azoxystrobin (AZOXY), and imidacloprid (IMIDA) in single-, bi-, and ternary-solute systems (Mandal et al. 2021). The Freundlich constant in the ternary system was as follows: AZOXY (1459) > IMIDA (1314) > ATZ (222.7). Figure 5A indicates that electrostatic interactions with the phosphate ester group in T-RSBC and non-bonding interactions among aromatic groups assumed an instrumental role in the adsorption process. Lee et al. (2021) conducted a comparative investigation of the elimination behaviors and related reactions of herbicides using biochar obtained from the residue of ground coffee without (GCRB) and with NaOH activation (GCRB-N). The total pore volume and specific surface area of GCRB-N (0.293 cm^3/g and 405.33 m^2/g) were higher than those of GCRB (0.014 cm^3/g and 3.83 m^2/g). GCBR-N could eradicate herbicides effectively (Simazine = 99.16 μmol/g, Alachlor = 122.71 μmol/g, and Diuron = 166.42 μmol/g) than GCRB (Simazine = 6.53 μmol/g, Diuron = 9.95 μmol/g, and Alachlor = 11.74 μmol/g). Graphite-like biochar was successfully synthesized and implemented to remove imidacloprid (IMI) and sulfadiazine (SUL) from wastewater (Zhang et al. 2021b). The elimination of IMI and SUL by graphite-like biochar was primarily through H-bonding, pore-filling, electrostatic interactions, and cation/p/π-π EDA interactions. In addition, the removal efficiency of biochar modified by ball-milling and TEMPO-mediated oxidation for SUL and IMI was greater than 85%, even after five successive adsorption/desorption recycling processes.

The traceable quantities of dyes in water, including rhodamine B (RhB), methylene blue (MB), congo red (CR), and methyl orange (MO) have been reported to be carcinogenic to humans (Zhang et al. 2021c). The elimination capacities of CR and MB dyes onto wet-torrefied *Chlorella* sp. microalgal biochar were 164.35 mg/g and 113.00 mg/g, correspondingly (Yu et al. 2021a). It was observed that nearly total removal of RhB, methyl violet, and MB dyes occurred when activated carbon produced from KOH activation of food wastage biochar as well as canola hull biochar was used in 0–2 h of reaction time (Patra et al. 2021). The removal efficiency of MO by biochar was 95–96% at pH 2–7, while it exhibited reduced adsorption capacity at pH > 7. In addition, the removal efficiency of MO was greater than 82% in 30 min, and the final reaction equilibrium reached at 120 min (Cuong Nguyen et al. 2021). As a promising material, lignin-derived porous biochar was successfully synthesized via chemical functionalization with various

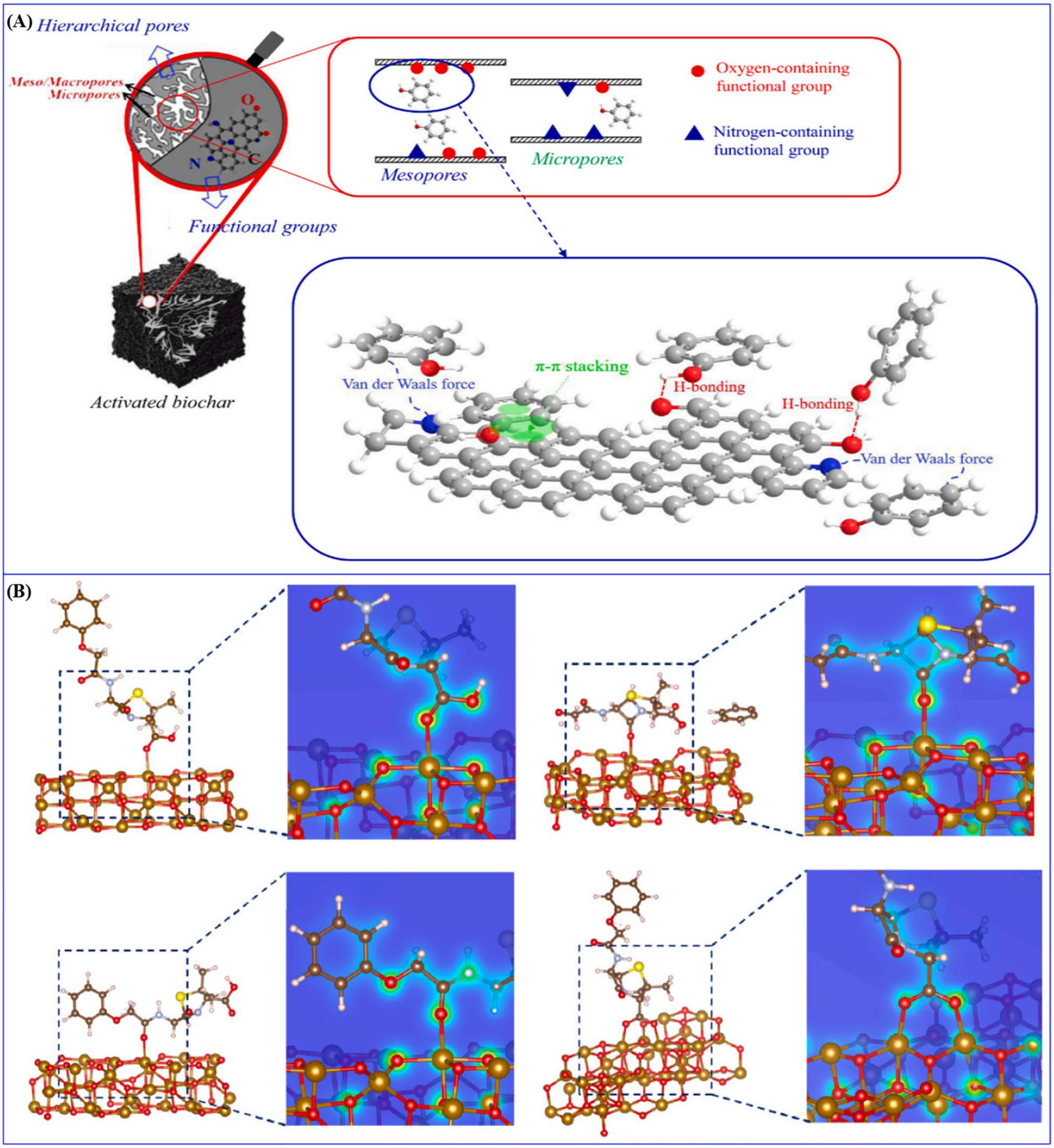

Fig. 4 **A** Pore hierarchical -functionalized structure adsorption mechanism of phenol (Feng et al. 2021). **B** Electronic density of different optimized structures of penicillin V and penicillin V- adsorbed on the (110) surface of Fe_3O_4 crystals (green rings around atoms represent the electron density) (Wang et al. 2021a)

oxidation number manganese compounds (MnO_2, $MnSO_4$, and $KMnO_4$) (Liu et al. 2021e). The highest elimination capacity of MB was 248.96 mg/g and the removal efficiency was 99.73%, when compared to 234.65 mg/g and 94.0% for pristine biochar. Lotus roots were modified into N-enriched biochar to remove azo dye MO. Biochar carbonized at 800 °C temperature with 693 m^2/g surface area exhibited the optimum property in terms of adsorption capacity, reaction kinetics, recyclability, and the highest removal capacity reached 449 mg/g (Hou et al. 2021). As illustrated in

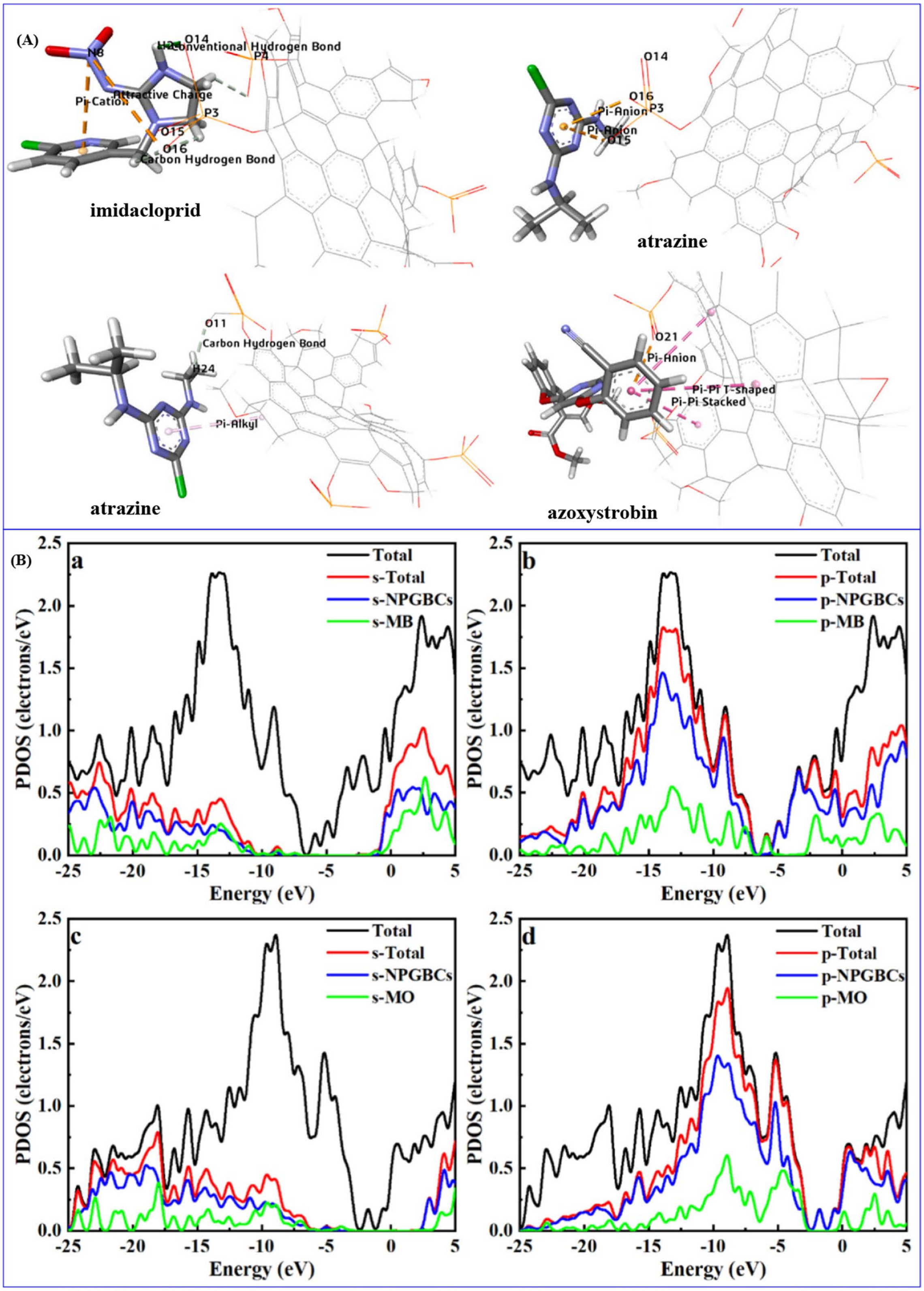

Fig. 5 **A** Important molecular non-bonding interactions that played a major role in the removal of imidacloprid, atrazine and azoxystrobin (Mandal et al. 2021). **B** The s-orbital and p-orbital PDOS of MB/MO adsorbed by NPGBCs (Cheng et al. 2021a)

Fig. 5B, the partial density of states (PDOS) was determined to examine the reaction procedure between N-doped porous graphitized biochar (NPGBCs) and organic dyes at the electronic level (Cheng et al. 2021a). Within proximity of the Fermi level, the PDOS of p-orbitals contained additional peaks than that of s-orbitals, demonstrating that p-electrons were instrumental during the reaction procedure. After reaction, the low-energy state p-electrons of NPGBCs and MB/MO were excited to high-energy states, which indicated the presence of stable π–π interactions.

4.2 Heavy metal ions

Biochar-based adsorbents have shown tremendous potential in removing heavy metal ions, such as Pb, Zn, Cd, Cu, U, Cr, etc. A variety of factors influence the adsorption performance of biochar in removing heavy metal ions, including the water environmental conditions and biochar characteristics. The characteristics of biochar depend on pyrolysis temperature, the composition of feedstocks, and duration. The water environmental conditions related to the eradication efficiency of heavy metal ions include reaction temperature, pH value, as well as competitive binding of co-existing compounds. The reaction mechanisms primarily include ion exchange, complexation, electrostatic interaction, and reduction.

Cadmium (Cd) is a representative toxic heavy metal ion that has caused wide concern owing to its difficulty in degradation and easy accumulation in the human body (Zhang et al. 2021a). The adsorption capacity of Cd(II) on blue algae-derived biochar was 135.7 mg/g, which was 66.9% and 85.9% greater than that of rice husk-derived biochar and corn straw-derived biochar, correspondingly (Liu et al. 2021c). Su et al. (2021) compared the elimination mechanisms of Cd(II) by fresh and aged ramie biochar. The results indicated that both physisorption and chemisorption existed, and chemisorption and physisorption were the major mechanism of fresh biochar and aged biochar, correspondingly. In addition, cation exchange, coprecipitation and cation-π interactions were stronger in fresh biochar than aged biochar. Carboxyl played a vital role in coordination of fresh biochar and hydroxy in aged biochar. The elimination behavior of Cd(II) by porous magnetic biochar (HMB) could be described by precipitation [$CdCO_3$ and $Cd(OH)_2$], surface complexation (–COOCd, –OCd), ion exchange (K^+, Ca^{2+}, Mg^{2+}), and physical adsorption (rich pore structure) (Fu et al. 2021). As illustrated in Fig. 6A, the retention efficiency of Cd(II) by HMB increased from 47.17% to 98.30% with the solution pH enhanced from 2.0 to 8.0, while the removal efficiency reduced from 91.50 to 65.47% with increased adsorption/desorption recycles. Ion exchange with Na^+, coordination with π electrons (C=C), surface precipitation ($CdSiO_3$, $CdCO_3$, or Cd_2SiO_4), and complexation with oxygen groups (O=C–O and Si–O) were the predominant sorption processes of Cd(II) using silicate functionalized oiltea camellia shell biochar (Cai et al. 2021). The elimination capacity of $MgCl_2$ functionalized biochar (MBC) to Cd(II) was 763.12 mg/g, which was 11.15 times greater than the capacity of pristine biochar. The removal of Cd(II) by MBC was primarily attributable to the mechanisms as follows: $Cd(OH)_2$ precipitation (73.43%) > ion exchange (22.67%) > Cd^{2+}-π interaction (3.88%), with slight interactions from electrostatic attraction, physical adsorption, and functional group complexation (Yin et al. 2021).

Adsorption of lead (Pb) from wastewater by biochar-based materials is a promising approach. The most crucial factors to consider when producing biochar to remove Pb(II) include the synthetic method, the reaction temperature, and the type of feedstock. Nzediegwu et al. (2021) examined the removal of Pb(II) by biochar produced via microwave-assisted pyrolysis using four feedstocks at three temperatures. The results indicated that canola straw biochar obtained at 500 °C exhibited the highest adsorption capacity of 165 mg/g. For a higher production temperature, Pb(II) elimination improved in biochar because of precipitation formed as hydrocerussite and lead oxide phosphate. Wheat straw biochar (WBC) was functionalized via phosphate/magnesium through the pre-treatment of biomass and post-treatment of biochar, noted as WBC_PMA and WBC_PMB, correspondingly (Miao and Li 2021). Since the pyrolysis process enhanced the loading capacity of phosphate/magnesium, WBC_PMA contained additional surface functional groups than WBC_PMB. The elimination capacity of Pb(II) in WBC_PMA and WBC_PMB was 470.09 mg/g and 308.39 mg/g, respectively, higher than that of WBC (59.93 mg/g). Jiang et al. (2022) investigated the elimination of Pb(II) by pristine biochar and nitrogen-doped biochar (NBC). As depicted in Fig. 6B, the underlying process of removing Pb(II) using BC was primarily attributed to the ion exchange and complexation with unsaturated C bonds, while NBC also had the interactions between graphitic-/pyridinic-N and Pb(II). A novel, cost-effective, and excellent adsorption biochar adsorbent to remove Pb(II) (1003.71 mg/g in 5 min) was fabricated via the pyrolysis of waste alkali lignin (Wu et al. 2021b). Mineral precipitation (88.72%) was the predominant reaction process, and surface complexation accounted for 8.25%. The study revealed that alkali lignin had the potential to be used in the preparation of biochar adsorbents to immobilize and eradicate Pb(II) from aqueous solutions.

Immobilization of aqueous Cr(VI) or transformation of Cr(VI) to other less toxic species, primarily to trivalent chromium [Cr(III)], has been adopted as a major strategy to reduce the adverse environmental effects of chromium (Li et al. 2021a). Generally, Cr(VI) occurs in oxy-anionic forms, as chromate (CrO_4^{2-}) or dichromate ($Cr_2O_7^{2-}$). A porous

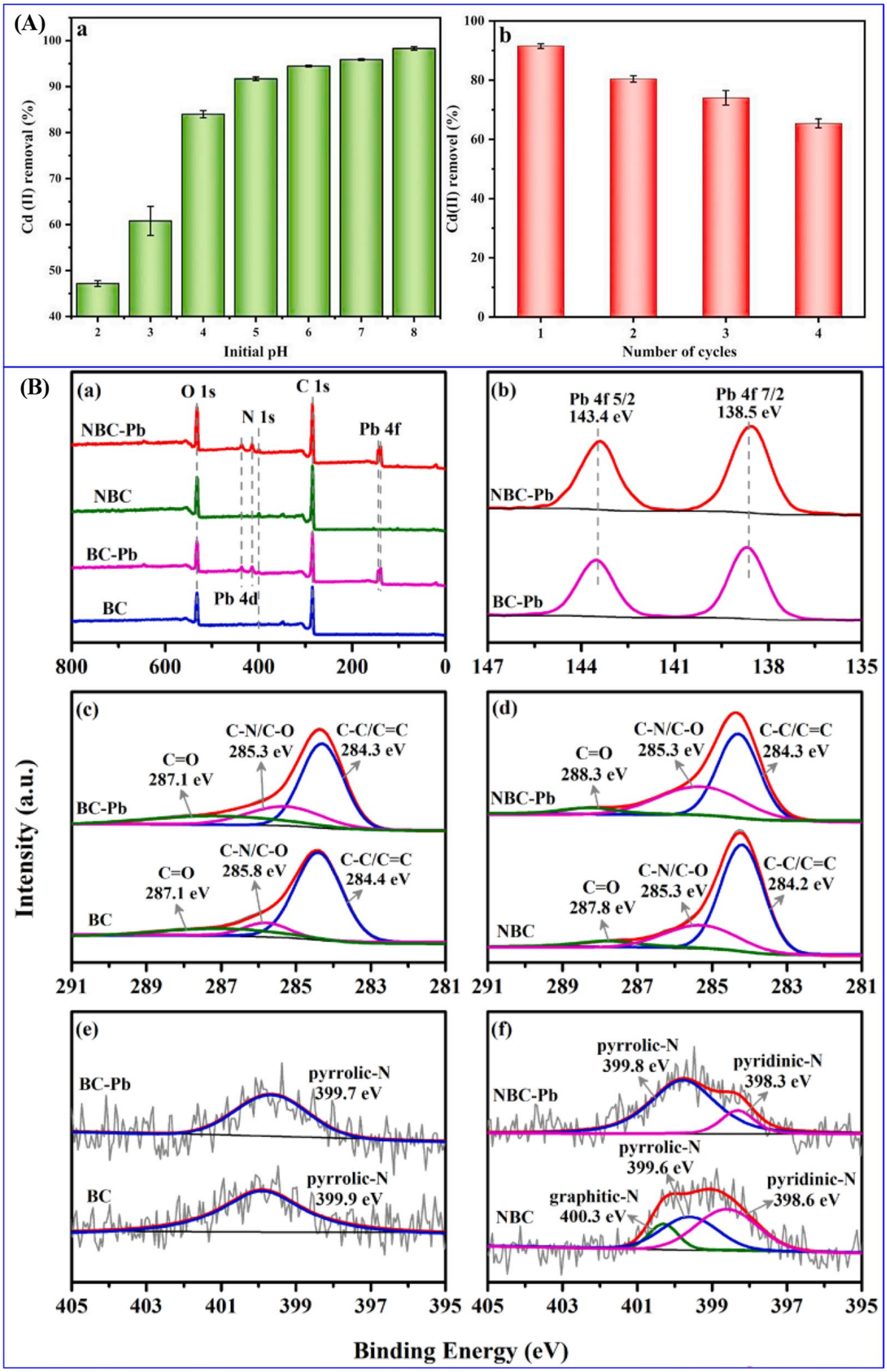

Fig. 6 **A** Effect of pH on the Cd(II) removal by HMB (a). Reusability of HMB as an adsorbent for Cd(II) in water (b) (Fu et al. 2021). **B** The spectra of (a) XPS; (b) Pb 4f; (c, d) C 1 s; and (e, f) N 1 s including BC or NBC-350-0.1 before and after adsorbing Pb(II) (Jiang et al. 2022)

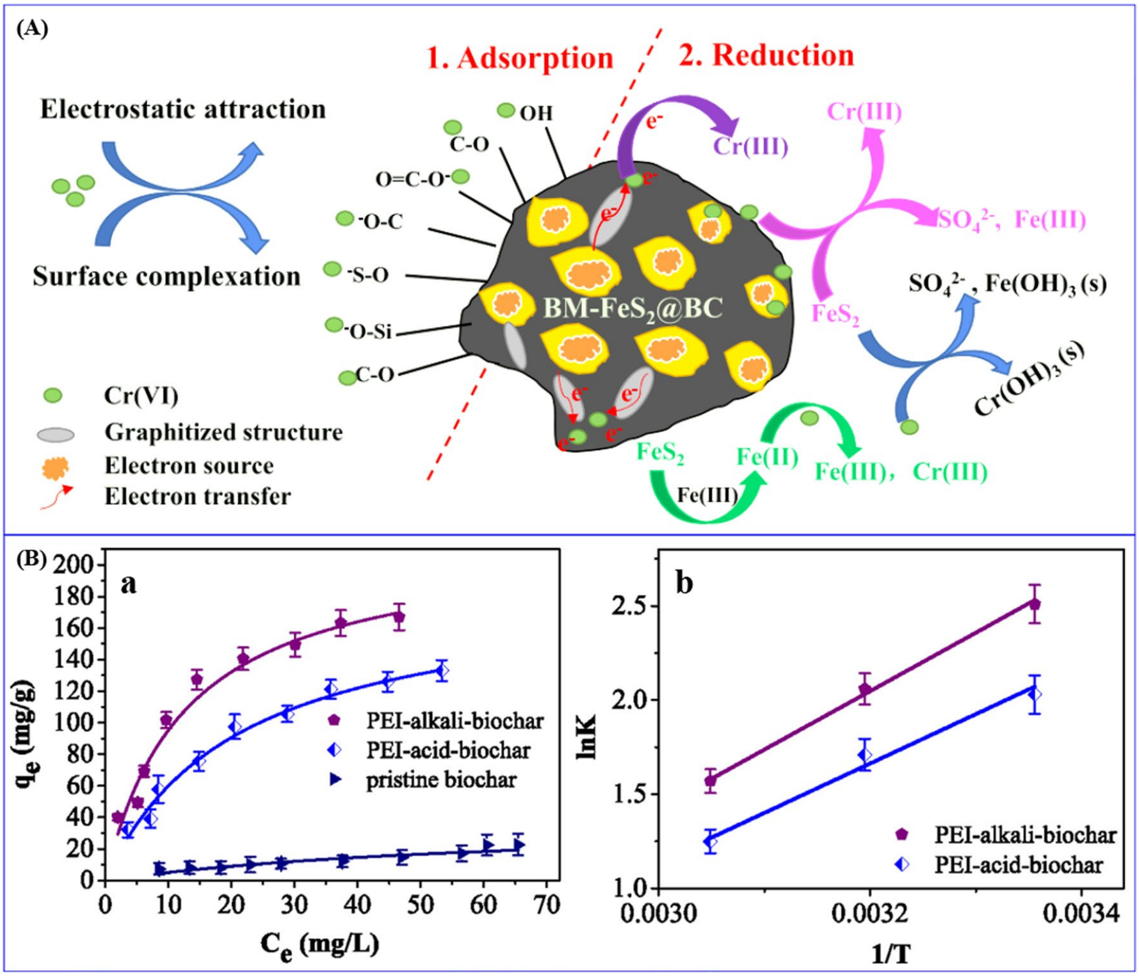

Fig. 7 **A** Cr(VI) removal mechanisms by the BM-FeS_2@BC (Tang et al. 2021b). **B** Adsorption isotherms of U(VI) on pristine biochar, PEI-alkali-biochar and PEI-acid-biochar at 25 °C (a). Thermodynamic investigations of U(VI) adsorption on PEI-alkali-biochar and PEI-acid-biochar (b) (Wang et al. 2020)

biochar based on corn straw with a sizable specific area of 2183.80 m^2/g was synthesized using two-step KOH-activated pyrolysis, and exhibited superior elimination performance with a theorized monolayer adsorb of 116.97 mg/g for Cr(VI) (Qu et al. 2021). A unique biochar/iron oxide composite (BM-Fe-HC) was effectively produced by ball milling iron-laden biochar (Fe-HC), which was applied for removing Cr(VI) (Zou et al. 2021). Acidic pH enhanced Cr(VI) elimination while competing ions (Cl^-, SO_4^{2-}, and PO_4^{3-}) inhibited Cr(VI) adsorption by BM-Fe-HC. After reaction, Fe(II) reduced a portion of the adsorbed Cr(VI) before being stabilized by Fe(III) as amorphous $Cr_xFe_{1-x}(OH)_3$ on the surface of the composite. As a naturally occurring reduction mineral, pyrite (FeS_2) was integrated with biochar through ball milling method to prepare FeS_2@biochar composite (BM-FeS_2@BC) and was employed to remove Cr(VI) from wastewater (Tang et al. 2021b). As exhibited in Fig. 7A, surface complexation, reduction, and adsorption were the primary mechanisms for the removal of Cr(VI) by BM-FeS_2@BC. Zhao et al. (2021e) united molecular simulation and spectroscopic strategies to examine the selective elimination of Cr(VI) on N-/O-rich biochar under the robust competition of anions. XPS and DFT simulations confirmed that the strong H-bonds between $HCrO_4^-$ and carboxyl/hydroxyl as well as surface complexation elevated Cr(VI) eradication by O-rich biochar, while for N-rich biochar, coexisting anions depressed Cr(VI) elimination in the order of $Cl^- > NO_3^- > SO_4^{2-}$ due to the weaker H-bond interaction between $HCrO_4^-$ and protonated amino groups. It is possible to efficiently eliminate Cr(VI) using different biochar-based materials through combined adsorption, reduction, and co-precipitation processes (Ma et al. 2022; Ri et al. 2022; Wen et al. 2022; Zhou et al. 2022).

Uranium (U) is a radioactive metal that is extremely toxic (Wang et al. 2022c). The presence of uranium above a certain threshold in aqueous environments can have lasting health implications that cause severe and irreversible damage (Wang et al. 2022b). The sorption-reduction-solidification is a good method for U(VI) immobilization and extraction from wastewater (Cheng et al. 2021d; Li et al. 2021d; Yang et al. 2021c). Ahmed et al. (2021a, b, c, d) prepared numerous biochar-based materials and tested performance in the adsorption of U(VI) from wastewater. Experimental results were good fit for the pseudo-second-order kinetic model and Langmuir isotherm. Thermodynamics indicated that the adsorption was endothermic and entropy-driven with an enhanced randomness in the solid-solution interface. Phosphate pre-impregnation pyrolysis proceeded by a hydrothermal approach was employed to prepare the phosphate-impregnation biochar (PBC) and Mg–Al layered double hydroxide (PBC@LDH) composite to remove U(VI) (Lyu et al. 2021). It was calculated that the highest adsorption threshold of U(VI) by the PBC@LDH was approximately 274.15 mg/g, which was an approximate 17-fold increase than that of pristine biochar. XPS and FTIR analyses verified that the extremely efficient U(VI) adsorption by PBC@LDH composite was ascribed to strong complexation and reduction interactions of Mg–O–H, P–O, and –OH groups to U(VI) and the co-precipitation of polyhydroxy aluminum cations captured U(VI). Wang et al. (2020) prepared the polyethyleneimine (PEI) modified moso bamboo biochar and applied it for the elimination of U(VI). The fitting of Langmuir model (Fig. 7B) found that the highest elimination capacities of U(VI) were 185.6 mg/g and 212.7 mg/g for PEI-acid-biochar and PEI-alkali-biochar ,respectively, which were nearly 9–10 times greater than that of unmodified biochar (20.1 mg/g). MnO_2/orange peel biochar composite was produced via a single-step method including activation and in situ deposit (Ying et al. 2020). The adsorption ability of U(VI) retained almost 95.6% initial elimination capacity even after five adsorption/desorption cycles. It has high availability in consideration of cost, raw materials, competitive adsorption capacity, and feasible preparation scheme, making MnO_2/OPC an effective scavenger to remove uranium from aqueous mediums.

In conclusion, biochar-based adsorbents could excellently eliminate target pollutants and the adsorption capacity was highly affected by water quality such as temperature, solution pH, and background ions. The major removal mechanisms of organic pollutants were van der Waals forces, π-π interactions, and hydrogen bonding. The dominant removal mechanisms of heavy metal ions were precipitation, ion exchange, and surface complexation. However, most studies focus on the elimination of one target pollutant, while there are variety of contaminants in aqueous solutions during field application, which are changeable and complex. Therefore, it is of great significance to further investigate the simultaneous treatment of multiple contaminants and/or selective adsorption of one contaminant by biochar-based materials for actual water environment management.

5 Conclusions and future perspectives

Water and soil contamination is an increasingly prevalent global issue. Using sustainable and renewable methods to eliminate pollutants in water and soil has become the pursuit of researchers. Thus, there is a demand for novel, efficient techniques and materials to eradicate organic and inorganic pollutants from nature, including heavy metal ions, dyes, antibiotics, and pesticides. Applying biochar to elevate the quality of soil and water by removing contaminants has been regarded as a feasible green strategy that is cost-effective. The performance characteristics of biochar are affected by the type of feedstock materials, residence time and pyrolysis temperature. Applying biochar to contaminated water and soil has been verified to be effective as a tool to remediate soil and water systems. The immobilization or mobilization mechanisms of heavy metal ions include reduction, complexation, electrostatic attraction, precipitation reactions, and cation exchange. The elimination processes of organic pollutants primarily include H-bonding, pore-filling, electrostatic interactions, hydrophobic interactions, and cation/p/π–π interactions. In contrast with aquatic systems, the intricate nature of soil systems has limited biochar applications. Based on the literature review, the aspects outlined below need further study before prior to achieving the operational application of biochar to remediate polluted water and soil environments and minimize the knowledge gap in this field:

1. It is crucial to conduct an environmental risk assessment prior to considering the widespread application of biochar to confirm that the utilization of biochar would not inflict any ecological risks. The toxicity of biochar-based materials is dependent on their physiochemical characterizations including raw materials, dose, and surface coating. To achieve large-scale environmental remediation applications, it is necessary to conduce in-depth investigations on the aging of biochar, associated toxicity, desorption of adsorbed pollutants in varying environmental conditions.
2. Generally, soil and water systems contain multiple co-existing organic/inorganic pollutants. Competitive elimination between toxic elements (particularly in inorganic contaminants) and targeted pollutants may occur on active sites in biochar-based adsorbents. Thus, the removal efficacy of engineered biochar for targeted pollutant in multi-contaminant environments needs testing.

3. Compared to pristine biochar, modified biochar exhibited superior eliminating effect for target pollutants in the soil and water system. However, extensive studies are required to verify the efficacy and superiority of engineered biochar in removing contaminants from water/soil system. The significant binding of contaminants onto biochar reduces the desorption of the adsorbed substances. Resultantly, it has an effect on the reusability of used biochar. Biochar functionalization is needed to decrease the binding energy of adsorbed pollutants on biochar, thus elevating the recyclability and desorbability of used biochar, especially for remediating pollutants in polluted water, where it is highly desirable to reuse spent biochar.
4. The elimination mechanisms of different contaminants by biochar should be in-depth investigated using theoretical calculation and molecular simulation technology, which is helpful to understand the contribution of different functional groups on the binding of pollutants. Theoretical calculation and molecular dynamics simulation can supply information that cannot be available in spectroscopic analysis, such as the structure, bond distance, binding energy of adsorption system. This information is useful for deeply understanding the reaction mechanisms between pollutants and different functional groups, which is important for the preparation of biochar and surface grafting of specific functional groups on material surfaces to improve the binding of contaminants, especially for the selective elimination of contaminants in multi-contaminant environments.

The review presents a comprehensive understanding of the synthesis of biochar-based materials and their potential applications in remediating contaminants from water and soil. We hope that extended investigations concentrated on mitigating the existing constraints would enable more people to adopt biochar-based materials to protect the environment sustainably.

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Declarations

Competing interests The authors declare that there is no competing interests in this manuscript.

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