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Biochar

REVIEW **Open Access**

Remediation of uranium-contaminated water and soil by biochar-based materials: a review

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Abstract

Uranium (U) resources play a crucial role in energy utilization; however, uranium contamination in wastewater and soil has caused severe damage to the ecosystem and human health. Addressing this challenge requires the development of cost-effective and environmentally sustainable remediation materials. This review highlights the environmental merits of biochar-based materials in uranium decontamination, focusing on the diverse applications of modification techniques for enhancing the properties of pristine biochar. By analyzing over 110 relevant studies, the review demonstrates that biochar derived from various biomass sources, with proper modification, could exhibit high adsorption capacities for immobilising uranium in aqueous and soil environments. The primary removal mechanisms identified include physical adsorption and chemical reduction. These works indicate that biochar, produced from green feedstocks and featuring superior reusability, represents a cost-effective, sustainable solution for uranium remediation. Moreover, its application aligns with carbon sequestration and waste valorization, supporting sustainable development goals. Looking ahead, the engineering performance-oriented biochar materials with tailored physicochemical properties hold significant promise for addressing uranium contamination challenges. This review provides a comprehensive evaluation of biochar-based materials as a green alternative for uranium remediation and offers valuable insights into advanced material modification strategies to enhance reactivity and effectiveness.

Article highlights

- Waste biomass can be carbonized for effective decontamination of uranium (U).
- Biochar modifications enhance reaction conditions and improve U removal efficiency.
- The prime mechanisms for U removal are physical adsorption and chemical reduction.

Keywords Biochar-based materials, Adsorption, Uranium (VI) remediation, Biochar modifications

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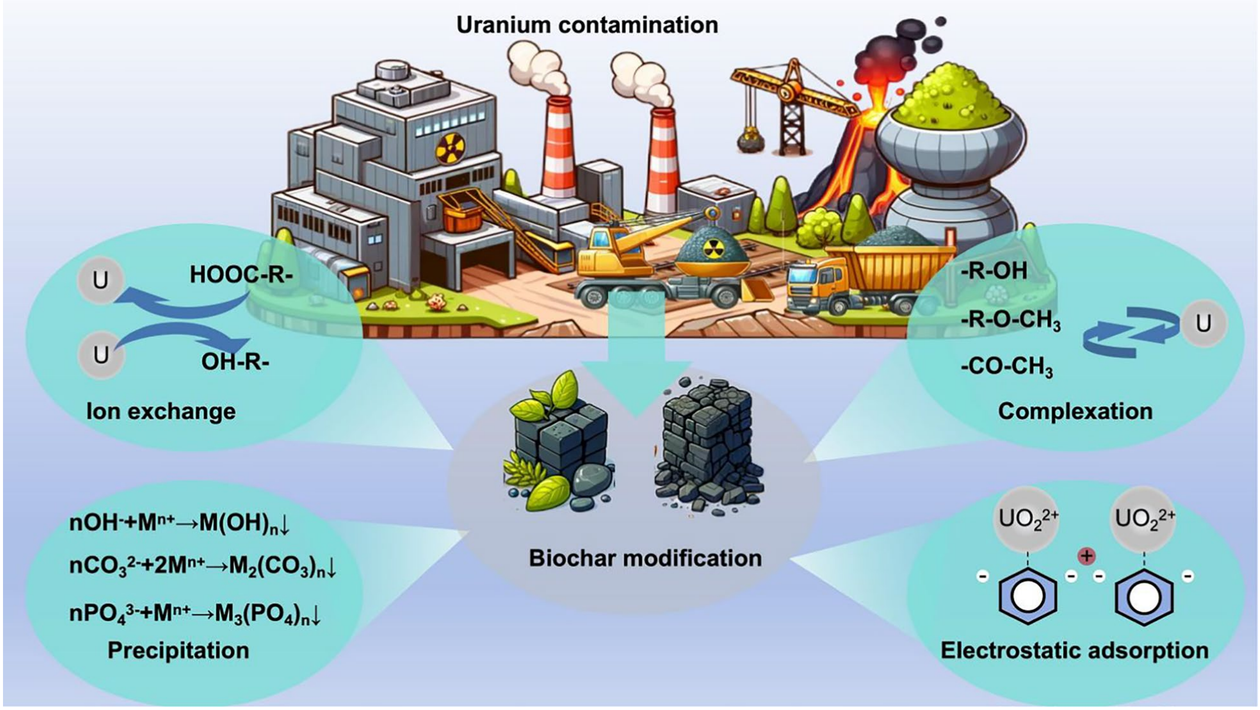
Graphical Abstract



1 Introduction

Uranium (U) is a silvery-white heavy metal and a typical radionuclide with both chemical and radiological toxicity. It is widely applied in the medical field, aerospace industry, and serves as a critical energy resource for nuclear power generation and military industry. Uranium is widely distributed in soils, rocks, and the Earth's crust at concentrations ranging from 2 to 4 mg kg^{-1}, and exists in various minerals, including brannerite, coffinite, davidite, pitchblende, thucholite, and uranite (Zhao et al. 2023). Among distinct isotopes of U, the most abundant, ^{238}U, has a half-life of approximately 4.5×10^9 years, while ^{235}U and ^{234}U have half-lifes of 7×10^8 and 2×10^5 years, respectively (Akash et al. 2022). These long half-lifes render U persistent and capable of accumulating in the environment. Uranium exists in various valence states, including 0, +2, +3, +4, +5, and +6, with U(VI) and U(IV) being the most prevalent species in the natural environment. Naturally occurring U is commonly found in mineral complexes, such as uranyl oxide hydrates, silicates, phosphates, sulphates, and carbonate.

Compared with natural U sources, including atmospheric deposition, volcanic eruptions, and rock weathering, anthropogenic activities such as mining, improper disposal and even leakage of nuclear waste have posed severe contamination in both terrestrial and aqueous ecosystems. The hexavalent uranium (U(VI)), which is highly soluble and mobile in oxidizing environments, forms uranyl ions (UO_2^{2+}) with a U atom bonded to two oxygen atoms via coordination bonds. Another commonly found oxidized form of U is pitchblende (U_3O_8). In soil, U can jeopardize the microorganisms through activity inhibition, transcriptional processes disruption, and oxidative damage. It can impair plants by disrupting root nutrition metabolism, inducing oxidative stress and interfering with photosynthesis and growth. Uranium contamination decreases photosynthetic rates by altering the expression of genes involved in the electron transport chain, Calvin cycle, and photorespiration pathways (Cui et al. 2023). Soil properties, such as redox potential, phosphorus content, organic matter, microorganisms and pH, influence U speciation and bioavailability (Kumar et al. 2023). Uranium in the contaminated soil–crop systems can enter the food chain and thus threaten human health. In water bodies, U primarily presents as mobile uranyl ions (UO_2^{2+}), which are highly transportable (Liu et al. 2023a, b). Both chemical toxicity and radiological risks of U cause severe environmental threats, with chemical toxicity being especially dangerous even at low concentrations. Uranium contaminants are transported via infiltration, tailing facilities, airborne particles, and pathways through both above the water table (e.g., pipeline leakage, leachate) and below the water table (e.g., drainage wells and groundwater withdrawal) media (Dinis and Fiúza 2021). Uranium can enter the human bodies through contaminated food or drinking water via the gastrointestinal tract (Chen et al. 2022). Exposure to U can impair metabolic activity, hematopoietic systems, nervous system, reproductive functions, and digestive system, which may possibly cause physical deformity or cancer (Akash et al. 2022; Cheng et al. 2022).

The extensive industrial utilization of nuclear energy production, mining, hydrometallurgy, nuclear power generation, and fuel fabrication has led to growing environmental concern. To explore the latest progress and frontiers in U studies, relevant literature published in the Web of Science database was identified and analyzed. According to the scientific knowledge map on the keyword "uranium" shown in Fig. 1, hot topics in U research include removal and adsorption techniques, highlighting the urgent need for efficient solutions to U decontamination. Over recent years, the U-contaminated soil, groundwater, and mine sites have been extensively identified worldwide. For example, the highest U concentration in groundwater from shallow aquifers reached 1443 mg L^{-1} in India (Balaram et al. 2022), while elevated levels (mean/median U concentration: 143/92 μg kg^{-1}) in the hair of residents living near mine tailings in South Africa (Zupunski et al. 2023).

To mitigate the severe hazards caused by U contamination, a variety of techniques have been employed, including leaching, adsorption, reduction, and phytoremediation (Prusty et al. 2022; Shen et al. 2023). Over the past decades, significant research efforts have been devoted to avoiding secondary pollution and developing cost-effective adsorptive materials for efficient U extraction, mitigation and recovery. Novel adsorbents for U remediation have been reported, such as fibrous polymer adsorbents like functionalized polyethylene (PE), polypropylene (PP), and polyacrylonitrile (PAN) (Ma et al. 2020). Particularly, carbon-based adsorbents (e.g., biochar, activated carbon, and graphene materials) with tunable surface characteristics have been shown desirable performance in removing U from aqueous media (Fahad et al. 2023). Compared with other carbonaceous adsorbents, waste biomass-derived biochar exhibits significant advantages in economic feasibility and complying with sustainable development concepts.

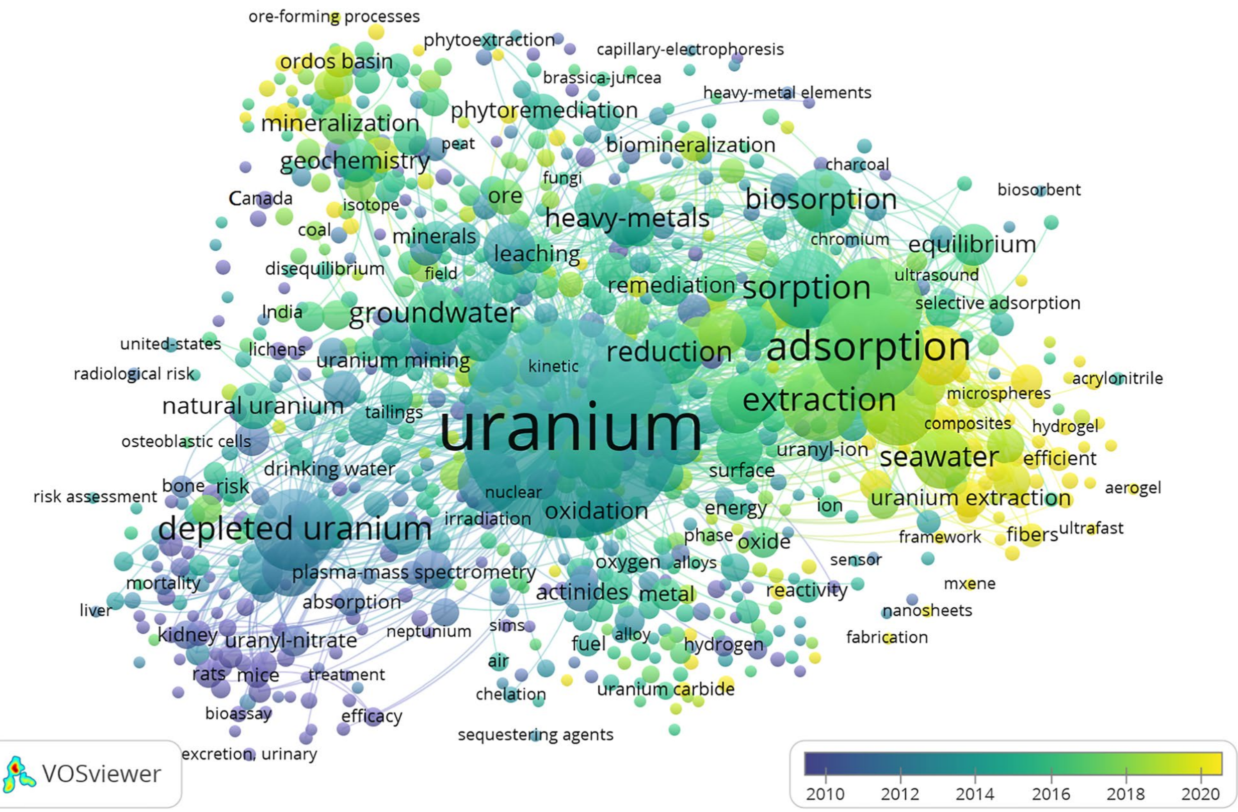


Fig. 1 Mapping analysis of scientific studies on keyword "uranium" with VOSviewer software that highlight adsorption, biosorption, and reduction as significant remediation techniques

Biochar is a carbon-based material synthesized by carbonizing organic biomass under oxygen-limited thermal treatment processes, including pyrolysis, gasification, and hydrothermal treatments. It has garnered growing research interest as a cost-efficient adsorbent material, extensively applied in environmental remediation owing to its biocompatibility, environmental friendliness, reusability, large surface area, well-developed pore structure, and diverse surface functional groups (Xiong et al. 2017). Based on the cluster analysis performed using VOSviewer (Fig. 2), growing research topics in biochar studies include adsorption and property optimization. As a carbonaceous material with a heterogeneous interface, biochar can reduce and regulate the bioavailiability of U via ion exchange, electrostatic attractions, and other sorptive interactions (Kumar et al. 2023; Huang et al. 2024). Biochar has demonstrated applicability in the treatment of various metal(loids) pollutants in both water and soil environments in an environmentally friendly manner (Lakshmi et al. 2021). Its potential for U decontamination can be promisingly improved by tailoring its physicochemical properties through application-oriented modifications. Currently, limited information exists on the use of biochar for remediating U-contaminated environments, including soil and water. This represents a novel and promising area for future large-scale applications of biochar to achieve biomass valorisation and sustainable development. In particular, there is a lack of comprehensive reviews that elucidate biochar performance and link its properties with the underlying decontamination mechanisms.

This work aims to provide cutting-edge knowledge on the remediation of U-induced contamination by systematically summarizing the synthesis of biochar-based materials and their applications in dominant environmental media, including soil and water. The review covers the latest technological advances in U decontamination using biochar, offering an in-depth discussion on the major mechanisms and key factors influencing the processes. The environmental merits of biochar are emphasized, particularly its role in sustainably recycling waste biomass, while also considering the limitations and future challenges. This work highlights significant scientific insights to stimulate further development in this field and offers guidance for the design of cost-efficient biochar as a green material for large-scale applications in U remediation.

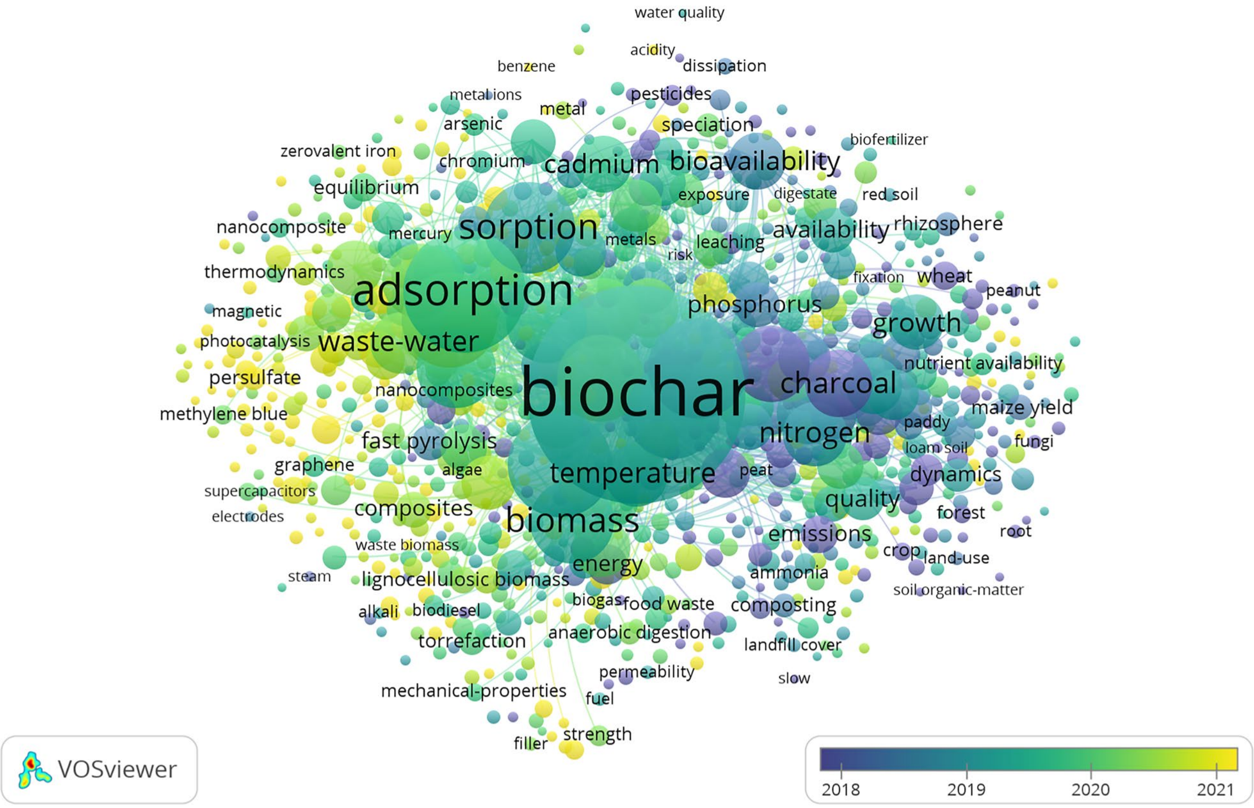


Fig. 2 Network visualization on keyword "biochar" according to VOSviewer that highlights its promising application for adsorption, amendment, and remediation

2 Common uranium remediation technologies

2.1 Physical and chemical approaches

Physical approaches, including coagulation, extraction, evaporation, precipitation, and membrane separation, are widely used for U removal in soil and aqueous media (Rosenberg et al. 2016). The reverse osmosis, electric repair, and thermal desorption have also been reported in previous literature, although their high cost and energy demands may limit large-scale applications (Balaram et al 2022). Chemical methods usually involve co-precipitation using effective adsorbent materials or ion exchange with anion exchange resins, such as commercially available polystyrene resins and silica (Rosenberg et al. 2016). Soil washing of U(VI)-contaminated soil, followed by precipitation/flocculation and filtration, has been proven effective in removing U pollutants. For example, a recent study used sulfuric acid to wash U-contaminated soil, removing U(VI) ions from the aqueous phase by flocculation and precipitation with polyacrylamide (PAM) (Lee et al. 2022). After neutralization and flocculation of the soil-washing effluent, the solid phase containing U(VI) underwent membrane filtration to form a filter cake, which was subsequently thermally decomposed without the loss of metal deposits, including U (Lee et al. 2022). Traditional physicochemical strategies, however, suffer from significant drawbacks, including secondary pollution, high cost, excessive reagent consumption, and damage to soil structure during in-situ remediation (Li and Zhang 2012). For practical large-scale remediation of contaminated sites, challenges such as high expenses, limited reusability, and slow exchange kinetics must be effectively addressed.

2.2 Biological and other emerging approaches

Bioremediation technologies, including phytoremediation and microbial remediation, are easy to implement, cost-effective, and environmentally friendly for U remediation, especially in soil, compared to conventional physical or chemical techniques. Bioremediation employs biological materials to address the environmental contamination, which requires certain substances (e.g., chitin and chitosan) produced by biological entities to accumulate contaminants in its cellular structures (Akash et al. 2022). Microorganisms play a key role in bioreduction and bioprecipitation of U(VI), decreasing the mobility of uranyl ions in soil. Immobilization of U can occur through functional groups on the cell surface, such as amino, hydroxyl, carboxyl, and sulfhydryl groups. Biomineralization, including microbial-induced phosphate precipitation, has recently emerged as an innovative strategy for remediation of U-contaminated soil (Jiang et al. 2020). For example, *Bacillus thuringiensis* was reported to have a strong ability to accumulate UO_2^{2+} by adsorbing it onto the bacterial surface through coordination with functional groups like phosphate, amide, and methyl groups, transforming UO_2^{2+} into crystalline nano-uramphite (Pan et al. 2015). Similarly, *Pseudomonas aeruginosa* can deposit uranium within the cell envelope and combine uranyl ions with phosphate to form uranium-phosphate minerals (Lyu et al. 2021b). Besides, some bacteria species secrete polymeric substances that facilitate U sequestration. However, microbial remediation is constrained by strict environmental conditions required for microbial growth, which makes large-scale application challenging (Lyu et al. 2021b). Integrating low-U-accumulating plants with microbial inoculants has been proposed as an efficient alternative for bioremediating U-contaminated soils (Chen et al. 2021). Phytoextraction involoves plant species with short growth cycles, massive biomass, and metal tolerance to uptake U from soil and water via their roots and accumulate it in aboveground structures (Cui et al. 2023). For instance, vetiver grass (*Vetiveria zizanioides L. Nash*) has been reported to efficiently phytoextract U at concentrations below 200 ppm (Pentyala and Eapen 2020). However, at high concentrations (e.g., 11,900 ppm), the recovery of U substantially dropped to 35%. Recent studies have shown that chelants can enhance phytoextraction efficiency by improving plant growth and strengthening the activity of defense system (Chengatt et al. 2023). Furthermore, the emerging technology of plant–microorganism joint remediation has also garnered attention, as it leverages the strengths of both approaches to improve the soil environments and remediation efficiency (Cheng et al. 2022).

Immobilization-stabilization technology has become a hotspot for in-situ U remediation due to its advantages of simple operation, high efficiency, environmental friendliness, and large-scale applicability. Some iron-based materials, such as nano zero-valent iron (nZVI), iron minerals, iron (oxyhydr)oxides, and other iron composites, have been reported to achieve effective U removal via mechanisms such as reductive precipitation, adsorption, inhibition reoxidation, and iron associated biotic processes (Chen et al. 2017). Nevertheless, these materials may cause environmental ecotoxicity to microorganisms by generating reactive oxygen species (ROS) within the cells (Chen et al. 2017). Overall, current remediation techniques require significant improvements in U removal efficiency and environmental compatibility. Challenges such as cost, secondary contamination, broad applicability, and ecological safety must be addressed to advance emerging U remediation techniques. Therefore, the development of cost-effective, stable, and environmentally friendly passivators to mitigate U mobility and bioaccessibility has become an essential issue to realize green remediation in a sustainable and efficient manner. In this regard, biochar derived from recycled waste biomass is equipped with various desirable physicochemical properties, showing huge potential for application in U removal.

3 Synthesis of biochar-based materials for uranium decontamination

3.1 Production of biochar

Biochar has garnered considerable interest for its wide-ranging applications, including carbon sequestration, soil amendment, wastewater treatment, energy storage, and heterogeneous catalysis. It is typically produced through the carbonization of carbon-rich biomass residues (e.g., forestry waste, agricultural waste, municipal sludge, and animal manure), which is a green solution to addressing waste management challenges while simultaneously synthesizing functionalized materials for environmental applications. Production of biochar involves the thermal degradation of waste biomass under oxygen-limited conditions, through processes such as pyrolysis, torrefaction, gasification, and hydrothermal treatment. The resulting cost-effective carbonaceous material possesses several favorable physicochemical properties, such as a large specific surface area, well-developed porosity, and abundant surface functional groups. These characteristics make biochar an effective adsorbent and an economical support material for active sites. Moreover, biochar has shown significant promise in environmental remediation. Its production from municipal organic wastes, agricultural and forestry residues, and anaerobic digestates represents an innovative approach to recycling renewable biomass waste, advancing sustainable development in alignment with the globally advocated concept of carbon neutrality (Zama et al. 2018; He et al. 2022).

Recycling waste biomass into biochar effectively alleviates the environmental burden associated with conventional waste management methods, such as landfills and incineration, which often face challenges like high energy consumption, secondary pollution, and limited land availability. Additionally, biochar contributes to resource utilization and carbon sequestration by reducing carbon emissions and mitigating greenhouse gas outputs. Compared to other functional carbon materials, such as graphene oxide and activated carbon, biochar takes the superior advantages, including low cost, a straightforward synthesis process, high adsorption capacity, and good recyclability. Its features include developed porosity, a large specific surface area, low solubility, stable carboxylate groups, aromatic ring structures, high specific capacitance, a robust carbon matrix, and especially tunable features. Recent studies have proved the feasibility of engineered biochar for large-scale applications in the remediation of organic contaminants and heavy metals from wastewater and soil (Wang et al. 2023a). A wide range of modification methods have been explored to enhance the properties and functionalities of biochar (Yu et al. 2023). Increasingly, studies confirm the potential of biochar-based materials for U removal (Table S1), highlighting their significant promise as cost-effective and environmentally friendly solutions for remediating U-contaminated environments.

Selection of biochar feedstock type plays a crucial role in influencing the properties of the final product. For example, the fibrous vascular system of *L. cylindrica* was proved to facilitate biochar adsorbent by promoting dense surface coverage and relatively rapid fluid exchange, which significantly increases the sorption behaviour (Liatsou et al. 2017). Similarly, animal manure was also used as a feedstock for biochar production. Compared to other biomass types, biochar derived from animal manure exhibits more active adsorption sites, such as $-NH_2$, $-OH$ and $P=O$ functional groups, which lead to the formation of stable compounds or precipitates. Additionally, calcium salts in the manure induce ion exchange, further enhancing the efficiency of U(VI) capture from wastewater (Liao et al. 2022c, 2022d). Sewage sludge, which is rich in phosphorus, nitrogen, organic matter, and micronutrients, also serves as an excellent raw material for producing mineral-rich biochar. For instance, hydrochar derived from residual sludge carbonized at 190 °C achieved a U(VI) adsorption capacity of 121.26 mg g^{-1} from aqueous solution, primarily through the formation of phosphorus-uranium complexes and electrostatic attraction (Zou et al. 2023). Notably, the ash content of biochar produced under these conditions reached 52.18%. Utilizing animal manure or sewage sludge as feedstock not only enhances the adsorption capabilities of biochar but also addresses the challenges of sustainable waste management, reliving the environmental burdens and contributing to carbon cycle closure.

Calcination temperature is another essential factor that determines the properties of biochar. Changing the pyrolysis temperature can alter the fixed carbon content, surface area, and pore volume of the produced biochar (Xiong et al. 2017). For instance, a study comparing the U(VI) adsorption capacities of magnesium oxide (MgO)-embedded biochar carbonized at 300, 500, and 700 °C found that biochar produced at 500 °C achieved the highest removal efficiency. This was attributed to the optimal graphitization degree of carbon particles and the uniform distribution of minerals (MgO, $CaCO_3$ and $Ca_3(PO_4)_2$), which provided abundant surface-active sites (Zheng et al. 2021). In general, pyrolysis temperatures below 500 °C partially carbonize biomass, resulting in biochar that is more favorable for removing inorganic pollutants owing to high levels of dissolved organic carbon and oxygen-containing functional groups (Daful and Chandraratne 2018). Nevertheless, for corn stover-derived biochars, pyrolysis temperature reportedly has a negligible impact on U(VI) adsorption efficiency (Tang et al. 2023). This discrepancy may be related to the properties of the feedstock, since calcination temperature manipulates the transformation of microcrystalline cellulose within the biomass.

As a novel approach to fabricating carbon materials in a more environmentally friendly and energy-efficient manner, hydrothermal carbonization (HTC) refers to the direct conversion of wet biomass under supercritical water pressure and relatively low temperatures (180–250 °C). Biochar derived from HTC, often referred to as hydrochar to distinguish that from pyrochar (produced from conventional pyrolysis), features a porous and amorphous structure enriched with abundant active functional groups, such as hydroxyl/phenolic, carboxylic, and carbonyl groups, which have a strong affinity for metal ions (Kumar et al. 2011). During the HTC process, supercritical water facilitates the cleavage of ether and ester bond, decreasing the activation energy required for biopolymer decomposition and enhancing biomass degradation and aromatization. The formed hydrochar is observed in a polyaromatic structure combined with polyfuranic rings (Zhang et al. 2019). Comparatively, pyrolysis often results in significantly fewer oxygen-containing surface groups due to more complete carbonization of biomass. As a relatively less energy-intensive process, HTC shows great potential for the large-scale production of cost-effective biochar adsorbents. Recent studies compared the adsorption performance of hydrochar and pyrochar in the treatment of U-containing water (Zou et al. 2023). Hydrochar adsorption behavior aligns with a heterogeneous and multilayer model, whereas pyrochar tends to exhibit a monolayer coverage of uranium (VI). This distinction results in maximum adsorption capacities of 121.26 for hydrochar and 66.74 mg g^{-1} for pyrochar, respectively (Zou et al. 2023). Compared to pyrochar, hydrochar is characterized by a lower degree of aromaticity, higher polarity, and lower mass recovery. These properties, combined with the advantages of HTC as a less energy-intensive method, underscore the promise of hydrochar as an effective and sustainable material in environmental remediation applications.

3.2 Biochar modification

Raw biochar, without modification, may have limited surface functional groups or active sites for interacting with contaminants (Table S2). Recent studies have reported that raw biochar produced from water hyacinth and Eucalyptus wood achieved adsorption capacities of 27.2 mg g^{-1} and 138.57 mg g^{-1} for U(VI) in solution, respectively (Xu et al. 2020; Mishra et al. 2017). Furthermore, a meta-analysis from a recent study verified that modified biochar presented around 15.6% larger efficiency in reducing exchangeable uranium in soil compared to raw biochar (Huang et al. 2024). The adsorption performance of biochar, which largely depends on the chemical nature of its carbon surfaces, can be significantly enhanced through physical, chemical, and biological modifications. These modifications enable the tailoring of biochar properties to optimize removal efficiency. Consequently, there has been a surge in research on biochar modification methods, which have successfully expanded the variety and abundance of surface functionalities on biochar materials (Fig. 3).

Compared to chemical composition, the structural properties of biochar play a more significant role in the adsorption of U, as demonstrated by an evaluation using a marching learning model (Da et al. 2022). In this study, the specific surface area was verified as the most vital parameter determining the adsorption efficacy of biochar, with an optimal range of 500–1200 m^2 g^{-1}. Moreover, O/C was found to be another significant chemical feature governing the adsorption capacity of biochar, which showed a positive correlation with performance (Da et al. 2022). Physical activation can be an effective solution to designing the surface morphology and porosity of biochar. For example, thermal air oxidation (TAO), a post-engineering technique that involves heating the biochar in air without requiring reagents or generating wastewater, can substantially tune the properties like surface functional groups and oxygen content. Biochar modified using TAO achieved a maximum U(VI) adsorption capacity of 163 mg g^{-1} (Dai et al. 2020a). Most studies produce biochar for U removal through pyrolysis under an inert gas atmosphere (e.g., nitrogen and argon). However, some researchers have synthesized magnetic biochar under mixed gas condition ($VN_2/VO_2 = 95/5$) (Hu et al. 2018). It was reported that using CO_2 as pyrolysis agent can lead to more vigorous biomass decomposition and potentially enhance the porous structure of biochar by creating more micropores (Lee et al. 2017). Mechanochemical treatments, such as ball-milling technology, can help further improve biochar by producing nano-biochar with superior surface areas (e.g., 400–500 m^2 g^{-1}) and a wide range of pore sizes (e.g., 0.5–1000 nm) (Kumar et al. 2020). Furthermore, crucial parameters including milling type, duration, and substrate-to-ball ratio can be adjusted to fine-tune the physicochemical properties of ball-milled biochar.

Chemical methods are crucial for biochar modification, in terms of both pre-treatment and post-treatment. Pre-treatment of raw biomass directly influences

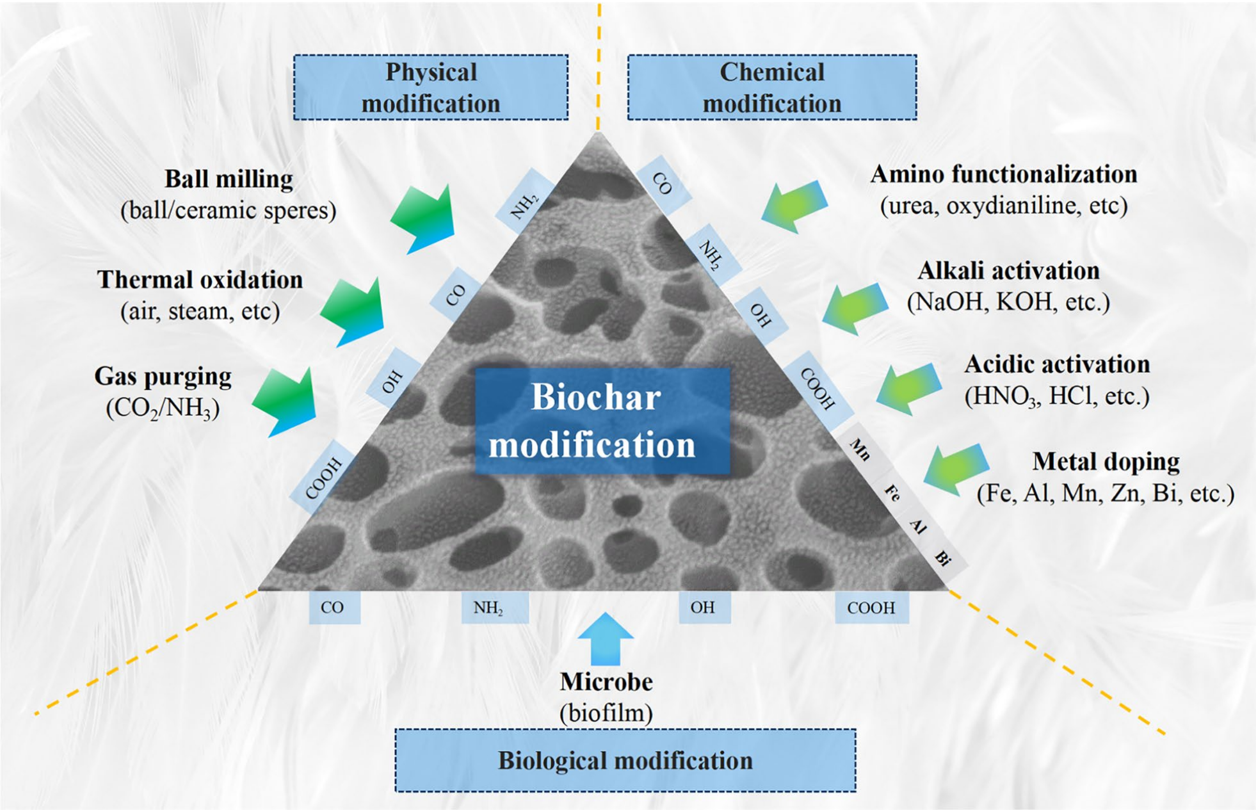


Fig. 3 Primary modification methods of engineering biochar-based materials for uranium decontamination

the adsorption efficacy of the resulting biochars toward U(VI). For instance, treating carbonaceous biomass materials with HCl or NaOH induces notable variations in the extraction of cellulose and hemicellulose, with alkaline treatments preferentially extracting hemicellulose components (Pakade et al. 2017). KOH modification has been shown to cause surface corrosion, generating a microporous structure with a higher surface area and pore volume, thus largely increasing the adsorption capacity of modified biochar (Yao et al. 2024). An investigation comparing acid- and alkali-modified biochars for U(VI) removal from wastewater found that NaOH pre-treatment rendered biochar with abundant oxygen-containing functional groups, which reached a superior adsorption capacity of 952.5 mg g^{-1} compared to 53.3 mg g^{-1} for HCl-pretreated biochar (Liao et al. 2022b). Acidic oxidation is another widely adopted modification method. The degree of surface oxidation depends on the reagent concentration and exposure time. For example, suspending biochar in HNO_3 at various concentrations (2, 4, 8, and 12 M) and reaction times (1, 2, and 3 h) at 80 °C under reflux and continuous stirring identified the optimum condition as 3-h oxidation with 8 M HNO_3 (Liatsou et al. 2017). This treatment increases the density of carboxylic moieties on the biochar surface, thus enhancing inner-sphere complex formation between U(VI) and biochar and improving adsorption capacity. Nevertheless, another HNO_3-treated biochar did not exhibit good selectivity for U(VI), since the sorption mechanism primarily involved coordination with oxygen-containing functional groups (Jin et al. 2018).

Phytic acid pre-treatment before pyrolysis can release hydrogen protons, modifying the biochar matrix with more developed micropores and introducing organic phosphorous-containing moieties. This treatment achieved a U (VI) adsorption capacity of 229.2 mg g^{-1} and showed good selectivity for U(VI) against co-existing metal ions (Hu et al. 2020). Similarly, ball-milling raw biochar with phytic acid produced phosphorus-functionalized biochar with an adsorption capacity of 128.5 mg g^{-1} (Zhou et al. 2020). While the presence of co-existing metal ions with higher valence and smaller ionic radii reduces U(VI) removal due to the competitive coordination, phosphorus-modified biochar demonstrates higher affinity for U(VI). This is attributed to the formation of stable U–O–P bonds and complexation with UO_2^{2+} (a strong Lewis acid) via Lewis base groups (e.g., $–PO_4$) (Hu et al. 2020). In addition, hydrothermal heating of biomass at 170 °C for 4 h with concentrated phosphoric and citric acids introduces abundant phosphoric-oxygen groups. This process produces granulated biochar with a specific surface area of 137.32 m^2g^{-1} and 11.76% phosphorus content through dehydration, condensation, and cyclization, leading to chemical grafting of P–O groups on phosphate and metaphosphate (Chen et al. 2023c). In parallel, other heterogeneous materials, such as chitosan-modified phosphate rock, have also demonstrated excellent performance in U(VI) adsorption (Sun et al. 2018). These studies highlight significant progress in developing phosphorus-modified biochar with enhanced adsorption efficiency.

Amino functionalization has been validated as an effective method to improve the biochar morphology, obtaining a very thin sheet with a rough porous surface and cluster structures. This enhancement is highly beneficial for U(VI) removal from aqueous solutions, reaching the theoretical maximum adsorption capacity of 367.99 mg g^{-1} (Lv et al. 2023). Phosphorylation modification introduces phosphate groups capable of selectively coordinating with uranyl ions. One study synthesized amino-reinforced phosphorylated biochar using urea, phosphoric acid, and N-dimethylformamide (DMF) after pyrolysis. This biochar, derived from cellulose, displayed diverse functional groups such as P = O and O = C–NH. These groups contributed to a maximum adsorption capacity of 150.38 mg g^{-1} for U(VI) through chelation and electrostatic interactions (Zhang et al. 2023b). Biochar can also be modified using salophen, a tetradentate ligand, to form stable uranyl-salophen complexes. Salophen-anchored biochar fibers demonstrated excellent U(VI) removal efficiency, with a maximum adsorption capacity of 833 mg g^{-1} at pH 5.5. This performance was attributed to the formation of inner-sphere complexes, showing low pH dependence and high selectivity for U(VI) (Liatsou et al. 2018). Other organic substances also show great prospect in tailoring biochar for effective U(VI) adsorption. For example, amidoxime group was reported to show excellent affinity and selectivity for U(VI) by chelating with uranyl ions (Wang et al. 2023b). The chitosan and polyethyleneimine-modified biochar composites, derived from uniform dispersion into the cross-linked network, provided diverse active sites, such as $-NH_2$, C–N, and –OH. These active sites were effective in forming U(VI)-complexes (Zhang et al. 2023a). Additionally, a hydrogel–biochar composite prepared through the polymerization of orange peel-derived biochar with guar gum and acrylamide exhibited a high adsorption capacity towards aqueous U(VI) ions of up to 263.2 mg g^{-1}. This composite also showed high selectivity against other competing cations (Akl et al. 2021). The modification employed a free radical graft polymerization technique to introduce amide groups, which actively participated in adsorption process. These amide groups contributed more to U binding than the hydroxyl groups.

Metal doping is widely used to tailor biochar adsorbents (Table S3). For instance, the bismuth-impregnated biochar (Bi_2O_3@HMDB), produced from slow pyrolysis of bismuth-doped H_2O_2-modified horse manure, reached approximately 99.7% U(VI) removal efficiency with a maximum adsorption capacity of 516.5 mg g^{-1} in solution. This performance is attributed to the existence of oxygen-containing functional groups, such as phosphates and carbonates, on biochar surface (Liao et al. 2022c). Doping of Bi_2O_3 greatly enhanced the elimination ability of biochar by inducing the deoxidation of soluble U(VI) species into insoluble U(IV) species. In this process, electrons and holes in the conduction and valance bands of Bi_2O_3 facilitated a redox reaction, converting soluble U(VI) into insoluble U(IV), while a portion of Bi^{3+} was transformed into Bi^{5+} during adsorption. Besides, iron compounds are commonly used for biochar modification. Magnetic biochar, with the advantage of easy separation after use, has been frequently studied for U(VI) mitigation/elimination. Using hydrothermal synthesis, iron-containing compounds such as siderite and $FeSO_4{\cdot}7H_2O$ combined with NaOH were used to deposit Fe_3O_4 onto the surface or into the pores of the modified biochar (Wang et al. 2018; Li et al. 2019). Alternatively, other researchers adopted co-precipitation of Fe(II) and Fe(III) (e.g., $FeCl_3{\cdot}6H_2O$ and $FeSO_4{\cdot}7H_2O$) to synthesize magnetic biochar (Hu et al. 2018), and achieved a maximum adsorption capacity of 323.56 mg g^{-1} for U(VI) from contaminated wastewater at pH 4.0 (Lingamdinne et al. 2022). Magnetic biochar containing iron oxide induces ion exchange and inner-sphere surface complexation with U(VI) and promotes reductive co-precipitation of U(VI) into U(IV). Modification with $FeCl_3$ has been shown to disperse numerous small particles on the rough biochar surface and increase its polarity (Dong et al. 2022). When comparing the efficiency of Fe(II) and Fe(III) in fabricating magnetic biochar, Fe(II)-based biochar exhibited superior adsorption performance for U(VI) species, even after five regeneration cycles (Liao et al. 2022c). The Fe(II) biochar formed a loose, folded layer structure coated with magnetic iron oxide, which remained stable in solution and enhanced U(VI) adsorption. In contrast, Fe(III)-based biochar produced Fe^{3+}-derived iron oxide that attached only to the surface, rather than integrating into the layer structure after calcination. This resulted in reduced magnetism and easier separation in solution. Biochar supported with nano zero-valent iron (nZVI) has been investigated to increase the U(VI) immobilization through reduction and precipitation. However, the required carbonization temperature to form nZVI nanosphere should be raised up to 900 °C (Ruan et al. 2022). nZVI-modified biochar, with Fe^0 particles on its surface, exhibited a synergistic effect on the adsorption and reduction of high-valent metal ions (Diao et al. 2018; Liu et al. 2018). Additionally, the biochar–nZVI composite has significant advantages in increasing the soil pH and organic matter (Qian et al. 2022). A phosphate-modified biochar supporting nZVI (PBC/nZVI) was synthesized by pretreating the corn stover biomass with ammonium polyphosphate, followed by post-synthesis through liquid-phase reduction (Tang et al. 2023). The material possessed an improved specific surface area and porous structure due to the introduction of polyphosphate, with nZVI particles uniformly distributed across the biochar surface. The aforementioned chemical treatments utilizing acid, base, organic substances, and metal compounds effectively tailor the surface properties and functional groups of biochar. These modifications facilitate more dispersed and abundant adsorption sites, enhancing its interactions with U species.

Biological modification makes a novel and environmentally friendly approach to synthesizing green and effective biosorbents, which enhances the functionality and selectivity of biochar for U removal. A biochar-based microbial agent was produced by immobilizing the microbial consortium containing *Bacillus subtilis*, *Bacillus cereus*, and *Citrobacter sp.* onto biochar, which demonstrated high efficiency in reducing soil U contamination (Qi et al. 2022). In aqueous solution, a composite trapping agent was prepared by blending *Leifsonia sp.* strains with biochar, which obtained 99.82% efficiency in removing U(VI) through U precipitation on the biosorbent surface (Ding et al. 2018). Another study employed microbial fermentation as a pretreatment approach to modify cotton stalk powder in a fermentor with elevated temperatures for 15 days before fabrication of biochar via hydrothermal carbonization (He et al. 2023). The results showed that the biochar fermented with *Aspergillus oryzae* presented the highest U(VI) adsorption capacity (100.31 mg g^{-1}) compared to other microorganism species (i.e., *Lactobacillus acidophilus*, *Bacillus licheniformis*, *Bacillus subtilis*, and *Saccharomyces cerevisiae).* Biological fermentation successfully tailored the biochar by increasing its surface area, porous structure, and functional groups, which interacted with aqueous U(VI) species through ion exchange by Ca^{2+} and complexation with phosphate groups (He et al. 2023). Additionally, *P. chrysogenum* mycelium was used in a study for loading polyamidoxime onto biochar, which exhibited superior permeability, porosity, and hydrophilicity, with a U extraction capacity of 211.35 mg/g from seawater (Wang et al. 2023b). After carbonization, the *P. chrysogenum* mycelium maintained an integrated structure, featuring massive fluffy hyphae with reduced diameter due to the loss of organic substances. The synthesized biochar composite exhibited a macroporous structure that facilitated the efficient transport of uranyl ions. Among the above diverse modification methods, the selection of the most appropriate approach for biochar promotion should consider the factors including biomass type, contaminant species, interfering substances, treatment scale, and other environmental conditions after remediation outcomes. Environmental impact is one of the most important perspectives to assess these approaches. For instance, chemical modifications may generate greater amounts of waste liquids that require further disposal, whereas physical modifications lead to less secondary pollution but require more energy inputs to achieve desirable properties.

4 Research advances on biochar remediation performance

4.1 Mechanisms on uranium decontamination by biochar-based materials

The mechanisms on U removal can be investigated using a wide range of advanced characterization techniques. For example, Fourier transform infrared (FTIR) spectroscopy provides supporting evidence for revealing the roles of oxygen-containing functional groups on biochar surface. Particle aggregation and the formation of U(VI)-complexes can be observed through scanning electron microscope (SEM) or transmission electron microscope (TEM) images. The N_2 adsorption–desorption isotherms offer valuable information about changes in specific surface area and porous structure. X-ray diffraction (XRD) can reveal the crystal structure of the material, while thermogravimetric analysis (TGA) can record its thermal stability. X-ray photoelectron spectroscopy (XPS) is a quantitative analytical technique to examine the electronic state of the elemental compositions. Comparing the relative area of peaks can demonstrate the participation of functional groups. High-energy-resolution fluorescence detection–X-ray absorption near-edge structure (HERFD-XANES) spectroscopy is an effective tool to offer information on the electronic structure and bonding of U atoms in solid material (Yomogida et al. 2022). These advanced techniques enable the comprehensive characterization of the physicochemical properties of biochar, ranging from morphology and structure to elemental composition, both before and after use. Such analyses facilitate a deeper understanding of the interaction mechanisms involved in U removal.

As shown in Fig. 4, the adsorption of aqueous U(VI) by biochar-based material involves different complex processes, including physical adsorption, surface complexation, and chemical reduction (Lyu et al. 2021b; Liao et al. 2023; Zheng et al. 2021). Particularly, chemical process

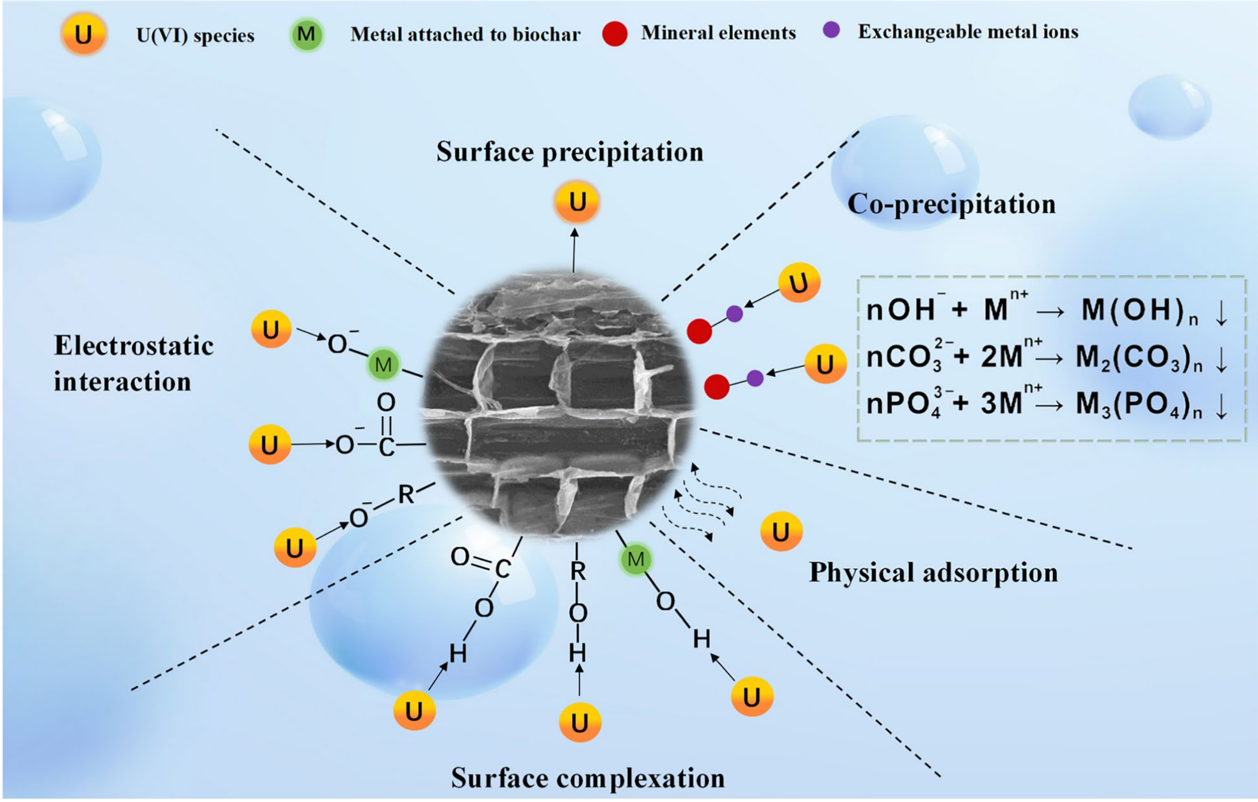


Fig. 4 Mechanisms on interactions between biochar-based materials and uranium

via monolayer uniform adsorption predominantly acts as the main mechanism (Albayari et al. 2021), in which electrostatic interactions and complexation play a dominant role. The negatively charged biochar surface can lead to a strong electrostatic interaction with positively charged U(VI) species, which is more favorable with oxidized biochars (Jin et al. 2018). The aqueous U(VI) adsorption by biochar is driven by the coordination of U(VI) with the abundant active groups (e.g., –COOH, –C=O, and –OH groups) on biochar surface, depending on species distribution and surface charge. Formation of inner-sphere complex takes place, which is minimally affected by salinity changes (Philippou et al. 2018). Morphological characterization of biochar before and after U(VI) removal in numerous studies has revealed the attachment of U(VI) species on biochar surface and formation of the complexes with its active sites. For example, a new FTIR spectra peak occurred at nearly 911 cm^{-1} after adsorption, which was attributed to the stretching vibrations of the $[U=O=U]^{2+}$ linear structure, indicating the incorporation of uranyl ions onto biochar (Ahmed et al. 2021b). As reported, U(VI) species are majorly bonded with surface oxygen on the carbon structure (Jin et al. 2018), which mainly involved functional groups such as hydroxyls and carboxylic acids (Guilhen et al. 2019). Besides, the aromatic groups with electron-rich domains on biochar were reported to interact with U species through π-π bonding and form stable complexes (Liu et al. 2021). A batch study of U(VI) adsorption onto biochar exhibited an H-type isotherm, which implied that binding of uranyl cations to biochar sites or pores is the dominant mechanism (Kumar et al. 2011). Therefore, surface complexation between U(VI) ions and diverse oxygenated functional groups (i.e., –COOH and –OH) on biochar surface predominantly contributes to U(VI) removal mechanisms.

Besides, the XRD pattern suggested the occurrence of uranium–carbonate complexes, indicating the complexation ability of CO_3^{2-} for uranium (VI) species during the adsorption process. Furthermore, based on FTIR and XPS analysis, it was found that oxygen-containing groups contribute significantly to the removal process by forming chemical bonds with U(VI) species (Liao et al. 2022b). Complexation between surface active sites and U(VI) species has been proven to be a significant mechanism, especially in the cases of biochar-based materials that have been modified with multiple functional groups like $-NH_2$ and –OH. Phosphorous-containing groups on biochar surface were also found to enhance the complexation with U(VI) in aqueous solutions (Tang et al.

2023). Phosphate, carbonate, and other structures, such as the strong covalent bonds of P–O–U, $-NH_2$, and –OH, depending on the feedstock biomass and modification methods, can significantly contribute to the complexation behaviour of biochar.

Intra-particle diffusion model was used to indicate the two major stages of U(VI) adsorption by amino functionalized biochar: the instantaneous adsorption stage and the final equilibrium stage (Lv et al. 2023). As reported, the adsorption process begins with uranyl ions moving rapidly toward the biochar surface, followed by a slower coordination reaction as uranyl ions enter the interior of the biochar due to limited adsorption sites. This finding is consistent with another study on magnetic biochar, where adsorption of U(VI) species adsorption commenced with a chemical reaction on the outer surfaces of the biochar, followed by the gradual diffusion of UO_2^{2+} ions into the interior of biochar until the internal adsorption sites saturated (Chen et al. 2023b). Additionally, a three-stage adsorption process was proposed in a study on biochar–magnesium silicate composites derived from orange waste (Narasimharao et al. 2023). Specifically, rapid U(VI) adsorption occurred as the initial stage due to the abundance of available active sites on the composite surface. This was followed by a slower adsorption phase, where the limited diffusion rate of U(VI) ions into the inner pores of biochar reduced the adsorption rate. Finally, the process reached a dynamic equilibrium state. These pieces of evidence conclude that chemical processes, rather than physical sorption, dominate the adsorption mechanism.

Moreover, other mechanisms have been reported in biochar-based materials after functional tailoring. In addition to surface functional moieties like hydroxyl and carboxyl groups, which are commonly mentioned in most studies, inherent minerals (e.g., quartz, phosphate, calcite) in biochar have been shown to participate in U(VI) adsorption through surface complexation, electrostatic attraction, and precipitation (Dai et al. 2020a). This emphasizes the significance of feedstock selection and mineral doping in the potential design of highly efficient biochar-based materials for U adsorption. In terms of Mg modified biochar, the adsorption of aqueous UO_2^{2+} primarily occurs via a micro-precipitation mechanism with minor surface complexation. Nano-MgO on biochar reacts with UO_2^{2+} to generate micro-precipitates (MgU_2O_7) with low molding degree or an amorphous shape (Hu et al. 2023). Ionization-precipitation accounts for U adsorption in magnetic biochar-hydroxyapatite composites, where the production of $Ca(UO_2)_2(PO_4)_2{\cdot}3H_2O$ was found based on XRD patterns of the material after U(VI) adsorption (Liao et al. 2023). This process is also observed when biochar is modified with other substances like chitosan and polyethyleneimine (Zhang et al. 2023a). The ionization-precipitation of calcium phosphate can be interpreted by the following Eqs. (1–2):

$$Ca_3(PO_4)_2 \rightleftharpoons 3Ca^{2+} + 2PO_4^{3-} \tag{1}$$

$$Ca^{2+} + 2PO_4^{3-} + 2UO_2^{2+} + 6H_2O \rightleftharpoons Ca(UO_2)_2(PO_4)_2 \cdot 6H_2O \tag{2}$$

For Bi_2O_3-doped biochar, the U removal involves the formation of steady compounds (with CO_2^{3-}, $-NH_2$, and –OH), precipitates (with PO_3^{4-}), ion exchange (with $Ca^{\ 2+}$), and redox reactions where U(VI) is converted to U(IV) (Liao et al. 2022c).

In terms of Fe-modified biochar, Fe-containing components such as Fe(0), Fe(II), oxygen-containing groups, and (hydr)oxides could lead to reduction and adsorption of U(VI) (Tang et al. 2023). Nevertheless, the reduced U(IV) could be vulnerable to reoxidation into U(VI), so both valence forms of U could be found through XPS analysis. A study on U(VI) removal via magnetic biochar observed the existence of U–Fe and U–U shells, indicating the adsorption mechanisms involving inner-sphere coordination and reductive co-precipitation of U(VI) into U(IV) at low pH (Hu et al. 2018). The redox process of U(VI) can be described by the following Eq. (3):

$$2Fe^{2+} + UO_2^{2+} \rightleftharpoons 2Fe^{3+} + UO_2(s) \tag{3}$$

The soluble U(VI) shifts into less soluble and more stable U(IV), which is more vulnerable to precipitation or adsorption onto biochar. Magnetic biochar also offers the advantage of easy separation from aqueous media after use, addressing challenges associated with its small size and high dispersion, thus making it more practical for U(VI) decontamination applications.

In recent years, biochar has received considerable attention as a soil amendment or stabilizer in remediation of U tailings and other associated tailings (e.g., Cu and Au tailings) containing U compounds (Liu et al. 2022a). By regulating metal solubility, biochar can transform contaminated sites into growth media for native plants. Moreover, biochar-based materials with bulking effects can reduce the bulk density of metal mine tailings and improve the abundance of functional microbial communities for organic matter decomposition. The addition of biochar has been proved to efficiently enhance the stabilisation of U-bearing minerals through direct adsorption onto biochar surfaces and by enhancing U sequestration via the formation of secondary Fe-minerals (Liu et al. 2022a). As shown in the Fig. 5, biochar amendments effectively reduce the bioavalability of U, inhibiting its uptake by plant roots and translocation to other

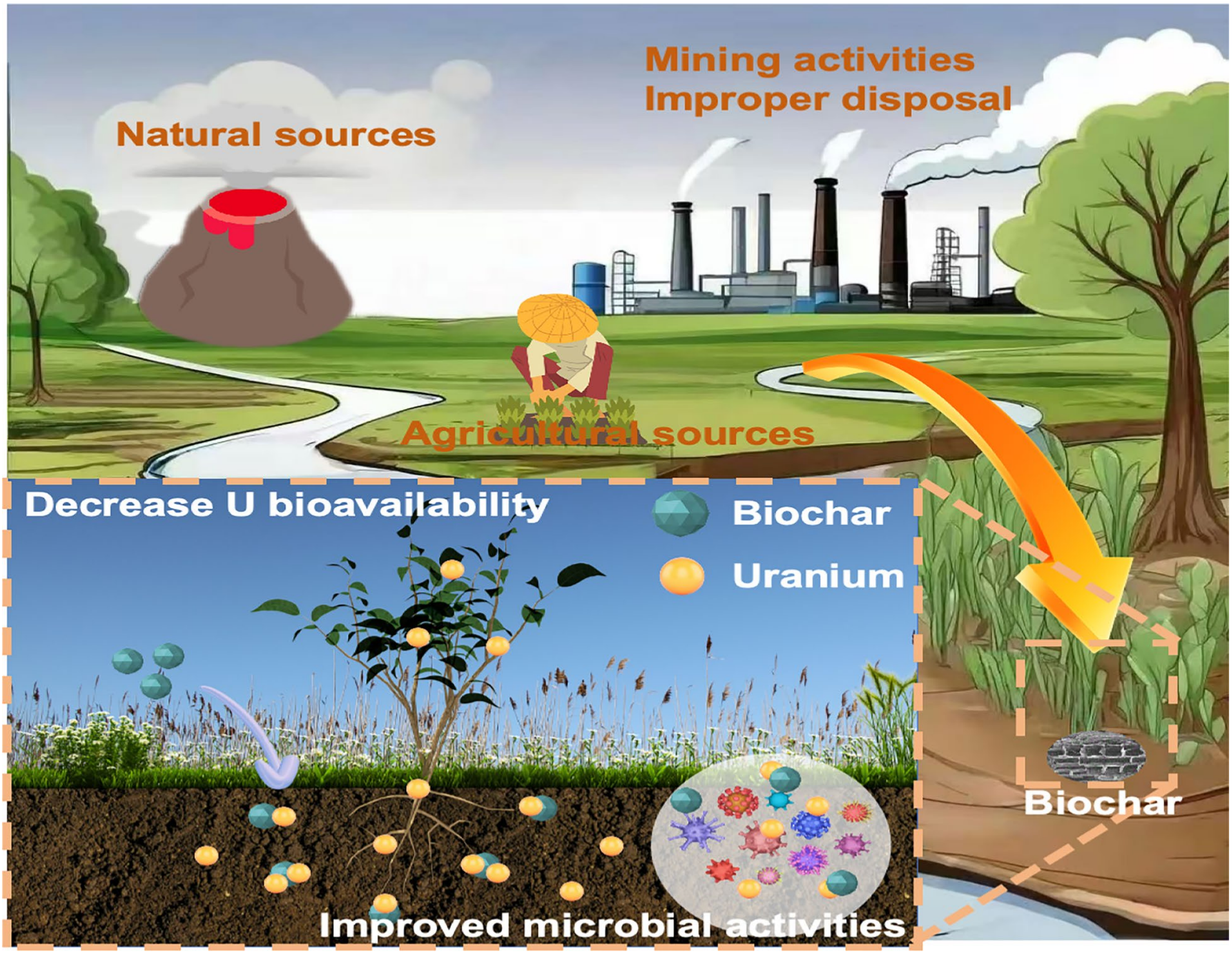


Fig. 5 Application of biochar-based materials in immobilization of uranium in the soil

plant organs (Huang et al. 2024). Beyond increasing soil organic matter and cation exchange capacity, biochar-based microbial agents have been found to improve the structure and function of rhizosphere microbial communities with the enhanced tightness, complexity, and stability (Qi et al. 2022).

4.2 Kinetics, isotherms, and thermodynamic studies of uranium adsorption

In thermodynamic studies, critical indicators including the standard enthalpy change (ΔH^o), standard entropy change (ΔS^o), and standard Gibbs free energy change (ΔG^o) are used to describe the thermodynamic properties of adsorption processes. Most studies report that adsorption of U(VI) is usually endothermic, entropy-driven, and of a random nature (Chen et al. 2023b). This conclusion is supported by the observation of negative ΔG^o values, along with positive ΔH^o and ΔS^o values, which are attributed to competitive dissolution in aqueous media (Ahmed et al. 2021a, 2021b). These results imply that the adsorption of U(VI) onto biochar-based materials is a spontaneous process at room temperature. However, deviations from this general trend have been observed. For instance, a study on oxidized biochar revealed that the U(VI) adsorption is exothermic at pH 5.5 (with negative ΔH^o), but becomes endothermic at pH 3, suggesting that adsorption mechanisms vary with pH (Liatsou et al. 2017).

Kinetics models are often employed to investigate the effect of reaction time on sorption properties. In most studies, the pseudo-second-order model provides a better fit for the biochar adsorption process, as indicated by larger coordination coefficients (R^2) compared to the pseudo-first-order kinetic model. This pattern is consistent with findings for other carbon-based nanomaterials for removing organic contaminants (Mahmoud et al. 2020). The suitability of the pseudo-second-order model suggests that chemical processes are the rate-controlling mechanism for U(VI) removal, with sorption through diffusion or surface complexation occurring after rapid initial adsorption steps (Ahmed et al. 2021a). For instance, a study on U(VI) removal using amino functionalized biochar derived from lotus seedpods reported R^2 values close to 1.0, further supporting the dominance of chemical adsorption (Lv et al. 2023). However, in other cases, the pseudo-first-order kinetic model aligns better with the experimental data for certain biochar samples, implying that physical adsorption may be the rate-controlling step depending on the specific biochar structure (He et al. 2023). Similar cases of better alignment with the pseudo-first-order-model were found for phosphate-modified biochar supporting nZVI composites (Tang et al. 2023). Although uranyl ions are primarily adsorbed onto biochar through chemisorption involving acidic surface functional groups like hydroxyl and carboxylic groups, physisorption also plays a role due to the large specific surface area of biochar (Guilhen et al. 2021). A study modifying macauba endocarp-derived biochar by thermal activation demonstrated that functional group loss during thermal decomposition reduced the surface acidity and polarity of the biochar. Nevertheless, a U(VI) removal efficiency of up to 99.2% was achieved at pH 3 with a biochar dosage of 10 g L^{-1}, ascribing to the physisorption process induced by an increased specific surface area and aromaticity of the activated biochar (Guilhen et al. 2021). These findings suggest that both chemisorption and physisorption contribute to the interaction between U(VI) and biochar-based materials, with the balance between these mechanisms influenced by the structure, surface properties and surrounding environmental conditions of biochar.

Langmuir adsorption model is the most frequently employed isotherm model to depict U(VI) removal by biochar materials. In most cases, this model shows a higher correlation coefficient (R^2) than that from the Freundlich model. This implies that Langmuir model is more suitable for describing the adsorption behaviour of U(VI) on biochar, in which the adsorption process is monolayer (single layer), and U(VI) ions are evenly dispersed on biochar surface with uniform binding energy and without any interaction between the adsorbate molecules (Li et al. 2019; Sun et al. 2022). Nevertheless, a study on various biochars derived from distinct feedstocks revealed that the Langmuir model performed better for ash poor biochar (e.g., corn cob biochar) with a more homogeneous surface structure, while the Freundlich model was more suitable for ash-rich biochar (e.g., sewage sludge biochar) with a more heterogeneous surface structure (Dai et al. 2020a, b). Moreover, the ash-poor biochar is more vulnerable to modification, with promoted efficiency in U(VI) adsorption through oxygenation of biochar, for example, via thermal air treatment. Fitting sorption data to the Freundlich isotherm implies the presence of varied sorption modes. A study modeled the adsorption and fixation of U(VI) by bone-derived biochar from aqueous media, employing a Freundlich adsorption isotherm coupled to a reversible first-order kinetic equation (Ashry et al. 2016). In terms of δ-MnO_2 modified biochar for U(VI) adsorption, the Freundlich model exhibited a better fit compared with the Langmuir model, suggesting multi-layered adsorption on a heterogeneous surface (Liu et al. 2023a, b). Such discrepancies might depend on the surface morphology or structure of the biochar absorbent, which is derived from specific feedstock biomass and modification processes. The intra-particle diffusion model can be utilized to depict the process and reveal the rate-limiting steps for for U(VI) adsorption on biochar, which was proved as a particle diffusion process (Liu et al. 2023a, b; Zhang et al. 2023a). It was suggested that the sorption of aqueous U(VI) on the activated biochar consists of two stages, where the first relatively fast step corresponds to the sorption process on the outer-surface of biochar, while the second slower step involves the sorption on biochar inner surface, resulting from the diffusion of the bulky U(VI) species into the micro-channels (Hadjittofi and Pashalidis, 2015). This also corresponds to another study employing biochar supported co-nanoparticles of nickel and cobalt oxides for U(VI) sorption, where the available active groups and reaction sites on biochar assured strong surface complexation in the first rapid stage, and afterwards, it took longer time for U(VI) to bond with inside active sites of biochar in the second slow stage (Naggar et al. 2019).

In some studies, the Redlich-Peterson isotherm model, which is a hybrid isotherm incorporating functionalities of both the Langmuir and the Freundlich ones, was found to best fit the experimental data on biochar adsorption of U(VI). This suggests a hybrid adsorption mechanism with heterogeneous adsorption sites to explain the adsorption process of biochar, especially for modified biochar (Guilhen et al. 2021). A study demonstrated that three-parameter models, such as Sips and Redlich-Peterson, by integrating three rather than two parameters, provided better fitting compared with two-parameter models (e.g., Langmuir, Freundlich and D-R isotherm) (Yin et al. 2022). It was indicated that Sthe ips and Redlich-Peterson models could be viewed as extensions of the Langmuir model at low U(VI) concentrations, implying monolayer adsorption behavior as well (Wang and Guo 2020). Besides, the Elovich model fitted well with the sorption of UO_2^{2+} by super-hydrophilic nano-MgO biochar and magnetic biochar-supported nano-hydroxyapatite in aqueous solution, evidencing the main role of chemisorption during the interaction (Hu et al. 2023; Liao et al. 2023).

4.3 Efficiency and influencing factor of uranium removal by biochar

The performance of U removal is usually assessed by removal efficiency and adsorption capacity (Table S4). As exhibited, the adsorption capacities of biochar-based materials for U species vary from 27.2 to 1723.5 mg g^{-1}. The highest U(VI) adsorption capacity, achieving 1723.5 mg g^{-1} and 99.4% adsorption efficiency, was achieved using a magnetic biochar–hydroxyapatite composite. This material was fabricated through a series of complex processes, including biomass activation, pyrolysis, oxidation, and magnetisation with nickel chloride (Liao et al. 2023). This biochar material maintained 96.3% uranium removal efficiency even after eight cycles of recycling. Both endopathic factors of the biochar material (surface area, porosity, and mineral content) and exopathic factors (e.g., pH, dosage, and other existing ions) in the solution or soil environment can determine the efficiency on uranium removal.

Therefore, engineering and modifying biochar are critical for designing materials with highly dispersed nanoparticles on surface and more available active sites. The adsorption performance of biochar is closely linked to its surface properties (such as specific surface area and functional groups, which can coordinate UO_2^{2+} ions with π electrons (C–C), forming stable organo-metal complexes). A large surface area with a porous structure is beneficial to cation exchange with H^+ and other metal ions (e.g., Ca^{2+}, Mg^{2+}, Na^+, and K^+), thus retaining metal(loid)s in the porous structure (Liu et al. 2022a). For instance, bamboo-derived biochar modified with phosphate groups obtained 781.02 mg g^{-1} adsorption capacity within 2 h and demonstrated 70.35% selectivity for U(VI) in a multi-ion solution (Chen et al. 2023c). The surface electronegativity of the biochar produced via HTC has higher affinity towards ions with high valence and large charge through Coulomb interactions. Moreover, the $-PO_4$ modified biochar showed high affinity for U(VI) due to the strong and stable coordination bond formed between U(VI) and $-PO_4$ groups on biochar. Additionally, UO_2^+ and $-PO_4$ can act as Lewis acids and bases, respectively, forming stable complexes (Chen et al. 2023c). Oxygenation of biochar in air can remarkably improve its surface area, increase oxygen-containing groups, and enhance mesoporosity. For example, the U(VI) adsorption capacity of ash-poor corn cob biochar elevated by 137% (from 69 to 163 mg g^{-1}) after thermal air treatment (Dai et al. 2020a). The reduced pore size, increased surface area, and enriched functional groups after thermal air treatment accounted for more accessible adsorption sites for U(VI) adsorption onto biochar. In soil media, one of the most significant factors that determine the adsorption efficiency and applicability of biochar-based materials is dissolved organic matter (DOM). For instance, fulvic- and humic-like substances in biochar preferentially combine with U(VI), promoting its adsorption (Guo et al. 2023a). Thermal air oxidation can alter the intrinsic DOM of biochar, such as its structure, fluorescent components, and elemental composition, thus increasing its binding properties as well as chemical stability of DOM-U(VI) complexes (Guo et al. 2023a). Currently, research on the biochar application in remediation of uranium-contaminated soil is limited, and most studies remain at the laboratorial stage.

In addition to the properties of biochar material, the environment conditions also significantly influence the adsorption process. Several factors, including solution pH, initial U(VI) concentration, ionic strength, contact time, and temperature, affect U(VI) removal efficacy (Zhang et al. 2013). Among these, pH is the most critical factor, as both the surface charge of biochar and the distribution of U(VI) species are strongly pH-dependent (Ahmed et al. 2021b). At pH values below 7, uranium predominantly exists as positively charged ions, such as UO_2^{2+}, $(UO_2)_2(OH)_2^{2+}$, UO_2OH^+, $(UO_2)_3(OH)_5^+$, and $(UO_2)_4(OH)_7^+$ (Liao et al. 2022b). Simultaneously, the surface of biochar-based materials is primarily negatively charged. At $pH < 4$, the extractable forms (e.g., UO_2^{2+}, $UO_2(OH)^+$, and $(UO_2)_2(OH)_2^{2+}$) dominate (Albayari et al. 2021). Among these, UO_2^{2+}, as the most abundant species (accounting for more than 90%), can easily bind to the negatively charged biochar surface through strong electrostatic interactions and the formation of stable complexes. Oxygen-containing functional groups on the biochar act as sorption sites for deprotonation and complexation with U(VI) (Hu et al. 2020). As the pH increases above 4, a great amount of UO_2^{2+} hydrolyzes to form larger, positively charged species such as UO_2OH^+, $(UO_2)_2(OH)_2^{2+}$, $(UO_2)_3(OH)_5^+$, and $(UO_2)_4(OH)_7^+$. These larger ionic forms may encounter steric hindrance, partially occupying the binding sites and slightly reducing uranium removal efficiency (Hu et al. 2023). At pH values higher than 8, negatively charged U(VI) species (e.g., $UO_2(OH)_3^-$and $(UO_2)_3(OH)_7^-$) are found in the solution (Li et al. 2019). These species experience electrostatic repulsion from negatively charged biochar surfaces, leading to a noticeable reduction in U(VI) sorption. Additionally, at higher pH levels, hydroxyl ions (OH^-) compete with UO_2^{2+} for binding sites, weakening the interaction between U(VI) species and the biochar surface (Liao et al. 2022d).

The environmental pH plays a crucial role in optimizing the performance of biochar-based materials for uranium adsorption. Studies have identified pH values between 4 and 6 as the optimal range for removal in most biochar systems. For instance, when the pH ranged from

5 to 8, U(VI) species mainly existed in the less positively charged $(UO_2)_3(OH)_5^+$ and $(UO_2)_4(OH)_7^+$ forms with slightly reduced adsorption efficiency (Chen et al. 2023c). At pH 2, the active competition between U(VI) species and H_3O^+ in the aqueous solution resulted in low adsorption performance (Liao et al. 2022b). A similar conclusion was found at the peak of pH 3.5 (Liao et al. 2023). Further increases in pH caused a slight reduction in adsorption capacity as well as efficiency, since the hydrolysates of uranyl ions (e.g., UO_2OH^+ and $(UO_2)_3(OH)_5^+$) formed in the solution, reducing the response of the active site to U(VI) species. Another study on arecanut husk fiber biochar indicated that the optimum pH is 6, where uranium domiantly presents in UO_2^{2+}, UO_2OH^+ and $(UO_2)_2(OH)_2^{2+}$ forms, promoting the electrostatic interactions (Dhanya and Rajesh 2023). This is in agreement with other research that also supposed the dividing line of pH effects was 6, indicating that aqueous U(VI) exclusively exists as the positively charged species (e.g. UO_2^{2+}, UO_2OH^+) when $pH<6$, and the adsorption process is controlled by cation exchange processes as indicated in Eq. (4) (Philippou et al. 2018).

$$R-CH_2OH+ UO_2OH^+ \leftrightarrow R-CH_2O-UO_2OH + H^+ \tag{4}$$

At higher pH values, deprotonation reactions on the biochar (Eq. (5)) result in a negatively charged surface with ample binding sites (Li et al. 2019). Meanwhile, the formation of the solid phase $UO_2(OH)_2$ was found at pH around 6, favoring the hydroxy deprotonation (Philippou et al. 2018).

$$-ROH_{(surface)} + OH^-_{(aqueous)} \leftrightarrow -RO^-_{(surface)} + H_2O \tag{5}$$

Therefore, the primary adsorption mechanisms are surface complexation and reduction of U(VI) species, where U(VI) is bound to biochar-based materials through formation of inner-sphere complexes. Moreover, modification by oxidation can tailor the biochar with carboxylic moieties that have a profound affinity for the UO_2^{2+} cation, where the interaction between the UO_2^{2+} cations and carboxylic surface groups on biochar follows Eq. (6) (Philippou et al. 2018).

$$R{-}COOH + UO_2^{2+} \leftrightarrow R{-}COO{-}UO_2^+ + H^+ \tag{6}$$

The above finding is consistent with the speculations from another study, which suggested different mechanisms occurring at pH 3 and 6 for U (VI) removal by a Fe_3O_4-loaded oxidized biochar (Philippou et al. 2019). An elevation of temperature from 25 to 50 °C at pH 3 was proved to cause an increase in the maximum monolayer adsorption capacity of the material. Contrarily, at pH 6, the raised temperature negatively influenced the adsorption capacity due to the formation of different surface species at pH 3 and 6, as well as the associated stability of the U(VI) species present on the biochar surface. It is supposed that ternary surface complexes form at higher pH owing to more OH^- and CO_3^{2-} in the solution (Philippou et al. 2019). In this context, the surface charges of biochar significantly influence U(VI) adsorption behaviour. Research has shown that when $pH<6$, the adsorption of uranium (VI) is controlled by inner-sphere surface complexation, whereas at 6–10, the process is mainly governed by outer-sphere surface complexation (Zou et al. 2023). This fact determines the role of ionic strength, which influences the sorption related to electrostatic interaction. In the acidic pH range, particularly from 5 to 6, biochar adsorption of U(VI) from aqueous solution is significantly facilitated. Medium acidity is beneficial for uranium adsorption by adjusting the distribution of uranium ions, as well as the protonation – deprotonation reactions of biochar functional groups and surface charge (Akl et al. 2021). Under circumneutral pH conditions, the U(VI) speciation is primarily manipulated by anionic uranyl carbonate species [e.g., $(UO_2)_2CO_3(OH)^{3-}$, $UO_2(CO_3)_3^{4-}$and $UO_2(CO_3)_2^{2-}$], causing the decline in adsorption capacity onto biochar due to electrostatic repulsion when pH exceeds 6 (Kumar et al. 2011). In summary, the optimum pH in different biochar-based adsorption systems mostly lies around 4–6, according to numerous previous studies. This implies the conclusion that an acidic environment is conducive to uranium adsorption. Therefore, the adsorption performance of aqueous U(VI) by biochar-based materials can be optimized by regulating the solution pH.

The increase of biochar dosage can enhance the U(VI) adsorption efficiency to some extent, since the available adsorption sites and surface area increase with higher doses. However, an excessive dosage of biochar adsorbents may lead to more unsaturated active sites during the adsorption process and uranium deficiency regarding to the available sites, resulting in decreased adsorption capacity. Similarly, the initial concentration of the contaminant also affects removal efficiency. A study observed elevated U(VI) adsorption capacity but reduced removal efficiency when the initial U(VI) concentration increased (Akl et al. 2021). At low initial concentrations, the U(VI) species are easily adsorbed due to the abundance of binding sites on the biochar surface. With higher concentrations, a larger driving force overcomes the mass transfer resistance between U(VI) and biochar, increasing the adsorption capacity and rate. However, as the initial U(VI) concentration further increases, most binding sites become occupied, leaving limited active sites available. In this case, the removal percentage decreases while the adsorption capacity plateaus. Therefore, determining an optimum dosage is critical for specific scenarios of uranium adsorption.

Minerals in biochar can potentially contribute to U(VI) adsorption in solution (Dai et al. 2020b). For example, a high Ca content in biochar was found to promote U(VI) adsorption via ion exchange (He et al. 2023). This agrees with another study that used biochar-supported nano-hydroxyapatite materials for U(VI) removal and found trace amounts of Ca^{2+} in the solution after adsorption (Liao et al. 2023). Interestingly, the existence of phosphate was shown to enhance the U immobilization through the formation of P–U complexes, with the reaction sequence of U, biochar adsorbent, and P affecting the U immobilization performance (Ruan et al. 2022). In this case, desorption of uranium is negligible due to the generation of P–U precipitate. The efficiency of U immobilization is greatly improved in the presence of phosphate, forming UO_2HPO_4 at acidic pH values ranging from 4 to 8. This information provides new insights into feedstock selection or mineral doping for the fabrication of biochar with improved properties.

The selectivity of U(VI) removal can be evaluated by considering the interference of competitive ions in solution. Studies have found that the adsorption process is independent of the ionic strengths of $NaClO_4$, NaCl, and $NaNO_3$ in the solution. This suggests the inner-sphere surface complexation between uranyl and biochar, since outer-sphere complexes are more vulnerable to changes in the solution ionic strength compared with inner-sphere complexes (Ahmed et al. 2021b; Li et al. 2019; Xia et al. 2022). This is probably because low charge density and bigger ionic size of Na^+ result in stronger interactions between other Na^+ ions and the surrounding water molecules rather than biochar. This finding is consistent with a study on N-doped biochar, where interfering ions, such as Cl^-, HCO_3^-, NO_3^-, ClO_4^-, SO_4^{2-}, PO_4^{2-}, K^+, Na^+, Ca^{2+}, Cu^{2+} Mg^{2+}, Zn^{2+}, and Fe^{2+} had negligible effects on the adsorption rate of U(VI) (Guo et al. 2023b). Nevertheless, it has been reported that the adsorption behavior of U(VI) over biochar is independent of the concentration of coexisting cations with low valence, except for Ca^{2+}, which competes for active sites and decreases adsorption efficiency for U(VI) (Liao et al. 2023). Moreover, the presence of CO_3^{2-} facilitates the formation of U-CO_3^{2-} complexes, thus weakening the response of active sites to U(VI) species (Liao et al. 2023). With increasing concentration of Na_2CO_3, the adsorption capacity of U(VI) decreases due to electrostatic repulsion between U(VI)–carbonate species and negatively charged surface of biochar. The presence of Na_2CO_3 decreases the amount of U(VI)–hydroxyl species and increases the amount of carbonate species, where both positively and negatively charged U(VI) species [e.g., $UO_2(CO_3)_2^{2-}$and $(UO2)_3(CO_3)_6^{6-}$] are observed at pH 4–8 (Li et al. 2019). Besides, the U(VI) adsorption is significantly improved with higher concentrations of humic acid at $pH > 6.0$. This can be explained by the diverse reactive functional groups (e.g., carboxyl, alcohol or phenolic hydroxyl, quinone or ketone carbonyl) on the humic acid surface, which actively participate in the adsorption, complexation, and redox reactions involving U(VI) (Li et al. 2019).

4.4 Regeneration of biochar adsorbent

Regeneration and recovery of biochar adsorbent after adsorption cater for the current concept of sustainable development by minimizing the waste and elevating the economic value of sythesized materials. As a heterogeneous carbon-based material, biochar can be separated and recycled over multiple adsorption–regeneration cycles, especially those modified with magnetic properties. Examining biochar regeneration efficacy is of great significance in assessing the technical feasibility, resource utilization, and economic benefits. For example, regeneration via solvents can assure additional adsorption cycles, thus elevating the practical application value of biochar. Most biochar-based materials could achieve good reusability after five to six adsorption–desorption cycles, in spite of some decline in adsorption capacities. Declined capacity can be explained by their decrease in surface area and pore volume, weakened functional groups, and leaching of active sites on the surficial layer of biochar during the soaking process with regeneration reagents (Wang et al. 2018). Common regeneration reagents usually include acids, alkalis, and organic solvents such as HCl, NaOH, and Na_2CO_3. As reported, 1.0 M Na_2CO_3 and 0.1 M H_2O_2 can be used to elute the bound uranium during adsorption–desorption processes (Wang et al. 2023b). Several cycles of reuse have proven biochar to possess excellent durability, suggesting its high availability due to a facile fabrication approach using economic and renewable raw materials. Chemisorption process is more easily influenced by the HCl soaking during the regeneration for biochar than physisorption (Wang et al. 2018). A study compared the efficacy of NaOH and HCl as the regeneration agents for biochar absorbents and found NaOH achieved better desorption ability (81.77%) over five cyclic processes (Sen et al. 2021). NaOH can efficiently participate in the regeneration of hexavalent metal ions from activated carbon material, facilitating the desorption of U(VI) in aqueous solution. Even though the strong elution ability of HCl solution also facilitates biochar adsorbent reuse, which implies that the competitiveness of H^+ for active sites is greater than that of U(VI) species at low pH (Liao et al. 2022b). The adsorbed U(VI) on biochar can be substituted by H^+ through ionic exchange and react with H_2O_2 to facilitate desorption.

When using the mixture of HCl and H_2O_2, the U(VI) recovery rate can reach 98.3% via chemical reaction and ionic exchange (Zhang et al. 2023a). Magnetic biochar modified with Fe_3O_4 is particularly suited for regeneration due to its stable magnetism. Excellent recyclability has been validated by magnetic hydrothermal biochar, which retained over 83% of its adsorption capacity for U(VI) after three adsorption–desorption cycles (Chen et al. 2023b).

Since U is a critical and useful resource, U recovery from waste materials is highly encouraged to address both environmental protection and sustainable development. Desorption is usually used to recycle U(VI) from nuclear wastewater. For example, an excellent desorption efficiency of 94.5% was achieved for N-doped biochar in the presence of Na_2CO_3 as a desorbent. This regenerated the active sites (graphitic N) through ion exchange with U(VI) species and achieved excellent adsorption–desorption performance after 12 cycles (Guo et al. 2023b). A study investigated mineralization recycling of biochar after adsorption of aqueous UO_2^{2+} by sintering waste biochar at 750 °C for 3 h. It was revealed that, after mineralization recycling, uranyl ions were transformed into U_3O_7, U_3O_8, and U_2O_5 (Hu et al. 2023). These components, which exist in uranium mines, could be further processed into nuclear fuel, which showed great prospects for resource recovery. Further studies on economic feasibility and life cycle assessment are encouraged to evaluate the carbon footprint of biochar regeneration processes.

5 Perspectives for future research work

For biochar modification, more exploration is required to figure out the roles of reagent form, concentration, environmental conditions, and timing for agent addition, meanwhile building a more reliable and scientific understanding that linked to application performance. For example, to prepare Mn-modified biochar, a study adopted an in situ deposition technique for MnO_2 loading (Dai et al. 2020b), while another study used post-modification by mixing biochar with manganese nitrate ($H_8MnN_2O_{10}$) and potassium permanganate ($KMnO_4$) solutions (Liu et al. 2023a, b), obtaining U(VI) adsorption capacities of 246.3 mg g^{-1} and 61.53 mg g^{-1}, respectively. Even though the addition of other activation regents can facilitate the modification process and produce biochar with a more sophisticated structure, secondary pollution and feasibility for manufacture must still be further assessed. Exploration into the environmental conditions is essential to optimize the potential of biochar performance, such as the effects of pH and salinity. This can rule out adverse external factors that affect adsorbents with distinctive physicochemical properties. Besides, new perspectives could focus on biochar-induced advanced oxidation processes for treating radioactive and highly toxic heavy metals. Currently, most research is based on laboratorial simulations employing self-made aqueous solutions or soils, and few studies focus on field trials. More efforts are required before application of biochar-based materials on in-situ U remediation. For example, it is supposed to comprehensively evaluate the environmental risks of biochar, especially chemically modified biochar, since improper disposal of excessive nitrogen and phosphorus could result in water eutrophication. Metal leaching should also be considered for metal-impregnated biochar. Long-term stability is critical to avoid leaching of the adsorbed U species back into the water or soil solutions, which requires strong and stable complexation via active functional groups on biochar. These factors might affect the feasibility for its application in practical treatment of U-containing wastewater or contaminated soil. Currently, studies related to safety evaluation of such biochar-based materials are lacking, especially regarding long-term stability under variable conditions, aging, and the leaching of potentially toxic components. In large-scale remediation, homogeneous biochar properties must be assured during manufacturing, and biochar addition dosage and rate should be carefully determined. It is also important to shed light on the sites to be remediated and evaluate energy input before designing the optimum parameters for remediation. Hence it is encouraged to deeply investigate the biotoxicity and ecological impacts of the biochar materials before large-scale application.

The criteria for selecting proper U remediation techniques should be site-specific, depending on an integrated analysis of the multitude of geographic and operational conditions. These factors can affect remediation performance and the technical feasibility of treatment approaches. The adopted remediation technique should be consistent with each environmental medium. Multidisciplinary approaches are encouraged to evaluate and develop the decontamination process. For instance, machine learning (ML) methods are drawing increasing attention as promising tools for predicting adsorption efficiency and capacity. ML can reveal complex nonlinear relationships and interaction patterns in biochar-based materials. Algorithms such as linear regression, support vector regression, random forest, and multilayer perception artificial neural networks are being applied (Da et al. 2022). Artificial intelligence (AI) can also be utilized to adjust the adsorption variables and biochar feedstock properties to obtain optimum performance in metal removal (Lakshmi et al. 2021). Such technologies can avoid excessive experimental resource consumption and efficiently predict the practical performance, promising to reveal the key factors in specific steps. Therefore, future research integrating emerging information technology can provide sufficient scientific information and useful guidance for efficiently designing biochar-based materials for further improving the performance in U adsorption.

Nevertheless, compared with studies on uranium removal from water, research on remediation of uranium-contaminated soil using biochar-based materials is significantly less developed. Soil remediation is much more difficult, time-consuming, and affected by more complicated environmental factors, which expect more research attention and breakthroughs. For example, in cases of hybrid contamination with other pollutants (e.g., emerging contaminants) in complex environmental media, whether uranium species would cause synergistic or antagonistic effects with other compounds remains unknown. Competitive sorption with biochar-based materials may also impact the immobilization of uranium. Soil compositions, microbiota, and plant coenobium can make a difference. Therefore, field trials are requested to monitor the long-term performance of biochar before practical application in real-world scenarios. Besides, considering the resource recovery and sustainable development, it is essential to put more research effort to separate and recycle uranium during the decontamination process. In this regard, biochar-based materials, as porous and renewable carbonaceous materials, show great prospect in reusability and recyclability, which deserves further explorations, as illustrated in Fig. 6.

6 Conclusion

Biochar has been proven to be a cost-effective and environmentally friendly material that can be promisingly applied for uranium decontamination in water and soil. Modification of biochar by thermal treatment, mineral doping, metal impregnation, and addition of other organic substances can enhance biochar, making it rich in active sites that can actively participate in binding with uranyl ions. Most uranium adsorption by biochar-based materials is spontaneous and endothermic, including some key mechanisms such as reduction, complexation, precipitation, and electrostatic attraction. The efficiency and adsorption capacity are highly dependent on the physicochemical properties of biochar, such as surface oxygen-containing groups and mineral contents, as well as the conditions like solution pH and ionic strength. A great number of studies have verified the feasibility and efficiency of recycling waste

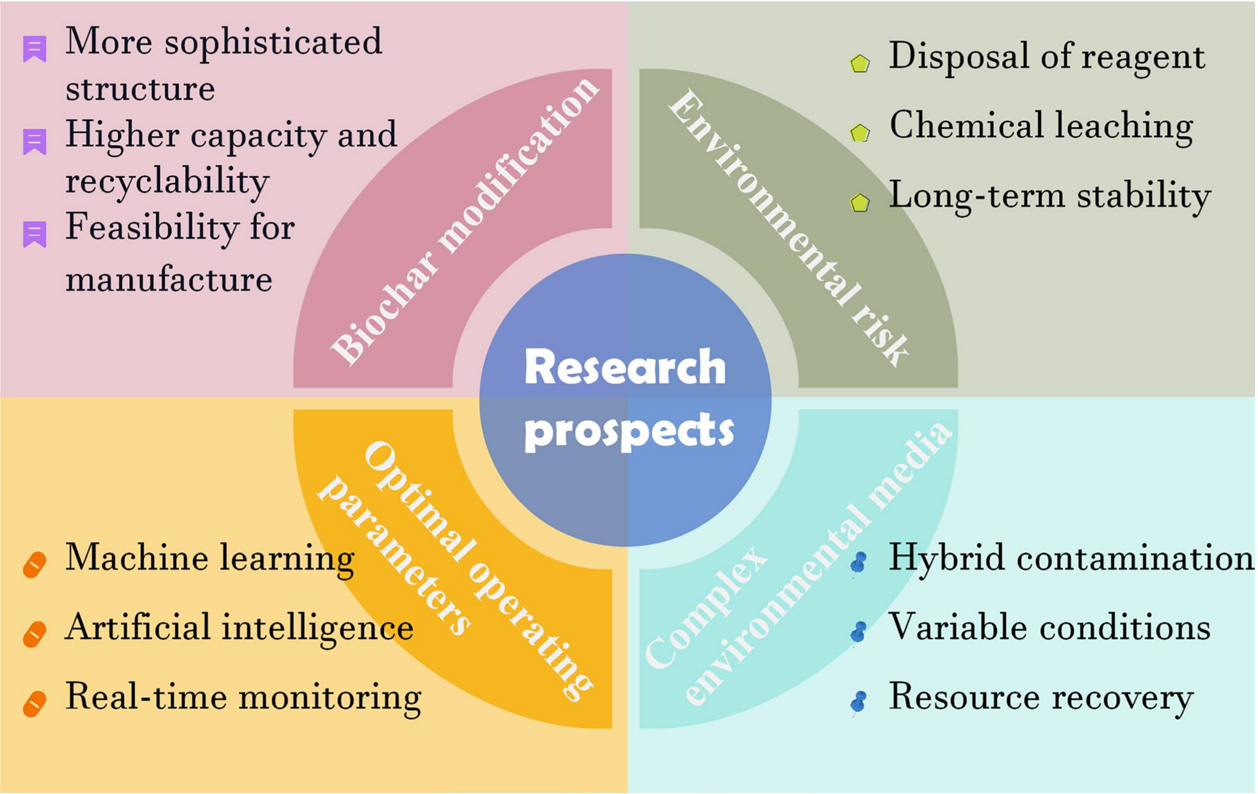


Fig. 6 Future research prospects for uranium decontamination by biochar-based materials

biomass for production of biochar-based materials with tailored properties. Such economic and environmentally friendly bio-materials have been extensively reported for removing uranium (VI) from aqueous solutions or soils with satisfactory adsorption capacities, suggesting great potential for practical applications in remediation of uranium-contaminated environmental media. Future studies are suggested to explore the remediation mechanisms under more complex and variable conditions, and also evaluate the effectiveness during large-scale production and application of biochar. It is recommended to focus on in-depth scientific knowledge for improving the biochar qualities by optimizing the conditions of biochar synthesis and modification, and combining the key properties that drive highly efficient uranium remediation. Therefore, this work highlights the function-oriented design of novel biochar-based material for U removal and provides scientific insights into the feasibility and viability of waste recycled materials in addressing uranium remediation in contaminated water and soil.

Supplementary Information

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Additional file 1.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Xinni Xiong, Juan Liu, Tangfu Xiao, Ke Lin and Jin Wang. Visualization was performed by Yaole Huang, Pengyuan Deng and Haiyao Hu. The first draft of the manuscript was written by Xinni Xiong and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Data availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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