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Biochar

REVIEW

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Highly selective separation of uranium by biochar-based porous materials through sorption, precipitation, photocatalysis, and electrocatalysis strategies

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Abstract

The fast utilization of nuclear energy requires the preconcentration and separation of uranium (U(VI)) from different kinds of water solutions, which is crucial for the sustainable development of nuclear power plants. Efficient recovery of U(VI) from different systems through the strategies of sorption, (co)precipitation, photocatalysis, electrocatalysis, etc., has been extensively studied. Among the studied materials, biochar and biochar-based porous materials exhibit potential real applications in U(VI) selective separation from solutions because of their easy synthesis at low cost on a large scale, eco-environmental friendliness, high surface areas with abundant special functional groups for strong binding of U(VI) ions and high stability/reusability. The selective separation of U(VI) is primarily governed by ligand-specific coordination (e.g., amidoxime and phosphate groups), surface charge-dependent electrostatic interactions, and redox transformation pathways under catalytic conditions. Herein, the applications of biochar and biochar-based porous materials for efficient and selective separation of U(VI) from complex systems through different strategies are described and summarized, and the reaction mechanisms of U(VI) interaction with biochar and biochar-based materials by different techniques are discussed at the molecular level. In the end, the use of machine learning for construction and evaluation of biochar and biochar-based porous materials in highly selective extraction of U(VI) and the challenges of biochar and biochar-based porous materials in U(VI) removal in real applications are described.

Highlights

- Biochar-based porous materials show high sorption ability of U(VI) from different solutions.
- Preconcentration of U(VI) through sorption, (co)precipitation, photocatalysis, and electrocatalysis is summarized.
- Interaction mechanisms of U(VI) with biochar-based porous materials are discussed from batch results and advanced spectroscopy characterizations.
- Machine learning is applied to evaluate the properties and applications of biochar-based materials.

Keywords Biochar-based porous materials, Uranium, Separation strategy, Machine learning, Interaction mechanism

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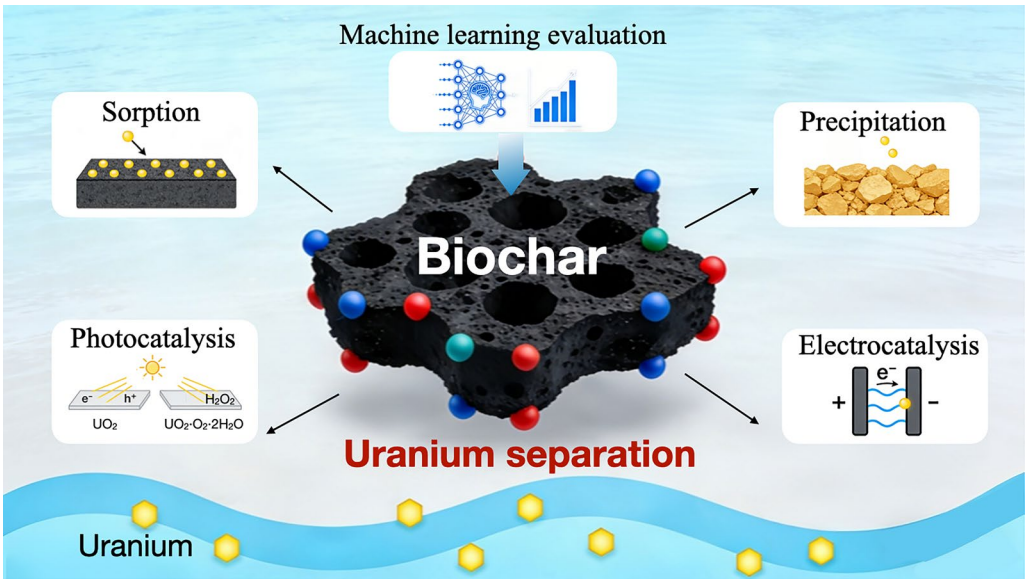
Graphical Abstract



1 Introduction

The rapid development of high-quality agriculture and industry together with continuous improvements in living standard levels requires sustainable supply of electric power. Among different kinds of electric power supply, nuclear energy has attracted great concern and has become of great importance because of its stable electric power output and nearly zero generation of CO_2 and other gases such as NOx and SOx, which are important not only to achieve the carbon peak and carbon neutrality goals, but also for effective air pollution control (Xie et al. 2024; Sun et al. 2026a). Uranium (^{235}U) is one of the key fissile radionuclides and is used in nuclear fuel fabrication, which is most important for the sustainable utilization of nuclear fission energy. According to the 15th Five-Year Plan, China will host the largest global amount of nuclear power energy in 2030. However, China is a depleted uranium country, which means that the imports of uranium from other countries such as Namibia, Kazakhstan, South Africa, Uzbekistan is critical for uranium supply to maintain nuclear power plant operation. Thereby, the efficient recovery of uranium from different kinds of U(VI)-containing solutions, including salt lakes and natural seawater, is critical for sustainable operation of nuclear power plants (Li et al. 2026; Hu et al. 2026; Sun et al. 2025a).

In last decade, a variety of separation strategies, including sorption, chemical (co)precipitation, electrocatalytic extraction, photocatalytic reduction/precipitation, have been explored widely for achieving the selective U(VI) separation across diverse aqueous systems (Cahill and Burkhart 1990; Liu et al. 2025; Gu et al. 2025; Oh et al. 2022; Wei et al. 2025; Zhang et al. 2026a). Sorption is suitable for low-concentration systems and large-scale applications, whereas precipitation is more effective at relatively high U(VI) concentrations. Photocatalysis and electrocatalysis are advantageous for continuous extraction under low concentrations but require specific energy input and catalyst design. The main disadvantages and advantages of each technique are tabulated in Table 1. One can see that sorption is widely used in the separation of U(VI) and is well suited for large-scale applications. Chemical precipitation is simply operated to form uranium-containing precipitates quickly, especially at relatively high concentrations. Photocatalysis could continuously preconcentrate uranium on the catalyst surfaces under light irradiation, especially for relatively low uranium concentrations. Electrocatalysis enables continuous uranium extraction on electrode surfaces and simultaneously induces the formation of uranium-containing precipitates, with much weak dependence on system conditions. For the efficient separation of U(VI) from different types of aqueous solutions, different strategies have their unique advantages, which are not only related to solution conditions but also dependent on the biochar-based porous materials' physicochemical properties. For example, Sharma et al. (2024) reviewed adsorption-based techniques for Th(IV) and U(VI) removal from different

Table 1 The main advantages and disadvantages of different methods for U(VI) removal from solutions

Method	Advantage	Disadvantage
Sorption	Easy operation, large scale applications, relative high sorption capacity, relative high selectivity of materials with special active sites and functional groups	Difficult separation from solutions, reusability and selectivity of materials should be considered
Photocatalysis	Continuously extract U(VI) under light irradiation, high selectivity for catalysts with special functional groups and active sites	The generation/separation of electron–hole pairs, the absorption of visible light, band gap and stability of catalysts should be considered
Electrocatalysis	Continuous extraction of U(VI) through electroreduction or electrochemical precipitation, related to the physicochemical properties of materials used as electrode and experimental conditions	The properties of electrode and voltage/electron current used in the experiments are related to final products. Stability of electrode and generation of H_2O_2 should be considered
Precipitation	Simple operation to separate U(VI) directly from solutions. U(VI) can form precipitate with high quality	Limited in high concentration soiutions and closed systems. The use of chemical reagents should be considered
Ion exchange	High selective separation of U(VI) through ion exchange mechanism. Generally the selectivity is related to the special functional groups and porous structures of ion exchange resin	The cost, regeneration and reusability of the ion exchange resins should beconsidered

types of solutions and summarized the removal mechanisms of electrostatic allure through special functional groups, chemical complexation by complex ligands, and ion inter-exchange reactions at exchangeable sites. The authors also reviewed the recent studies on Th(VI) and U(VI) sorption by various materials including biochar-based, amino-based, COF-based, magnetite-based, graphene-based, membrane-based, silica-based, and MOF-based porous materials. The sorption of Th(IV) and U(VI) under different solution conditions, such as pH, contact time, ionic strength, and temperature, was compared. The U(VI) sorption to different porous materials is strongly affected by pH, ionic strength, and temperatures; i.e., generally higher sorption at higher relative pH values, high concentrations of coexisted ions reduce sorption percentage, and higher sorption efficiency at relative higher temperature with endothermic reactions. These effects are closely related to U(VI) speciation in solution, where UO_2^{2+} dominates under acidic conditions, while carbonate complexes (e.g., $UO_2(CO_3)_3^{4-}$) prevail at neutral to alkaline pH, significantly influencing sorption affinity and selectivity. Zhang et al. (2025a) summarized and compared the recent studies on U(VI) separation from the natural seawater using different biomimetic and bio-based porous materials. The removal capacities and selectivity of U(VI) by different types of porous materials were compared. The authors pointed out that the simplicity of material synthesis, high adsorption capacity, selectivity, rapid sorption kinetics, stability, antibacterial ability, and reusability of the porous materials are crucial for U(VI) extraction, especially for the extraction from complex systems such as extra-low- or high-pH solutions, salt lakes or natural seawater. Hao et al. (2023) reviewed the removal of U(VI) and other radionuclides using a variety of porous nanomaterials, including MOFs, COFs, and porous organic polymers The removal of U(VI) from seawater, salt lakes, organic solutions, fluoride-containing solutions, and uranium mine wastewater through different separation strategies was summarized. The authors achieved the conclusion that porous structures, special functional groups, high specific surface areas, active exchangeable reaction sites, and tunable pore sizes are important for the sorption of U(VI) ions and other radionuclides on the porous material's surface or for the diffusion into the inner channels. The interactions of radionuclides with the porous materials are mainly attributed to the mechanisms of surface chemical complexation, cationic exchange, surface (co) precipitation, Lewis acid–base reactions, and electrostatic reactions (electrostatic attraction or repulsion). Sun et al. (2025b) summarized different techniques for the constructions of carbon-based porous materials and their possible applications in environmental and energy fields. The elimination of U(VI) by biochar-based porous materials was described in detail. Based on the properties of solution systems, applied experimental conditions, and the structure-properties of carbon-based porous composites, the elimination of U(VI) was mainly attributed to sorption, photo-reduction, chemical reduction, photo-precipitation, chemical precipitation, electrochemical reduction, electrochemical precipitation, ion exchange, chemical complexation, etc., which were closely related to the structures and properties of porous materials, application conditions, and solution properties. From the above-mentioned reviews, it is evident that the mechanism of U(VI) interaction with porous materials has been well elucidated from laboratory experimental results, advanced spectroscopic characterizations, artificial intelligence (AI) including machine learning (ML) and theoretical calculations, etc. The collaborative utilizations of two or more techniques together are helpful to improve the removal efficiency in real conditions. For some real

applications, the combination of two or more techniques is more efficient for highly selective extraction of U(VI) from complex systems. Although some reviews have described the sorption or recovery of U(VI) from different kinds of solutions by different kinds of materials, the highly selective separation of U(VI) by biochar-based porous materials through sorption, precipitation, photocatalysis, and electrocatalysis strategies have not been systematically summarized, which is crucial to easily understand the possible applications of biochar-based porous materials for U(VI) highly selective separation from different kinds of solutions.

Biochar and biochar-based porous materials are environmentally friendly organic–inorganic composites which can be largely synthesized at relatively low cost. They can be considered as the strategy of "turning waste into treasure" (George and Gujeran 2025; Shi et al. 2025). The properties of high relative surface areas, high stability, easy modification/grafting of other special functional groups, abundant active binding sites, and porous structures make biochar-based porous materials eco-environmentally friendly in environmental pollution treatments, such as removal of organic–inorganic chemical pollutants through (ad)sorption, degradation of organic chemicals, and reduction of high-valent metal ions to form precipitates through photocatalysis strategy; the elimination of different metal ions from solutions and subsequent immobilization on solid phases through electrochemical method, etc. (Ahmaruzzaman 2021; Kahkeci and El-Din 2023; Javanmard et al. 2024; Wei et al. 2024; Zhu et al. 2025). Although biochar and biochar-based materials have shown excellent properties in U(VI) removal from solutions, the selectivity of U(VI) from complex systems is still low because of the poor special functional groups such as amidoxime groups for U(VI) binding, the sorption capacity is not high enough compared to man-made nanoporous materials such as COFs or MOFs, and the porous structures are not tunable. Many reviews about the use of biochar-based porous composites in environmental organic/inorganic pollutants' treatments have been published in the last decade, and the main contents of some published reviews are described in Table 2. For example, Fang et al. (2023) summarized the techniques for the synthesis of biochars and their applications in efficient elimination of organic pollutants, metal ions, and radionuclides (including U(VI) separation from the natural seawater and real wastewater) and other research areas such as CO_2 capture and H_2 production using biochar-based materials as catalysts. Liang et al. (2021) summarized and compared different methods for the synthesis and modification of biochar and biochar-based porous composites. The physical and chemical properties of biochar and the biochar-based porous materials prepared by different techniques were described and compared. The elimination of different types of organic–inorganic chemical pollutants from different aqueous solutions under various conditions using different techniques was investigated and the removal mechanisms were described from the results of advanced spectroscopic characterizations and theoretical calculations. From Table 2, it is clear that biochar-based porous materials exhibit good properties in the treatment of organic/inorganic pollutants through different methods, and the methods are closely related to the properties of the organic/inorganic pollutants. However, the review of biochar-based porous materials for U(VI) separation/preconcentration from U(VI)-containing solutions using the aforementioned techniques is still not available. Considering the outstanding chemical and physical properties of biochar-based porous materials and a large number of studies on biochar-based porous materials in the separation-immobilization of U(VI) from complex systems, it is urgent to summarize the recent studies on U(VI) extraction using biochar-based porous materials through different methods, especially the most efficient techniques such as sorption, (co)precipitation, photocatalysis, and electrocatalysis strategies, —as this is essential for understanding the recent advances the use of biochar and biochar-based composites for highly U(VI) separation from complex solutions.

In this review, we summarize the methods for preparation and modification of biochar to prepare different kinds of biochar-based porous materials. The highly selective extraction of U(VI) using biochar-based porous materials through sorption, (co)precipitation, photocatalysis, electrocatalysis and other techniques is described in detail. The characterization of uranium interaction with biochar-based porous materials and the interaction mechanisms are discussed at the molecular level in detail in the sections of U(VI) separation by different methods.

As data-driven and machine-learning-assisted analyses have become a mainstream approach for addressing chemistry and materials science, incorporating an interpretable, data-driven framework would enable the consolidation of diverse results into unified and generalizable design and operational principles. Machine learning (ML) in the evaluation of the biochar-based porous materials' properties, and their future possible application in U(VI) separation are also described and discussed. In the end, from the authors' knowledge and viewpoints, the possible challenges and perspectives of biochar and biochar-based porous materials in future real applications are described.

Table 2 The main contents of some biochar-based porous materials described in reviews

Main contents of reviews	References
Properties of biochar-hydrogel composites and their applications in the removal of heavy metal ions and organic pollutants. The agricultural applications such as slow-release fertilizer, soil microbial activities, plant performances, etc.	Siryk et al. (2024)
Sorption of U(VI) and Th(IV) by MOFs, COFs, biochar-based materials, amino-based materials, graphene-based materials, and membrane-based materials. Sorption capacity, contact time, pH sensitivity, and time required for these adsorbents to capture U(VI) or Th(IV) efficiently. Mechanism discussion based on batch results	Sharma et al. (2024)
U(VI) extraction from seawater by different biomimetic and bio-based materials. Sorption capacity and selectivity of U(VI) by different materials. Mechanism was discussed from batch experiments	Zhang et al. (2025a)
Different techniques for biochar modification. Physicochemical behavior of biochar in soil–water-air-plant-animal systems. Potential risks of biochar to soil environment and plants	Yang et al. (2024)
Synthesis and application of biochar-immobilized enzymes in environmental pollution treatment. Organic pollutants degradation, soil contaminant remediation and dyes decolorization. Challenges from laboratory study to large-scale real applications	Zhang et al. (2026b)
Preparation and physicochemical properties of biochar and biochar-based materials. Removal of organic and inorganic pollutants by biochar and biochar-based materials through different strategies. Potential ecotoxicity in solution and soils	Liang et al. (2021)
Methods of metal-doping to biochar. Application of metal-doped biochar in environment and energy areas such as: removal of pollutants in wastewater treatment as adsorbents or catalysts; soil fertilizer; energy storage and CO_2 capture. Description from preparation-properties-application of metal-doped biochar	Zhao et al. (2025)
Application of biochar as adsorbents in radiation cleanup and nuclear waste management from macro perspectives. Economic studies from lifetime analysis and artificial intelligence for biochar optimization	Kordrostami and Ghasemi-Soloklui (2025)
Modification of biochar using different techniques. Sorption and immobilization of U(VI) by biochar-based materials. Remediation of U(VI) from wastewater and immobilization of U(VI) in soil. Mainly focusing on adsorption and immobilization of U(VI) by biochar-based materials	Xiong et al. (2025)
Remediation of emerging inorganic pollutants (V, Sb, Tl, Hg, fluoride and rare earth elements) in soils and water by biochar. Ion exchange, electrostatic reaction, complexation and precipitation were discussed for the inorganic pollutants' removal and immobilization	Shaheen et al. (2025)
Removal of trace elements from solutions using crop residue-based biochar. Feedstock type and production conditions of biochar, solution conditions such as pH, temperature, ionic strength on trace elements were reviewed. Economic assessment and cost–benefit of biochar in trace element removal were discussed	Haris et al. (2024)
Synthesis and modification of carbon-based materials using different techniques. Sorption of U(VI) by different kinds of carbon-based materials (carbon-, graphene oxide-, CNT-, carbon dot-based materials) from wastewater	Mittal et al.(2024)
Synthesis of carbon-based materials (activated carbon, graphene, CNTs, biochar) by different techniques. Removal of U(VI) by afore mentioned carbon-based materials from wastewater. DFT calculation of U(VI) interaction with graphene	Fahad et al. (2023)
Synthesis and modification of biochar using different methods. Removal and comparison of U(VI) from solutions by different biochar-based materials by batch sorption strategies under different experimental conditions. XPS, FTIR and XRD characterizations to understand sorption mechanism	Jun et al. (2025a)
Preparation and modification of biomass-based materials (plant-based, microorganism-based, biological-based materials). U(VI) elimination from solutions by biomass-based materials by batch sorption technique. Comparison of U(VI) adsorption capacities by different kinds of biomass-based materials	Fan et al. (2021)

2 Synthesis of biochar-based porous materials

Synthesis of biochar using different kinds of raw materials as precursors has been studied extensively in recent years. Yang et al. (2024) compared the advantages/disadvantages of different techniques for biochar synthesis and further modifications to improve the physicochemical properties, such as physical and chemical methods, biological techniques, organic/inorganic recombination, single metal atom-doping, metal/nonmetal oxide-loading, etc. Generally, different modification techniques are adopted for specific applications of biochar, for example, single atom-doping is favorable to improve photocatalytic activities, and organic/inorganic recombination can enhance sorption ability. Overall, functional group grafting mainly enhances selective coordination, metal-doping improves catalytic activity, and pore structure engineering facilitates mass transfer, collectively determining the separation performance of biochar-based materials. The methods for the construction of different biochar-based composites using different materials under different experimental conditions have been described in detail in each published paper. Therefore, in this section, the techniques for the synthesis of biochar and biochar-based porous materials are only illustrated in Fig. 1. The modification of biochar with other kinds of chemical materials, grafting special functional groups, loading of metal/nonmetal oxides, doping/co-doping of single metal atoms, cooperation with other organic or inorganic composites, could improve the sorption selectivity, enhance the photocatalytic activity, and increase

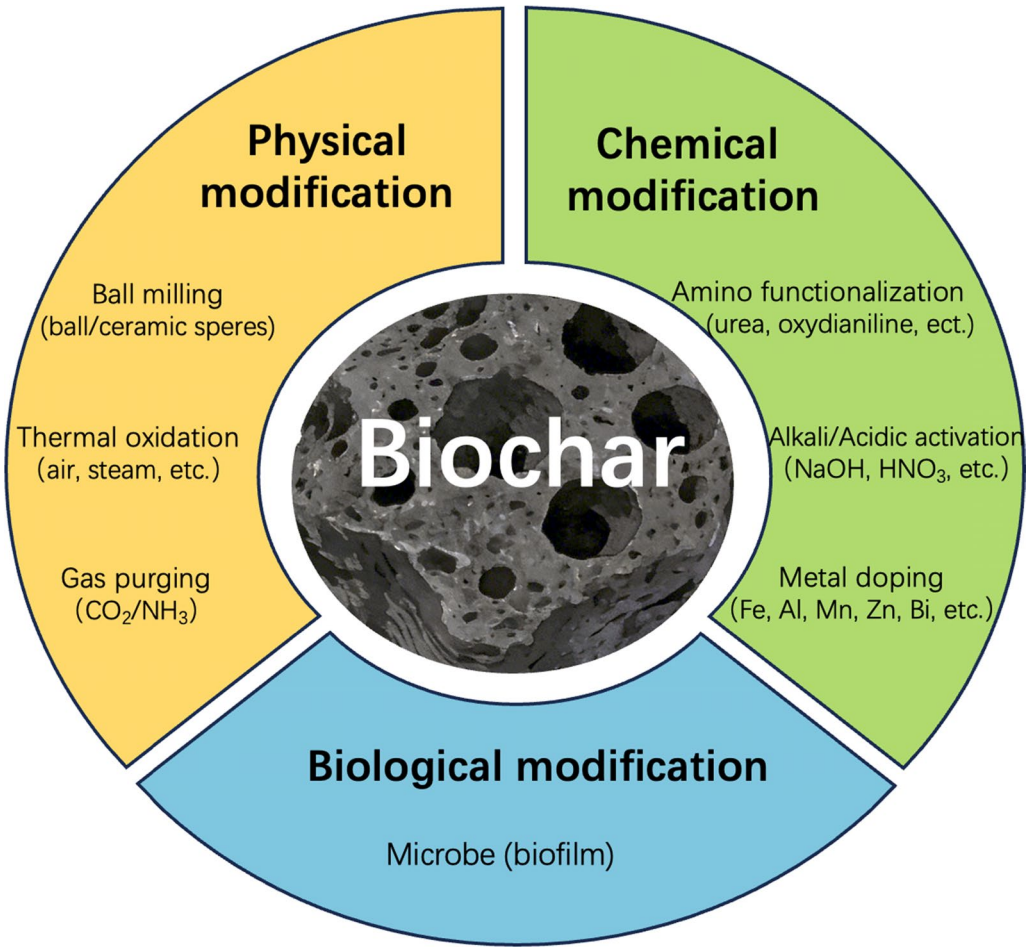


Fig. 1 Different methods for the modification of biochar

the electrocatalytic ability and other properties such as sorption ability, binding activity, antibacterial property, visible light absorption, coordination ability, photocatalytic electron–hole generation/separation, adjusting bandgap values, and electronic conductivity. The coordination of biochar with other materials to construct biochar-based porous materials can improve the properties of biochar such as sorption capacity and selectivity, photocatalytic degradation and/or chemical conversion of organic chemicals, and sorption–catalysis improvement. Although some biochar-based porous materials showed relatively low sorption capacities of organic/inorganic pollutants compared to the raw biochar because the surface areas, active sites or inner pore sizes of the biochar after modification with other materials were decreased, the comprehensive utilization of both biochar and materials' advantages could improve the abovementioned physicochemical properties of biochar-based porous composites obviously (Ghaedi et al. 2025; He et al. 2022). Nevertheless, from the authors' viewpoint, the modification of raw biochar is an efficient technique to improve/change biochar's physicochemical properties, especially to improve sorption selectivity, enhance photocatalytic activity, and increase electrochemical ability. It is necessary to note that raw biochar has very poor selectivity for U(VI) sorption from a complex system although enough function groups and active binding sites are available on biochar surfaces. This is mainly attributed to the non-specific interactions of native surface functional groups (e.g., –OH and –COOH), which lack strong coordination affinity toward U(VI) compared to competing metal ions. For selective extraction/separation of U(VI) in the presence of other competing metal ions, surface modification with special functional groups such as Lewis acid groups or amidoxime-containing groups is critical for the selective binding/complexation of U(VI). Single metal-doping is most important to improve the electrocatalytic or electrochemical reduction/precipitation of U(VI) to form U-containing compounds. The coordination of some metal/nonmetal oxides is

helpful to improve the absorption ability of visible light, to enhance the photocatalytic generation and separation of electron–hole pairs, and thereby to improve the photocatalytic reduction of U(VI) to produce UO_2(s) precipitates, or photocatalytic generation of H_2O_2 to react with the surface-adsorbed U(VI) to generate U-precipitates ($(UO_2)\cdot O_2\cdot 2H_2O$, etc.) (Hao et al. 2026; Lu et al. 2025; Jin et al. 2025; Xiao et al. 2025). More detailed results and mechanism discussion are described in the following section.

3 Separation of U(VI) by different strategies

Extraction of U(VI) from different aqueous solutions is strongly dependent on the solution conditions, applied methods, and materials' physicochemical properties. Based on the biochar-based porous materials' properties, the suitable strategy can be selected and applied for U(VI) highly selective separation from aqueous solutions. Many kinds of biochar-based porous materials have similar properties, and one kind of biochar-based composites also exhibit different properties. Thereby, in this section, the separation-recovery of U(VI) is described according to the used methods, which are different from most recent studies based on the types of porous materials.

3.1 Sorption

Key parameters of sorption. Sorption method is the most simple technique for U(VI) separation, which has been studied extensively, and can be easily operated on a large scale. For highly selective preconcentration of U(VI) from water solutions in the (co)presence of other coexisting metal ions, grafting special functional groups, such as amidoxime-, O-, N-, S-, and P-containing special groups, can selectively bind U(VI) by forming strong chemical complexes through Lewis acid–base reactions, thereby improving the selective separation of U(VI) from different kinds of aqueous solutions.

Recent representative studies and mechanisms. Considering the high stability, abundant special functional groups and enough active binding sites of biochar-based porous materials, the highly selective separation of U(VI) ions from water solutions by biochar-based porous composites have been investigated extensively. In this review, selectivity is mainly evaluated based on distribution coefficients (K_d), selectivity coefficients, or the relative removal efficiency of U(VI) compared to competing ions under identical conditions. Li et al. (2025a) prepared biochar using microalgae as raw precursors by dual-template carbonization. The positive UO_2^{2+} ions were adsorbed to the negatively charged surface of biochar by electrostatic interaction. Simultaneously, the special functional groups such as -NH_2 and –COOH groups, could form strong chemical complexes with UO_2^{2+} ions (Fig. 2a), thereby achieving high U(VI) adsorption ability with high relative selectivity. The sorption of U(VI) by hydroxyapatite-biochar (HAP-BR) also showed that the binding of U(VI) to HAP-BR was mainly dominated by the chemical surface complexation of UO_2^{2+} with –OH and –COOH special functional groups. However, the relatively selection of U(VI) removal from solutions containing coexisting metal ions by HAP-BR was not yet investigated in this work (Ahmed et al. 2021). Lv et al. (2023) used amino-functional groups to functionalize biochar, and applied it as adsorbent for the separation of U(VI) from wastewater. Under the experimental conditions of pH 5.0 and 25 °C, the amino-functionalized biochar achieved high U(VI) adsorption capacity (368 mg g^{-1}) with high relative selectivity. The analysis results of FTIR and XPS characterizations indicated that chemical complexation of U(VI) with surface abundant carboxyl, hydroxyl, and amino special functional groups contributed the high selective U(VI) sorption. Yang et al. (2025a) used phytic acid to functionalize biochar and applied the functionalized biochar as adsorbent for U(VI) preconcentration from different solutions. The sorption capacity of 625 mg g^{-1} was achieved at pH = 6 and T = 25 °C with high relative selectivity in the (co)presence of Ca^{2+}, Mg^{2+}, Zn^{2+}, Mn^{2+}, Cd^{2+}, and Cu^{2+} ions. From the XPS and FTIR characterizations, one can see that the surface complexation of UO_2^{2+} ions with surface special functional groups (–COO– and –P=O– groups), electrostatic attraction of positively charged UO_2^{2+} to the negatively charged surface of phytic acid-biochar, and ion exchange of the protonated $-HPO_4^-$ groups with UO_2^{2+} ions are the main reaction mechanisms for the highly selective separation of U(VI) under acidic conditions. The authors also used column experiments to investigate the possible applications of the phosphorus-doped biochar in real wastewater treatment. The column results also indicated that U(VI) concentration was decreased efficiently from 0.456 to 0.082 mg L^{-1} after the solution passing through the bed-column device. More importantly, the phosphorus-doped biochar can be regenerated with 0.1 M HCl with high reusability. Liu et al. (2023) modified raw biochar with δ-MnO_2 and applied the δ-MnO_2-biochar for the separation of U(VI) from wastewater. The batch experimental results showed that about 96% U(VI) was eliminated, whereas ~ 92% coexisting metal ions (such as Co, Zn, Cu, Pb, and Tl) were also removed simultaneously from solutions. Based on FTIR and XPS characterizations, the high sorption ability was mainly attributed to the chemical complexation of U(VI) ions with O-containing special functional groups (i.e., O–C=O, O–Mn groups) and ion exchange with the ≡MnOH special functional groups. Although high removal efficiency was reported by the δ-MnO_2-biochar,

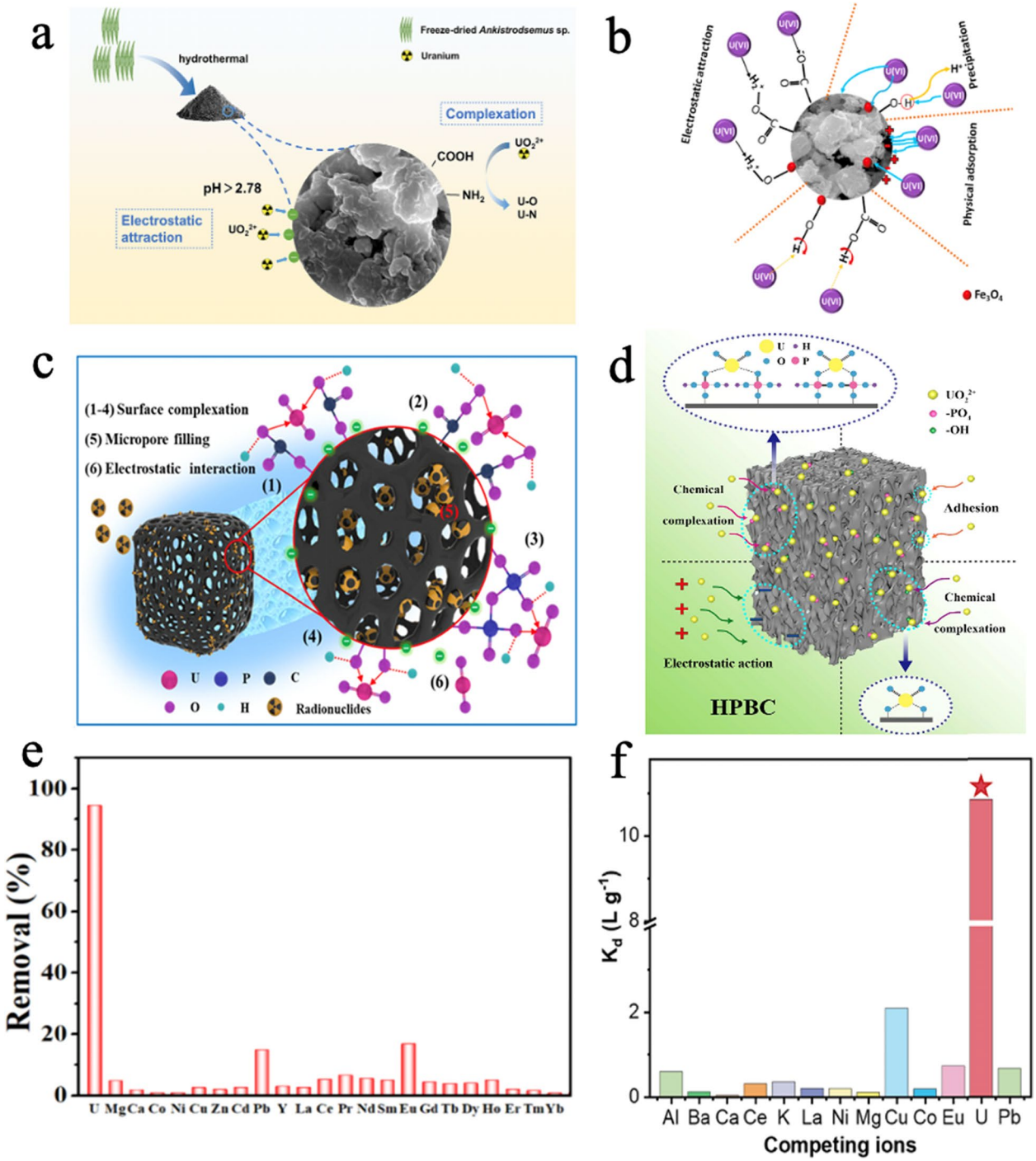


Fig. 2 **a** Electrostatic attraction and complexation of U(VI) to biochar (Li et al. 2025a). **b** Different interaction mechanisms of U(VI) with magnetic biochar (Lingamdinne et al. 2022). **c** Sorption of U(VI) to $KMnO_4$-treated biochar through surface complexation, micropore filling and electrostatic interactions (Liao et al. 2022a). **d** Sorption of U(VI) to HPBC through chemical complexation, electrostatic attraction, and chemical complexation (Chen et al. 2023a). **e** Selective sorption of U(VI) by phosphate-grafted biochar in the presence of different metal ions (Xia et al. 2025). **f** Selective sorption of U(VI) by phosphorus-doped biochar in the presence of other metal ions (Li et al. 2024)

the selectivity of U(VI) sorption was still not resolved, which was attributed to the non-selective complexation of the functional groups with U(VI) ions. Lingamdinne et al. (2022) synthesized magnetic biochar and used the magnetic biochar for U(VI) separation. The adsorption ability of 324 mg g^{-1} was achieved at pH 4 under ambient conditions, much higher than raw biochar and other sourced biochar. The high surface areas and abundant surface special functional groups contributed to the physical and chemical adsorption of U(VI) onto the magnetic biochar, and XPS characterizations showed that the interaction of O-containing groups and carbonyl groups with U(VI) was the main reaction mechanism for U(VI) elimination by the magnetic biochar, resulting in the high elimination of U(VI). The electrostatic attraction of the positively charged UO_2^{2+} to negatively charged biochar surface at pH 4 also dominates the high sorption of UO_2^{2+} to biochar, which is not in good agreement with the mechanism described by the authors in Fig. 2b. In Fig. 2b, the surface charge of biochar at the experimental pH values should be negative, not positive as described in Fig. 2b. Liao et al. (2022a) treated biochar with $KMnO_4$ to create more mesoporous ordered structures and increase surface special functional groups. The $KMnO_4$-treated biochar achieved the maximum U(VI) sorption amount of 979 mg g^{-1}, much higher than that of H_2O_2-treated biochar (772 mg g^{-1}) and that of raw biochar (370 mg g^{-1}) at pH 4. The special functional groups can form strong complexes with U(VI) ions whereas the mesoporous channels can promote the micropore filling of U(VI) into the inner porous channels of $KMnO_4$-treated biochar. The positive U(VI) ions can also be adsorbed to the negatively charged biochar surfaces through the electrostatic attraction at pH 4 (Fig. 2c). Although a high sorption ability of U(VI) by $KMnO_4$-treated biochar was achieved, the selective sorption of U(VI) from different types of wastewater containing various coexisting metal ions was not investigated. In real scenarios, the concentrations of U(VI) are generally much lower than those of other coexisting metal ions; thus, the highly selective binding of U(VI) from complex solutions to biochar-based composites is the most important parameter to be considered. Wang et al. (2024) loaded MgO nanoparticles on biochar and applied the MnO-biochar composites for U(VI) elimination from wastewater. The U(VI) sorption ability of 906 mg g^{-1} was achieved at $T = 298$ K and pH = 5. The authors also investigated the selective sorption of U(VI) from different types of wastewater containing different other coexisting metal ions, and concluded that the high relative sorption selectivity was mainly attributed to the interaction of deprotonated ≡MnOH with U(VI), i.e., $\equiv MnOH + UO_2^{2+} \rightarrow \equiv MnO{-}UO_2^{+} + H^+$, through cation exchange reactions. Chen et al. (2023a) grafted phosphate groups to biochar surfaces (HPBC) and applied the HPBC as an adsorbent for U(VI) preconcentration from different kinds of wastewater. The HPBC achieved the adsorption capacity of 781 mg g^{-1} with the selectivity of ~70% compared to other coexisting metal ions. The highly relative sorption selectivity was mainly attributed to the abundant phosphate groups, which could bind U(VI) ions by strong chemical complexation through the formation of P–O–O chemical complexes, i.e., P=O→U and P–O→U complexes. The C–OH groups can also form C–O→U complexes for U(VI) binding onto biochar. Besides the formation of chemical complexes, the positively charged UO_2^{2+} can be electrostatically attracted to the negatively charged biochar surfaces through electrostatic attraction (Fig. 2d), which is in good agreement with the experimental results of U(VI) removal by other phosphate-functionalized biochar (Hu et al. 2020a). Luo et al. (2024) synthesized ZIF-8/chitosan/algal (ZIF/CP/CT) and applied it for the sorption of U(VI) from solutions, and achieved a sorption capacity of 873 mg g^{-1} at pH 6. The FTIR and XPS analysis indicated that amino, hydroxyl, N=O and P=O bonds contributed to the high binding of UVI) to ZIF/CP/CT. Xia et al. (2025) grafted phosphate groups onto biochar and used it as an adsorbent for U(VI)sorption from mining wastewater. The phosphate groups on biochar contributed to the high sorption of U(VI) with relatively high selectivity through electrostatic attraction and chemical complexation, achieving the removal capacity of 492 mg g^{-1} with high relative selectivity (Fig. 2e). Akl et al. (2021) constructed hydrogel-biochar composites for the sorption of U(VI) from different solutions. Relatively high sorption of U(VI) from binary systems containing U(VI) and other coexisting metal ions was achieved. Based on the high sorption ability, the authors pointed out that high sorption of U(VI) from complex solutions can be considered as highly selective U(VI) sorption. From the authors' viewpoints, selectivity of U(VI) sorption can only be achieved from the results of very high U(VI) sorption and very low sorption of other coexisting metal ions (as shown in Fig. 2e and 2f). Li et al. (2024) used phosphoric acid to activate biochar and applied the phosphoric acid-activated biochar for U(VI) separation from nuclear wastewater. The phosphorus-grafted biochar exhibited excellent ability in U(VI) removal (99% removal efficiency) and could achieve a sorption ability of 422 mg g^{-1} from real nuclear wastewater with high sorption selectivity (Fig. 2f). More importantly, the authors used DFT calculations to understand the reactions of U(VI) with phosphonate groups. The results showed that the electron-deficient phosphoric acid groups (Fig. 3a) are favorable for U(VI) complexation. The phosphonate could form stable complexes with U(VI) (i.e.,

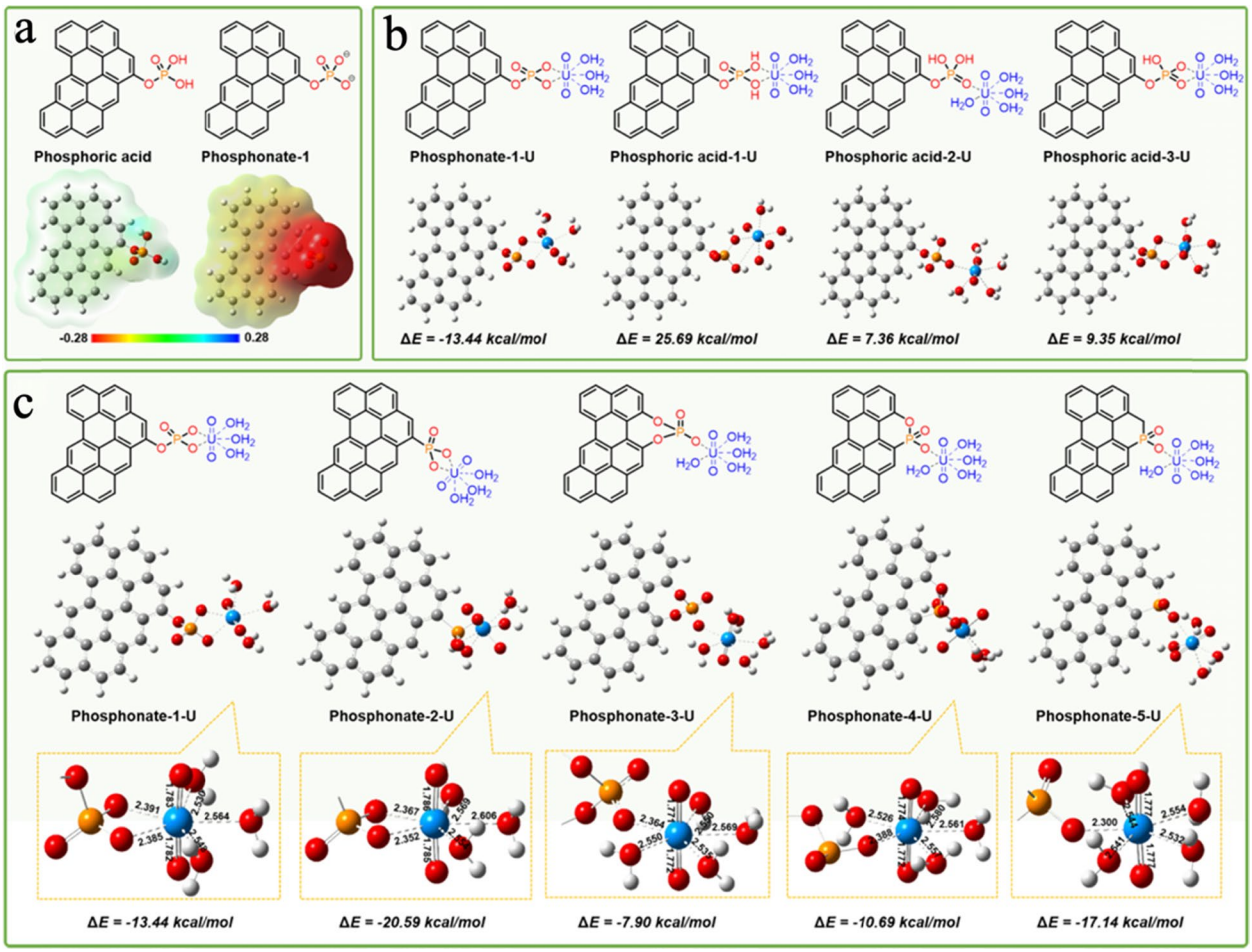


Fig. 3 DFT calculations of U(VI) interaction with phosphoric-doped biochar with U(VI) (Li et al. 2024). **a** Structures and electrostatic potentials of phosphoric acid and phosphonate groups on biochar (Li et al. 2024). **b** Possible interactions of U(VI) with phosphoric acid and phosphonate groups. **c** Structures of five representative U(VI)-phosphonate complexes (Li et al. 2024)

phosphonate-1-U) (i.e., phosphonate-1-U) with reaction energy (ΔE) of −13.44 kcal mol^{-1}, suggesting the formation of stable complexes (Fig. 3b). The calculated (ΔE) values and bond distances of hydrated U(VI) ions with different phosphonates are given in Fig. 3c. Although this work presented the DFT calculation of U(VI) interaction with biochar-based porous materials, the reaction of U(VI) with biochar was still not available. The authors only calculated the reactions of U(VI) with phosphonate groups, not the reactions of U(VI) ions with the surface functional groups of biochar. From published papers, theoretical calculations of organic and/or inorganic pollutants' interaction with biochar at the molecular level are still not available, which is attributed to the indeterminate structures of biochar (Hu et al. 2020b). Although direct theoretical modeling of biochar remains challenging due to its structural heterogeneity, some studies have adopted simplified models (e.g., graphene-like structures) to approximate interactions. However, a comprehensive molecular-level description is still limited. The structures and surface groups of biochar are still unclear, and it is impossible to construct the reaction frameworks of U(VI) with biochar. Thereby, the research studies about the relationship between biochar's structures and U(VI) (even other metal ions) from theoretical calculations and machine learning are still not available.

Challenges and perspective. Sorption of U(VI) from complex systems by biochar and biochar-based porous materials is easily carried out on a large scale. The modification of special functional groups onto biochar surface to form strong chemical complexes with U(VI), to construct suitable inner porous structures for U(VI) diffusion, to graft Lewis acid groups to form strong Lewis acid–base complexes or other strategies to improve U(VI) sorption are efficient methods to enhance the high relative selectivity of U(VI) binding on biochar and biochar-based materials. Besides the high adsorption capacity and highly selective ability, the reusability,

stability, recovery, and environmental friendliness of biochar-based porous materials are also crucial for their real applications.

3.2 Precipitation

Key parameters of precipitation. Extraction of U(VI) from different types of solutions through precipitation is the most simple and fast technique, especially the formation of precipitates directly without addition of other solid materials. Generally, direct separation of U(VI) from solutions by forming precipitates is applicable for relatively high U(VI) concentrations. For example, through adjusting solution pH values, U(VI) can form precipitates at high pH values. In a close system, the addition of special chemicals such as H_2O_2 could form U-containing precipitates directly through the reaction of $UO_2^{2+} + H_2O_2 \rightarrow (UO_2)O_2{\cdot}2H_2O\downarrow$, which has been used for U(VI) separation since the 1950s.

Recent representative studies and mechanisms. Under the irradiation of light and coexistence of organic chemicals in solutions, soluble U(VI) species could form precipitates through ligand-to-metal-charge-transfer reactions, i.e., stable U(VI) species were reduced to unstable U(V) species and then transferred to form $U(IV)O_2$ precipitates through disproportionation reactions (Li et al. 2021). This research highlights the selective extraction of U(VI) by solidification strategy under light irradiation without the addition of other solid materials. Herein, we mainly focus on the extraction/separation of U(VI) ions from solutions using biochar-based porous materials through the formation of U-containing precipitates. Zhang et al. (2023) prepared biochar@chitosan-polyethyleneimine with 3D interpenetrating structures, abundant active sites, and special functional amino/hydroxyl groups. The groups are beneficial for biochar to increase the high selective binding of U(VI) ions. The U(VI) high removal mechanisms include surface complexation of UO_2^{2+} $-NH_2$ and $-OH$ special functional groups, and precipitation of UO_2^{2+} with Ca^{2+} and PO_4^{3-} to form $Ca(UO_2)_2(PO_4)_2{\cdot}6H_2O$ precipitates, which further immobilizes UO_2^{2+} on biochar, thereby resulting in the highly selective and efficient separation of U(VI) from solutions (Fig. 4a). Ruan et al. (2022) modified phosphate groups onto ZVI-supported biochar (ZVI-B) and applied the phosphate-grafted ZVI-B for precipitation–immobilization of U(VI). The characterization results of XRD patterns and XPS spectra indicated the formation of P–O–U chemical complexes and reduction of U(VI) ions to $U(IV)O_2$ solid by ZVI, thereby achieving the precipitation and immobilization of U(VI) on phosphate-grafted ZVI-B. Liao et al. (2022b) doped Bi_2O_3 to biochar for U(VI) preconcentration from different solutions, and the experimental results showed that Bi_2O_3-doped biochar achieved a U(VI) sorption ability of 516 mg g^{-1} at pH 4, much higher than that of the raw biochar. The XRD, XPS, and SEM–EDS characterizations showed that part of adsorbed U(VI) species was photo-catalytically reduced to insoluble U(IV) species under sunlight irradiation (attributed to Bi_2O_3 photocatalytic reduction activity), the chemical complexation of U(VI) ions with $-OH$ groups, $-NH_2$ groups, and PO_4^{3-} special functional groups (from the change of XPS spectra analysis to understand the complexation of U(VI) with these special groups), formation of precipitates (from XRD characterization) and possible ion exchange of U(VI) with Ca^{2+} (from reduced peak strength change of Ca_{2p} spectrum after U(VI) sorption and the change of Ca^{2+} concentrations in solution) (Fig. 4b). Wang et al. (2025a) synthesized biochar by pyrolysis of pig manure and then modified the prepared biochar with phosphate groups and microorganisms. The phosphate-biochar showed relatively high selective sorption of U(VI) from different wastewaters. Spectroscopic characterizations revealed that the interaction mechanisms involved the adsorption through the complexation with the special functional groups, ion exchange with Mg^{2+} or Al^{3+} active sites in biochar, complexation with O-containing groups, and interaction with PO_4^{3-} to form $H_2(UO_2)_2(PO_4)_2{\cdot}8H_2O$ precipitates (Fig. 4c). Lv et al. (2025) synthesized biochar using waste biomas (denoted as CSB) and then modified CSB through imcorporating hydroxyapatite (denoted as CSB@HAP). The CSB@HAP exhibited a high U(VI) sorption ability of 557 mg g^{-1} at $T = 25$ °C and pH = 5.0. The coexisting Na^+, K^+, and Mg^{2+} ions did not affect U(VI) sorption obviously, whereas the coexisting Ca^{2+} and Al^{3+} ions affected U(VI) sorption obviously. The interaction of U(VI) with CSB@HAP was characterized by FTIR spectra, XRD patterns, and XPS spectra. In XRD patterns, the new peaks appearing after U(VI) loading indicated the formation of metaautunite-9A (i.e., $Ca(UO_2)_2(PO_4)_2{\cdot}3H_2O$, No. 39–1351 JCPDS card) (Su et al. 2019). In FTIR spectrum, the peak intensities of CO_3^{2-} and PO_4^{3-} decreased, and a new peak appeared at 905.9 cm^{-1} after U(VI) sorption, suggesting that PO_4^{3-} and CO_3^{2-} groups participated in U(VI) adsorption. The shift of binding energies of P_{2p} and Ca_{2p} XPS spectra after U(VI)-loading indicated the formation of new phases via dissolution–precipitation reactions ($Ca^{2+} + UO_2^{2+} + PO_4^{3-} + 3H_2O \rightarrow Ca(UO_2)_2(PO_4)_2{\cdot}3H_2O$) and ion exchange ($\equiv Ca^{2+} + UO_2^{2+} \rightarrow \equiv UO_2^{2+} + Ca^{2+}$) between CSB@HAP and U(VI) (as proposed in Fig. 4d) (Lv et al. 2025). However, the reason for the different effects of coexisting cation ions on U(VI) sorption was still not explained in detail. Liao

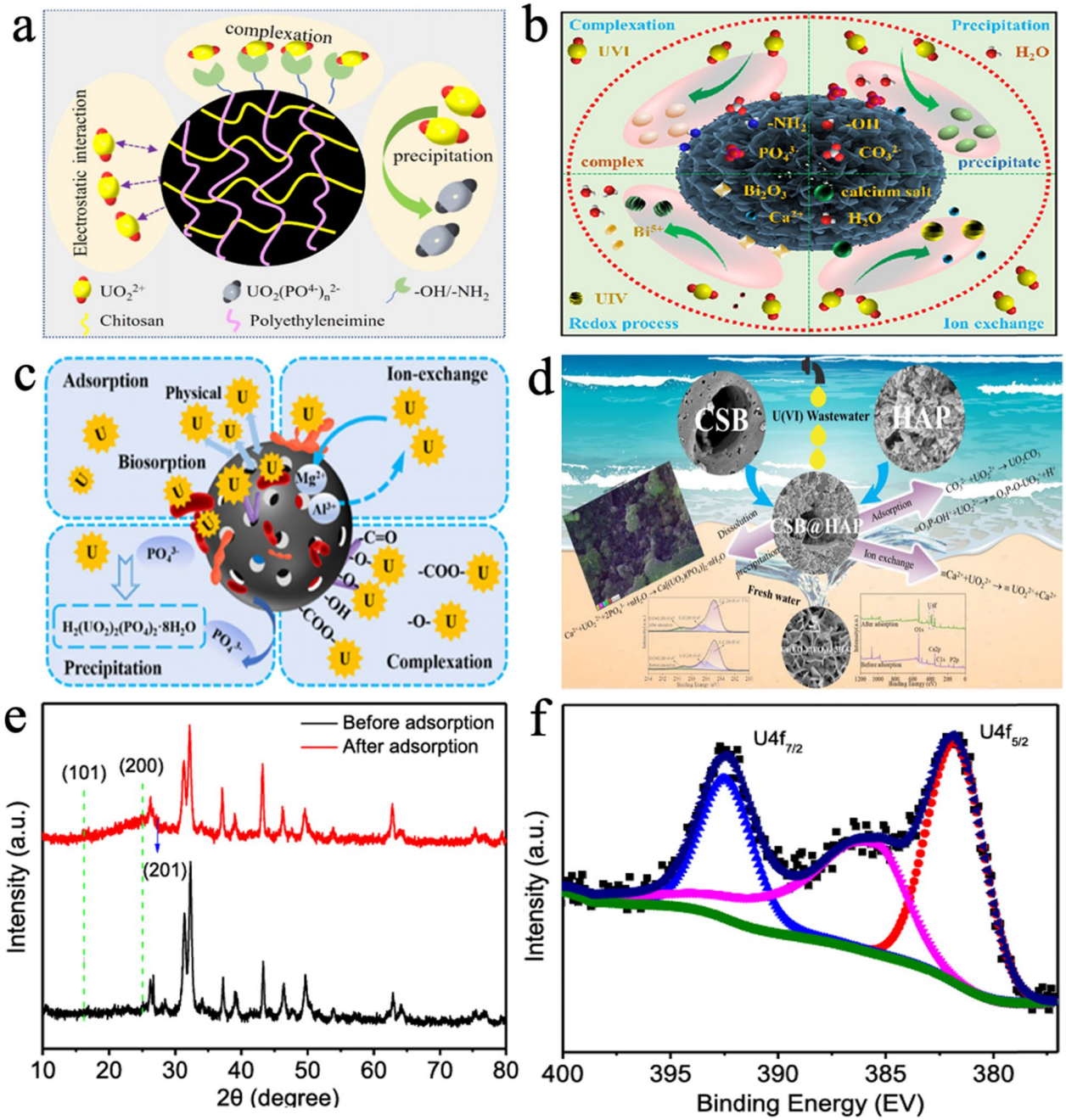


Fig. 4 **a** Electrostatic attraction, surface complexation and precipitation of UO_2^{2+} to form $Ca(UO_2)_2(PO_4)_2{\cdot}6H_2O$ precipitate (Zhang et al. 2023); **b** Sorption of U(VI) through complexation, reduction, ion exchange and precipitation reactions (Liao et al. 2022b); **c** Removal of U(VI) through ion exchange with Mg^{2+} or Al^{3+}, complexation with O-containing groups, physical adsorption and interaction with PO_4^{3-} to form $H_2(UO_2)_2(PO_4)_2{\cdot}8H_2O$ precipitates (Wang et al. 2025a); **d** Interaction mechanisms of U(VI) with CSB@HAP (Lv et al. 2025); **e** XRD characterizations of biochar before and after U(VI) sorption (Liao et al. 2023); **f** XPS spectrum of U(VI)-loaded biochar (Liao et al. 2023)

et al. (2023) constructed hydroxyapatite-modified biochar for U(VI) separation from different types of solutions and achieved the maximum adsorption value of 1616 mg g^{-1} with high re-usability. The XRD characterizations revealed that three weak diffraction peaks related to the planes of (201), (200), and (101) were the $Ca(UO_2)_2(PO_4)_2{\cdot}3H_2O$ precipitate (NO. 39–1351 JCPDS card), suggesting the formation of ionization-precipitation (Fig. 4e). The high-resolution XPS spectrum of U_{4f} also indicated the reaction of U(VI) and

biochar with binding energies higher than 380 eV, suggesting no reduction of soluble U(VI) species to un-soluble U(IV) species in the sorption process (Fig. 4f).

Challenges and perspective. Although the aforementioned mechanisms of U(VI) removal from solutions by biochar-based porous materials can be qualitatively characterized, it is still difficult to distinguish the quantitative contribution of different mechanisms, i.e., the contribution of sorption, surface complexation, precipitation, and ion exchange to U(VI) elimination from solutions. From the aforementioned references, it is clear that U(VI) sorption onto the surfaces of biochar-based porous materials, and subsequent in situ formation of precipitation on biochar surface, or diffusion of U(VI) ions from surface sites to the inner porous channels are generally the processes for U(VI) removal from different types of aqueous solutions. The current studies mainly focus on high removal efficiencies or sorption capacities of U(VI) by biochar-based porous materials, yet the quantitative analysis of different interactions between U(VI) and biochar-based porous materials remains challenging. Till now, no research work is available to distinguish the contribution of different reaction mechanisms exactly. Future studies may combine advanced spectroscopic techniques (e.g., in situ XAS), isotopic tracing, and kinetic modeling to quantitatively distinguish the contributions of sorption, precipitation, and ion exchange processes. The selectivity, cost-efficiency, reusability, and stability of biochar-based porous materials, which are crucial parameters to evaluate the potential future applications of biochar-based porous composites in real wastewater uranium extraction, should be considered in future studies.

3.3 Photocatalysis

Key parameters of photocatalysis. Extraction of U(VI) efficiently from various solutions through a photocatalysis strategy could continuously separate U(VI) through sorption-photocatalytic reduction/transformation processes (Chen et al. 2026). Based on the physicochemical properties of the photocatalyst, electron–hole pairs or H_2O_2 can be photogenerated under light irradiation (Lin et al. 2026). From the published papers, the absorption ability of visible light, the generation and separation of electrons and holes, and the transfer of separated electrons to adsorbed U(VI) are the most important parameters for the photoreduction of U(VI) to form UO_2 precipitates, whereas the photogenerated H_2O_2 can react with the adsorbed U(VI) species to form studtite ($(UO_2)O_2{\cdot}2H_2O$). For the photogeneration of electron–hole pairs, the light absorption, generation and separation of e^-–h^+ pairs, the efficient transfer of electrons to the adsorbed U(VI), and the high selective sorption of U(VI) on photocatalyst are critical parameters for high elimination of U(VI) from solutions (Fig. 5a) (Chen et al. 2023b). For the formation of studtite precipitates, the selective sorption of U(VI) on photocatalyst and in situ generation of H_2O_2 under light irradiation are crucial to form $(UO_2)O_2{\cdot}2H_2O$ through the reaction of $UO_2^{2+} + H_2O_2 \rightarrow (UO_2)O_2{\cdot}2H_2O\downarrow$ (Fig. 5b) (Dong et al. 2025).

Recent representative studies and mechanisms. Liu et al. (2024a, b) synthesized a biochar/g-C_3N_4/MoS_2 photocatalyst and applied the photocatalyst for sorption and photoreduction of U(VI) from solutions. The composites showed very high sorption efficiency with high relative selectivity. The quenching tests revealed that photogenerated $\cdot O_2^-$ and e^- free active species were the most important parameters for U(VI) photocatalytic reduction. The high photocatalytic activity was attributed to the enhanced acceleration of electron transfer through incorporation of the biochar and the Z-scheme composite for the charge transfer. He et al. (2023) constructed biochar/g-C_3N_4 composites and applied the prepared composites as photocatalysts for U(VI) extraction through photocatalytic adsorption–reduction processes. About 99.6% U(VI) was separated from the solutions after 30 min under the irradiation conditions of visible light at pH 4. The bandgap of g-C_3N_4 decreased from 2.63 to 2.14 eV after its cooperation with biochar, which enhanced the absorption of visible light, promoted the photocatalytic generation/separation of electron–hole pairs, reduced the difficulty of electron transfer to adsorbed U(VI), and therefore enhanced the photocatalytic property. Hu et al. (2024) doped single Fe-atoms into a catalyst and used it for U(VI) photocatalytic reduction. The generated Fe^{2+} and $\cdot O_2^-$ free radicals mainly contributed to U(VI) photoreduction rather than other active species. This work highlights the single-atom doping on biochar to improve the photocatalytic activity, thereby enhancing the photocatalytic extraction of U(VI) from solutions. Zhang et al. (2025b) fabricated 2D/2D Bi_2WO_6/C_3N_4/biochar heterojunctions and applied the composites as photocatalysts for U(VI) extraction from natural seawater and simulated nuclear wastewater. The heterojunction enhanced the absorption of visible light and photocatalytic generation/separation of electrons and holes, and promoted electron transfer to the adsorbed U(VI). The photogenerated $\cdot O_2^-$ and e^- active species reacted with the adsorbed U(VI) to form stabilized metastudtite ($(UO_2)O_2{\cdot}2H_2O$) with high selective separation ability under visible light irradiation (Fig. 5c). The U(VI) extraction ability of 3.2 mg g^{-1} was reported in 7 days from natural seawater and ~86% U(VI) was removed from simulated nuclear wastewater, suggesting the potential application of biochar-based catalysts in real scenarios. Xiang et al. (2020) constructed ZVI-supported carbon nanomaterials for photocatalytic

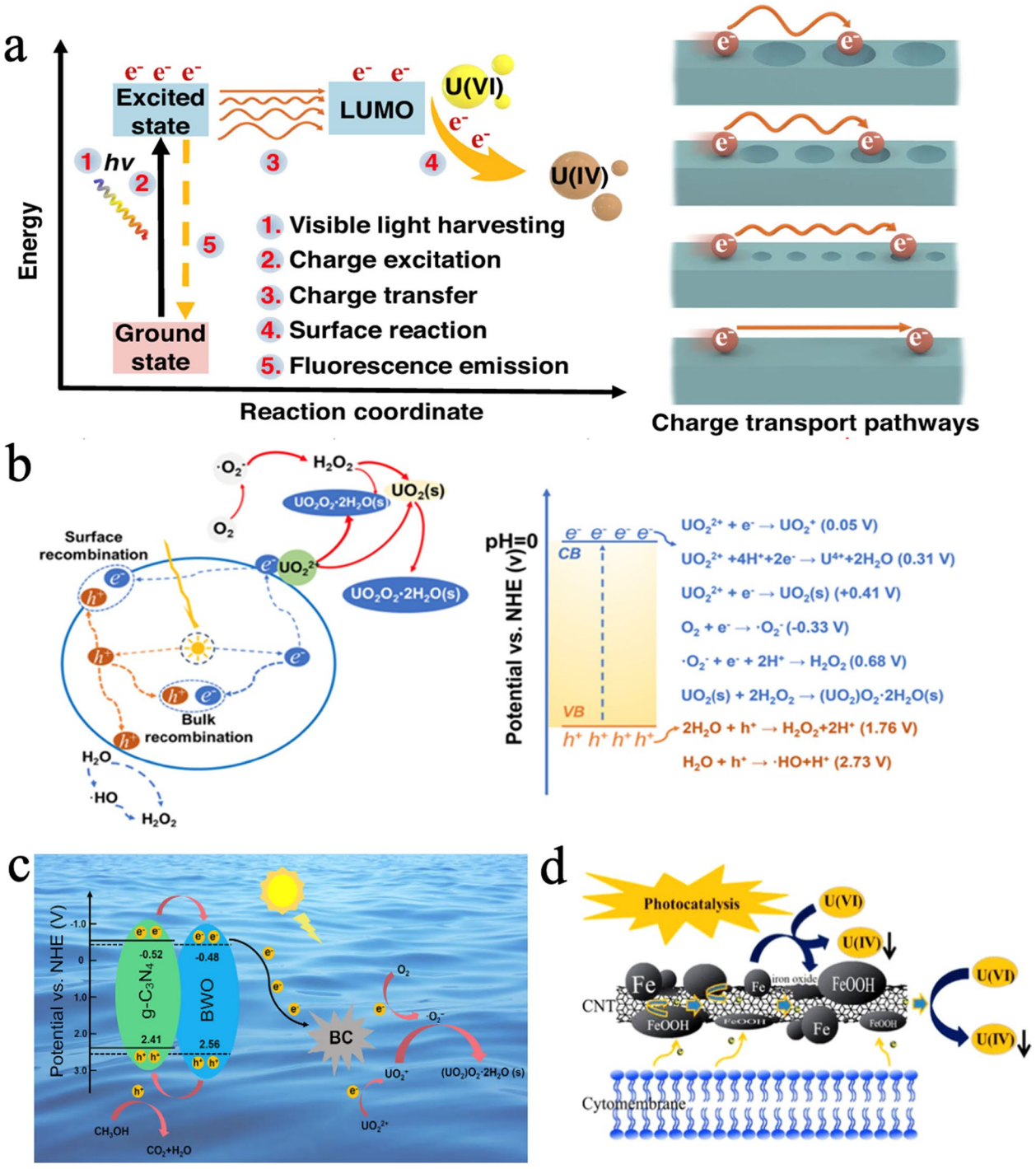


Fig. 5 **a** Generation of electron–hole pairs and electron transfer to adsorbed U(VI) (Chen et al. 2023b); **b** Possible mechanisms of U(VI) photocatalytic separation from solutions (Dong et al. 2025); **c** Mechanism of photogenerated $\cdot O_2^-$ and e^- reaction with surface adsorbed U(VI) to form $((UO_2)O_2 \cdot 2H_2O$ (Zhang et al. 2025a); **d** Photocatalytic reduction of U(VI) to form U(IV)O_2 precipitates (Xiang et al. 2020)

separation of U(VI) from different aqueous solutions. In the solutions containing *S. Putrefaciens*, the *S. Putrefaciens* and ZVI-supported carbon exhibited a synergistic effect on U(VI) photocatalytic reduction to form U(IV) solid products (Fig. 5d). From the XRD and XPS characterizations, the presence of *S. Putrefaciens* decreased the interfacial energy barrier, enhanced electron transfer to adsorbed U(VI), and thereby improved the photocatalytic

reduction of U(VI). This work highlights that the presence of *S. Putrefaciens* in aqueous solutions can not only reduce U(VI) itself, but also promote the photocatalytic activity through the reduction of the energy barrier and enhancement of electron transfer.

Challenges and perspective. From the above-mentioned research studies on photocatalytic preconcentration of U(VI) from various solutions, one can conclude that the incorporation of metal oxides and/or nonmetal oxides and/or catalytic particles, and doping of single metal atoms on biochar are the most efficient techniques to enhance photocatalytic activity of the semi-conductor photocatalysts. Biochar can provide enough active sites and special functional groups to improve the sorption ability of U(VI) ions, to enhance the photocatalytic generation/separation of electrons and holes, to accelerate the transfer of separated electrons, and to reduce the bandgap energy, thereby improving the sorption ability and photocatalytic activity for U(VI) photocatalytic reduction (Mian and Liu 2018). However, there are still some aspects which should be considered, such as the effect of heating operation conditions for biochar synthesis, the ratio of biochar to other materials, and incorporation conditions for synthesis of biochar-based photocatalysts, which are crucial parameters to improve the photocatalytic properties of biochar-based photocatalysts in the selective binding of U(VI) and then further photocatalytic reduction of U(VI). Studies on the mechanism by which photogenerated H_2O_2 interacts with the adsorbed U(VI) to form $(UO_2)O_2{\cdot}2H_2O$ precipitates are still scarce, which may be related to biochar-based catalysts' physicochemical properties. The final products are dominated by the photogenerated active species, which are closely related to the physicochemical properties of biochar-based photocatalysts. Although the photocatalytic activities of biochar-based photocatalysts are still lower than those of other kinds of nano-catalysts such as C_3N_4, MOFs or COFs, it is necessary to point out that biochar-based photocatalysts can be easily prepared on a large scale and at low cost. The low cost, environmental friendliness, high reusability, and stability are the advantages of biochar-based porous materials for the real applications in the future.

3.4 Electrocatalysis

Key parameters of electrocatalysis. Electrochemical strategy is also a promising technique to preconcentrate U(VI) from complex systems continuously. Under suitable voltage and electron current conditions, the soluble U(VI) ions can move to the cathode. The special functional groups of electrodes could bind U(VI) species with high relative selectivity, and the electrons could then react with the adsorbed U(VI) ions for electroreduction of U(VI) into UO_2 solid or through electron transfer to form other kinds of precipitates, which are related not only to solution conditions but also to the electrode properties. Another mechanism is electro-generation of H_2O_2 through the reaction of $O_2 + H_2O \rightarrow H_2O_2$, followed by the precipitation reaction of $UO_2^{2+} + H_2O_2 \rightarrow (UO_2)O_2{\cdot}2H_2O$ to realize the efficient precipitation of U(VI) on electrode. One can see that the mechanisms of U(VI) separation by electrocatalysis strategy are very similar to those by photocatalysis strategy. The common points of the two methods are the use of active free species or H_2O_2 for U(VI) reduction or precipitation. The differences are the active species generated by electrical conditions or light irradiation, and the materials used as photocatalysts or electrocatalysts.

Recent representative studies and mechanisms. Wang et al. (2025b) synthesized N/P co-doped graphene-like biochar, and then used the N/P-co-doped biochar as an electrode for electro-sorption of U(VI) from different wastewaters. The amidoxime-containing groups could form strong chemical complexes with U(VI) with high selectivity, and the $-PO_3/C-O-PO_3$, $-OH$, and $-C(NH_2)=NOH$ functional groups could also synergistically bind U(VI), which further enhanced U(VI) sorption to the graphene-like biochar (Fig. 6a). Through amidoxime coordination chelation with coupling double electric layer enrichment, electrosorption equilibrium of U(VI) (with the maximum sorption capacity of 987 mg g^{-1}) was achieved in 6 h with the distribution coefficient (K_d) value of 1.1×10^4 mg L^{-1} from solutions. This work provides a novel approach for biochar as an electrode in electrosorption of U(VI) from wastewater. Yang et al. (2021) functionalized single Fe-atoms on N-doped porous carbon to construct Fe-Nx active centres on an electrode, and then grafted functional amidoxime groups to the porous carbon (denoted as Fe-Nx-C-R). The amidoxime special functional groups contributed to the highly selective and strong binding of U(VI) from solutions to Fe-Nx-C-R, whereas Fe-Nx centres acted as a reversible platform for electron reversible transfer. Using the Fe-Nx-C-R porous carbon as an electrode, the electrochemical extraction of U(VI) from the real natural seawater showed that U(VI) could be deposited on the surface of electrode continuously from natural seawater through electrochemical transformation of U(VI) to generate U-containing precipitates, on Fe-Nx-C-R. The results of XRD, Raman, XAFS, and Mössbauer transmission characterizations indicate that the electro-adsorbed U(VI) is initially reduced to unstable U(V) species by electrons, which are subsequently re-oxidized to form $Na_2O(UO_3{\cdot}H_2O)_x$ precipitates in the presence of high concentrations of Na^+. It is interesting to note that $Na_2O(UO_3{\cdot}H_2O)_x$ precipitates were not formed in groundwater or other solutions

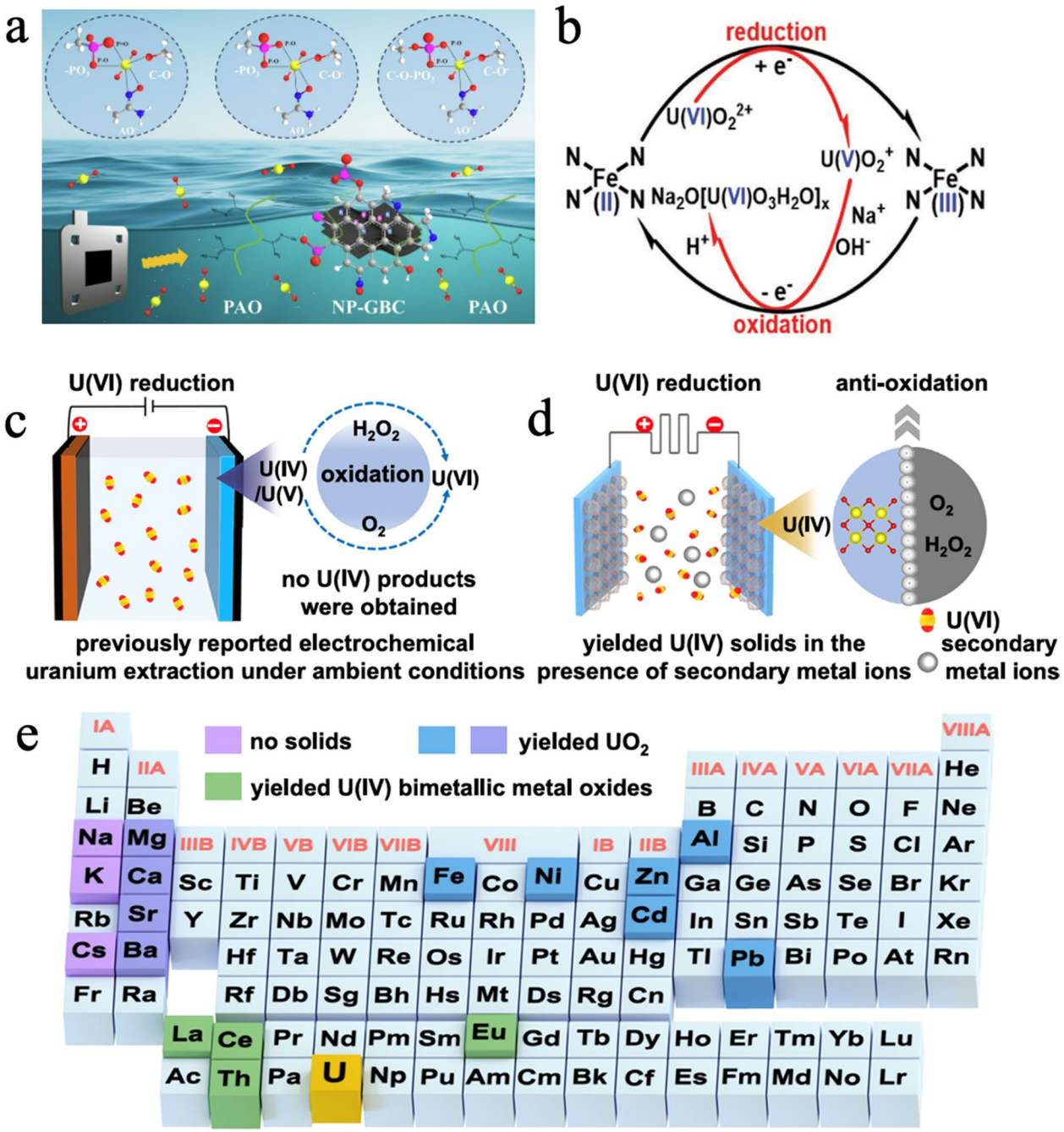


Fig. 6 **a** Electrochemical removal of U(VI) through amidoxime group, $-PO_3$/C–O–PO_3 and $-C(NH_2)=NOH$ groups to form strong surface complexes with U(VI) (Wang et al. 2025b). **b** Reduction of U(VI) to form U(V) and then re-oxidation of U(V) to form $Na_2O(UO_3{\cdot}H_2O)_x$ through electron transfer processes (Yang et al. 2021). **c** Traditional electrochemical U(VI) extraction method (Liu et al. 2024b). **d** Square wave conversion technique for U(VI) extraction(Liu et al. 2024b). **e** Electrochemical separation of U(VI) from wastewater containing different metal ions (Liu et al. , 2024b)

without high concentrations of Na^+, suggesting the contribution of Na^+ ions on U(VI) chemical transformation from U(VI) species to form stable $Na_2O(UO_3{\cdot}H_2O)_x$ solids. In this process, the amidoxime-containing special groups contributed to the highly selective binding of U(VI), whereas Fe-Nx centres acted as a platform for electron reversible transfer (Fig. 6b). This work highlights the construction of electron transfer platform and modification of special functional groups on biochar, and its subsequent use as an electrode for continuous

separation–preconcentration–solidification of U(VI) ions from the natural seawater, which is a promising technique for continuous electrochemical extraction of U(VI) in real applications. Liu et al. (2024a, b) designed single gallium atoms on nitrogen-doped porous carbon (denoted as Ga-Nx-C) and then used it as an electrode for electrocatalytic reduction of U(VI) to achieve U(VI) separation from various wastewaters. Different from the traditional electrochemical U(VI) extraction method (Fig. 6c), the authors used a square wave conversion technique to extract U(VI) from U(VI)-containing solutions (Fig. 6d). It is necessary to note that U(VI) ions were not extracted from wastewater only containing alkali metal ions, formed UO_2 precipitates from solutions containing transition metals or alkaline earth metals, and formed U(IV)-containing bimetallic oxides from wastewater containing lanthanide/actinide metal ions, through 2-electron transfer processes (Fig. 6e). Advanced spectroscopic characterizations and theoretical calculations revealed that the strong interaction affinity between U(VI) ions and metal ions suppressed the re-oxidation of U(IV) to U(VI), thereby resulting in the formation of $U(IV)O_2$ or bi-metallic $U(IV)_xM_yO_2$ (M represents lanthanide or actinide metals) precipitates. This research work highlights the electrocatalytic extraction of U(VI) from solutions to form $U(IV)O_2$ or $U(IV)_xM_yO_2$ solid products, not U(VI) solid products, which is of board interest for the solidification-separation of U(VI) ions from different kinds of wastewater containing different kinds of metal ions. U(VI) can form bi-metallic oxides directly from solutions, which is the first important step to preconcentrate U(VI) from different kinds of wastewater. Fan et al. (2025) synthesized Cu-based single atom carbon nitride (Cu-SA/C_3N_4) and applied it for the photocatalytic, electrocatalytic, and photoelectric cooperative methods for U(VI) separation from solution. The results showed that ~98% U(VI) could be removed within 5 min at pH 6 and U(VI) concentration of 10 mg L^{-1} through the photoelectric method. More importantly, the removal rate of photoelectric method was 13 times that of electrocatalysis and 23 times that of photocatalysis alone. The Raman and XRD characterization indicated the formation of U(V) unstable intermediates, which were then re-oxidized to form $Na_2O(UO_3{\cdot}H_2O)_x$ precipitates on the electrode. The single-atom electrocatalysis and photocatalysis were fully utilized to enhance the removal rate. This work highlights the combination of photocatalysis and electrocatalysis to improve the removal efficiency continuously.

Challenges and perspective. From the aforementioned studies, one can see that the mechanisms of U(VI) electrochemical extraction from solutions are dependent on the physicochemical properties of the electrode and the methods used in the processes. The solution properties, such as the concentrations of different coexisted metal ions, types of coexisting metal ions, pH values, coexisting organic chemicals, affect the final products of U(VI) on the electrode obviously. The mechanism for U(VI) transformation to final products is affected by electrochemically generated active species, the species and types of co-present metal ions, and the used methods such as voltage and electric current. Like photochemical separation of U(VI) from various solutions, the final products are mainly dependent on the electrogenerated active species, which then interact with U(VI) to form the final precipitates through different mechanisms. Nevertheless, the highly selective extraction of soluble U(VI) ions from various complex systems is crucial for the continuous extraction of U(VI). Based on the high efficiency, selectivity, stability, and continuous deposition properties, we think that the electrochemical method is a promising way for U(VI) separation in real applications in near future.

3.5 Other strategies

Besides the above-mentioned techniques, different methods can also be studied for U(VI) removal from different kinds of solutions, which is generally related to the coexisting substances in solutions and the surface/structure properties of biochar-based porous composites.

Bio-sorption and bio-reduction. Bio-reduction of soluble U(VI) to insoluble $U(IV)O_2$ is one efficient way for U(VI) removal from wastewaters, which is an environmentally friendly way to separate U(VI) with high relative efficiency and economic cost. Yang et al. (2025b) modified biochar with nitric acid (denoted as RHB) and applied RHB as an adsorbent to study the effect of oxygen-centred persistent free radicals on U(VI) biosorption and bioreduction through *Desulfovibrio vulgaris*. The results showed that RHB achieved U(VI) reduction efficiency with about a 57% increase as compared to the unmodified biochar. The increase of U(VI) reduction was mainly attributed to the high concentration of oxygen-centred persistent free radicals in the leachate of RHB. The soluble oxygen-centred persistent active free radicals could mediate the extracellular transfer of electrons for *Desulfovibrio vulgaris,* which enhanced U(VI) biosorption and bioreduction. This work highlights the use of microbial flora-biochar for biochar-mediated biosorption and bioreduction of U(VI) to improve U(VI) separation from wastewater. The biochar contributed to the sorption of U(VI), whereas the microbial flora further bioreduced the adsorbed U(VI) to form U(IV) precipitates on biochar.

Piezo-catalysis. Cai et al. (2022) synthesized a piezocatalyst and applied it for the piezo-catalytic separation of U(VI) with highly selective extraction efficiency from

different types of solutions. Under ultrasound irradiation conditions, electron–hole pairs were piezo-catalytically generated, and H_2O_2 was also generated through the reaction of soluble O_2 with H_2O. Electrons transferred to the adsorbed U(VI) and reduced U(VI) to produce the UO_2 solid, whereas H_2O_2 reacted with the adsorbed U(VI) to form $(UO_2)O_2{\cdot}2H_2O$ solid. Under the piezo condition, the piezo-catalyst generated free active species, which reacted with the U(VI) adsorbed on piezo-catalyst surface and thereby extracted U(VI) from the complex solutions. For the use of piezo-catalysis strategy, it is necessary to note that the biochar-based porous composites should have piezo-catalytic properties and highly selective binding ability with U(VI), which is crucial for piezo-catalytic removal of U(VI). Reports on raw biochar materials as piezo-catalysts are still scarce, which is mainly attributed to the non-piezo-catalytic properties of raw biochar. Doping/(co)doping of some special metal oxides/bimetallic oxides with biochar, which may have piezo-catalytic properties, could generate free active species under ultrasound irradiation. Theoretically, the utilization of mechanical energies harvested from different types of natural activities, such as wind, flowing water, tides, ocean waves, and rain drops, could generate piezo-catalytic activities. For piezo-catalyst, the use of natural activities is a green environmentally friendly way for piezo-catalytic applications. Considering the special outstanding properties of biochar-based porous materials, it is undoubtedly that biochar-based porous composites cooperating with some special types of (bi)metal oxides will be applied as piezo-catalysts for U(VI) piezo-catalytic extraction in real applications. The piezo-catalytic method for U(VI) separation using biochar-based porous composites is still in its infancy, and more details such as effects of coordinated (bi)metal oxides on piezo-catalytic activity, effects of different parameters on U(VI) piezo-catalytic extraction, and the characterization of the final products should be studied.

Sorption-chemical deposition. In the sorption processes, it is inevitable to accompany chemical deposition. Huang et al. (2025) modified different kinds of functional groups such as hydroxyl, sulfur and amino groups on Cu-MOF@CSTA and applied for U(VI) removal from different wastewater. The results showed high sorption capacity with high selectivity, achieved 2507 mg g^{-1} at pH = 5, suggesting the potential applications in real wastewater treatment. Theoretical calculation and spectroscopic analysis suggested that the functional groups contributed U(VI) binding through chemical sorption and the Cu^{2+} also facilitated U(VI) interaction. The high sorption ability was also attributed to the chemical deposition through the hydrogen and hydrophobic binding interactions, which further resulted in the deposition and precipitation of U(VI). It is necessary to note that the contribution of chemical deposition, sorption and other mechanism on U(VI) separation is qualitative. The precise quantitative analysis of the contributions of different parameters on U(VI) binding is still difficult, even at in-situ on-line analysis.

Crystallization separation. Crystallization is a promising method for highly selective separation of target nuclides. Li et al. (2025b) applied a crystallization method to separate U(VI) from simulated nuclear wastewater and achieved high separation factors with other co-existing ions such as Ce, Pr, Eu, Gd, Y, and Dy. The efficient separation of U(VI) was mainly dominated by the properties of special ligands. Shore et al. (2025) utilized noncovalent interactions to form U(IV)-chloro crystallization units. The UV–vis–NIR spectroscopic characterization showed the uranium-crystallization structures in the +4 oxidation state. Wang et al. (2025c) used (*E*)-*N*′-(pyridin-2-ylmethylene) picolinohydrazide (PYPH) for U(VI) recovery from spent fuel. The PYPH reacted with U(VI), forming PYPH-U crystalline structures with 2D coordination complexes with >99% selectivity and purity. However, it is necessary to point out that the crystallization strategy for U(VI) separation is mainly related to the ligand used to form U-crystal structures. The application of biochar and biochar-based porous materials for the formation of U-crystal structures is still not available. The formation of U-crystal structures occurred between free ligand and soluble U(VI) ions in solution. For biochar and biochar-based porous materials, no free ligand was available to react with U(VI) ions.

4 Machine learning in property evaluation

With the increasing diversity of biochar feedstocks, modification strategies and experimental conditions, evaluation of U(VI) sorption performance has become increasingly complex, motivating the adoption of ML as a data-driven approach for quantitative prediction and key factor identification in the biochar–uranium systems. Different modeling strategies, including regression models, ensemble methods, and neural networks, exhibit distinct advantages in terms of interpretability, predictive accuracy, and applicability to complex systems. Da et al. (2022) employed ML techniques to predict U(VI) sorption capacities of biochar. Four regression models (support vector regression, linear regression, multilayer perceptron neural networks, and random forest) were developed, which incorporated multiple influencing factors including biochar physicochemical properties and experimental conditions. Model performance was assessed using statistical error metrics, including the RMSE (root mean square error) and R^2 (the coefficient of determination). The results demonstrated that the

multilayer perceptron model achieved the highest predictive accuracy. Feature importance analysis further revealed that experimental conditions and specific surface area exert a stronger effect on U(VI) sorption than chemical composition of biochar (Fig. 7a). Independent batch adsorption experiments were conducted to verify its generalization capability, and the verification results are satisfactory. This study demonstrated the vast application prospects of ML technology in adsorption research. Jun et al. (2025b) synthesized pristine biochar and ZnFe-modified biochar, and applied them for U(VI) removal from real acidic effluent solutions. The ZnFe-modified biochar had much the surface area of ~1218 m^2 g^{-1}, much higher than the pristine biochar (~41 m^2 g^{-1}), whereas the pristine biochar had much higher U(VI) sorption capacity than the ZnFe-modified biochar. At pH 4, the pristine biochar had a negative surface charge, whereas the surface charge of ZnFe-modified biochar was positive, which hindered U(VI) sorption through electrostatic repulsion. The authors used ML models (LGBM, XGBoost, and RF) to evaluate the relationship of U(VI) sorption with experimental conditions, and the relative

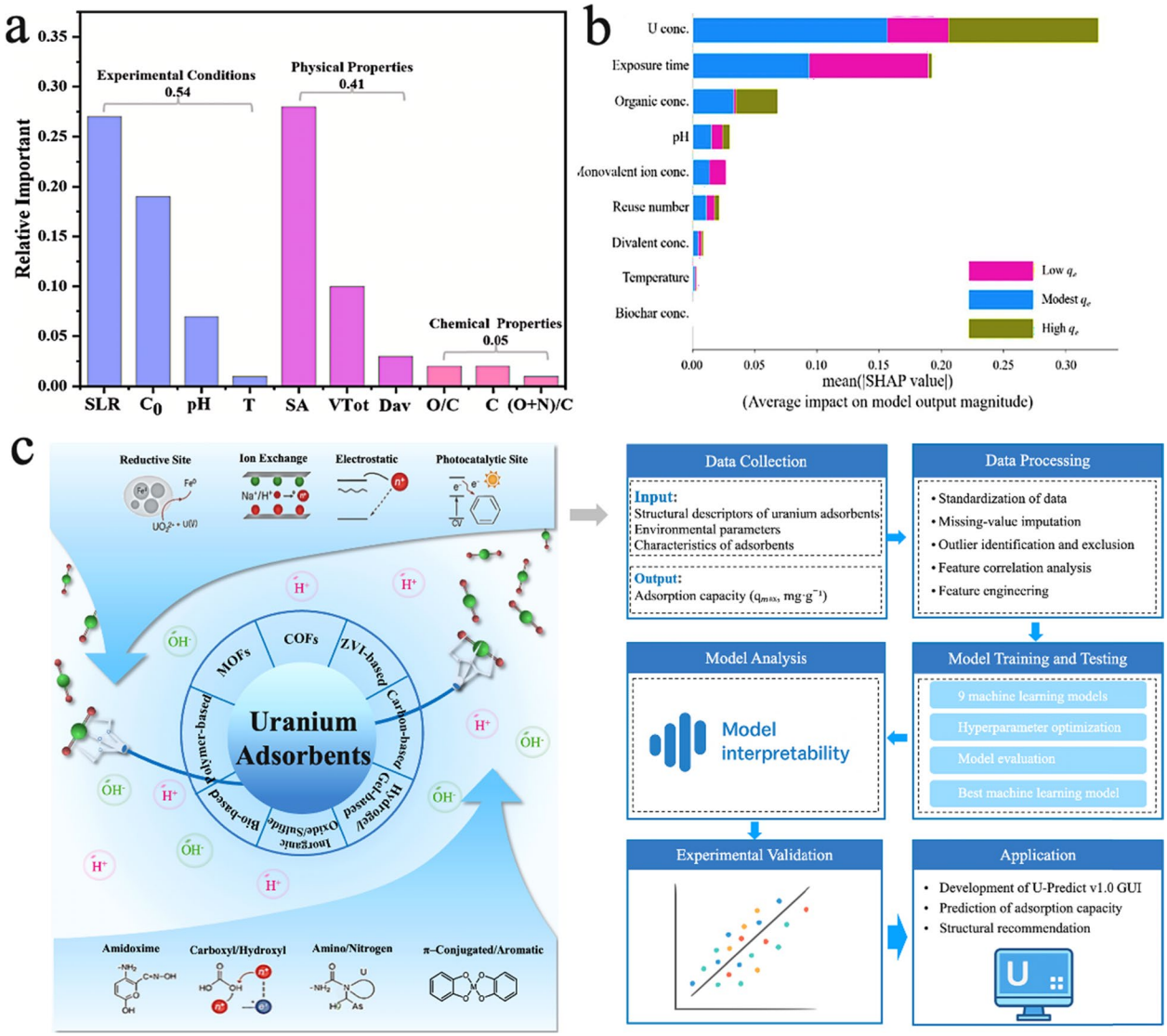


Fig. 7 Machine learning–assisted evaluation of U(VI) adsorption performance of biochar-based materials. **a** Relative contribution of experimental conditions, physical properties, and chemical properties derived from multilayer perceptron-based input factor contribution analysis (Da et al. 2022). **b** SHAP-based global feature importance showing the contributions of individual variables to adsorption capacity (q_e) (Jun et al. 2025b). **c** Integrated schematic of an interpretable machine learning framework and uranium adsorption-related material features considered in data-driven analysis (Sun et al. 2026b)

contributions of different features to the q_e (target data) values were subsequently examined using the SHAP (SHapley Additive exPlanations) analysis, which identified exposure time, initial U(VI) concentration, and solution pH as the most influential parameters governing adsorption behavior (Fig. 7b). Sun et al. (2026b) extended ML applications beyond individual biochar systems by establishing a literature-derived sorption database and developing an interpretable ML framework to predict uranium sorption performance across diverse adsorbent materials (Fig. 7c). By integrating structural descriptors, environmental parameters, and adsorption metrics, the proposed model achieved robust predictive performance across highly heterogeneous, literature-derived datasets, while providing mechanistic insights through feature attribution analysis. The results revealed that uranium sorption capacity is jointly governed by functional group chemistry, solution pH, and surface area through nonlinear interactions, highlighting the importance of synergistic structure–environment effects rather than any single physicochemical parameter. Although not limited to biochar materials, this work demonstrates the potential of explainable ML approaches to uncover generalizable structure–performance relationships and guide rational adsorbent evaluation and optimization. Because the structures of biochar are indeterminate, the description of the biochar structure–sorption relationship by ML is still difficult. With the development of artificial intelligence (AI), the relationship between active sites, functional groups, porous structures, tunable pore channels and U(VI) interactions can be predicted, which is helpful for the design and post-modification of biochar and biochar-based porous materials to improve their ability to separate U(VI) from solutions. In the future, the integration of machine learning with experimental design and material optimization is expected to accelerate the development of high-performance adsorbents and enable more efficient and targeted uranium separation strategies.

5 Conclusion and perspective

Biochar-based porous composites, a kind of environmentally friendly porous materials, can be used as adsorbents, photocatalysts, or electrocatalysts, etc., for the selective and high sorption properties of U(VI) from various solutions. Different removal methods were reported for the removal of U(VI) ions through sorption, reduction or precipitation mechanisms, which were mainly dependent on the biochar/biochar-based porous materials' properties, and also related to the solution conditions. Sorption technique is a widely used method, which can be applied on a large scale. Under light irradiation, U(VI) species can be photocatalytically reduced to form UO_2 solids by the photogenerated electron reduction or form (UO_2) $O_2{\cdot}2H_2O$ precipitates by the photogenerated H_2O_2. U(VI) could continuously deposit on the electrode under electrochemical conditions, and the final product is strongly related to the properties of the electrode and solution conditions such as co-existing metal ions, pH. Microbes or bacteria can not only affect the interaction of biochar/biochar-based porous materials with U(VI), but also react with U(VI) through chemical complexation or bioreduction. Nevertheless, biochar/biochar-based porous materials exhibit relatively high removal efficiency in U(VI) separation from different solutions under various conditions. The mechanism of U(VI) preconcentration/separation is dependent on materials' properties and solution conditions.

Although great progress has been achieved in U(VI) separation from solutions using biochar and biochar-based porous materials, some challenges still exist for large-scale real applications, for example:

1) The high selectivity of U(VI) binding to biochar/biochar-based porous materials should be considered, although the selectivity can be achieved through modification of some special functional groups such as amidoxime groups, O-, S-, P- or N-containing groups;
2) The generation of active free radicals or H_2O_2 should be enhanced under visible light conditions, which is crucial for the enhancement of photocatalytic activity;
3) The antibacterial properties should be enhanced for efficient U(VI) extraction in the natural seawater;
4) The possible release of nanoparticles from biochar/biochar-based porous materials to solutions may cause eco-toxicity to the environment;
5) The stability of biochar-based porous materials under extra strong acidic or basic conditions is important, which affects the dissolution of metal oxides or metal particles from biochar-based porous materials to solutions;
6) Synthesis of biochar-based materials at low cost on a large scale under environmentally friendly conditions is an important parameter for real application;
7) The reusability of biochar-based porous materials for sustainable U(VI) extraction is helpful to improve U(VI) separation ability;
8) ML techniques for the construction of biochar-based porous materials to improve the sorption–photocatalysis or sorption–electrocatalysis abilities with high stability, reusability, and selectivity are still challenges because of the unknown porous structures of biochar;

9) The potential use of biochar-based porous materials in other areas after long-term usability may be a new "open window" for further utilization of U-loaded biochar-based materials;
10) Last but not least, some unknown challenges of biochar-based materials from "Bench to Buoy" may be faced and should be considered for real applications.

Although there are many above-mentioned problems for biochar-based porous materials in U(VI) separation from solutions in real applications, these difficulties can be resolved with the development of technology. From the advantages and outstanding properties, biochar-based porous composites should have promising applications in U(VI) extraction in the near future.

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Data availability
Authors can confirm that all relevant data are included in the article.

Declarations

Ethics approval and consent to participate
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