



Advanced Materials and Processes for Uranium Removal from Water: Mechanism, Selectivity and Scalability

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Abstract

Original Research Article

Background: Uranium contamination in water from mining, nuclear activities, and wastewater poses serious risks to human health and ecosystems. Traditional techniques lack selectivity in complex matrices, and are not readily scalable.

Aim: This review focuses on advanced materials and processes to remove uranium in water with special focus on mechanism, selectivity and scale. It sheds light on the latest advances in MOFs, COFs, graphene oxide, MXenes, amidoxime-based hydrogels and hierarchical materials.

Methodology: A thorough narrative review was performed through the synthesis of recent peer-reviewed studies (2024-2026) of databases such as Web of Science, Scopus, and Google scholar. Thematic analysis of key studies on material performance, characterization methods (XPS, FTIR, EXAFS), real-water tests, and pilot deployments was performed.

Findings: Advanced materials and processes for uranium removal from water demonstrate that high adsorption capacities (up to 1200 mg/g under laboratory conditions) are primarily governed by coordination/chelation and ion-exchange mechanisms, which underpin both selectivity and uptake efficiency. Materials such as hierarchical triple-channel polyamidoxime hydrogels exhibit notable performance, achieving 14.69 mg/g in natural seawater after 35 days without external energy input, and up to 43.89 mg/g in concentrated brine using PVPA-PAO composites. These systems show strong selectivity for uranium over competing ions and retain performance over multiple reuse cycles (≥ 5) even as scalability remains a challenge.

Conclusion: Uranium removal and seawater extraction have transformative potential in advanced materials and processes to sustain cleaner water and sustainable nuclear energy. The practical challenges to be addressed using structural engineering and life-cycle assessment will be paramount to large-scale implementation.

Keywords: Uranium removal, advanced adsorbent materials, metal-organic frameworks (MOFs), adsorption mechanisms and selectivity, water treatment technologies.

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1. Introduction

The problem of uranium contamination of water resources has become a major environmental and social issue in the world especially in areas where mining operations are undertaken, the use of nuclear energy and agriculture (Xie et al., 2023; Wang et al., 2021). Uranium is a naturally occurring radioactive element that can occur in geological materials, but its levels in water systems can be significantly increased by human activities like uranium mining and milling, processing of nuclear fuel, improper disposal of radioactive wastes, and the widespread use of phosphate fertilisers which usually contain trace levels of uranium (Zhu et al., 2023). These activities enable mobilization of uranium into surface and groundwater systems that cause increased risk of human exposure through drinking water and food chains (Liu et al., 2025; Liu et al., 2024).

Uranium is mainly found in the hexavalent oxidation state in aqueous environment as the uranyl ion (UO_2^{2+}) that is very soluble and mobile, particularly in oxidizing conditions (Xie et al., 2023). This chemical form is easily formed as a stable complex with carbonate and other ligands, which further increases its persistence in the aquatic systems (Kong et al., 2026; Zhang et al., 2024). Consequently, the uranium contamination is not just localized to the regions of direct industrial work but may extend over broad geographical areas, creating a long-term problem to the environment (Liu et al., 2024).

Uranium has a two-fold toxicological effect, which comprises both chemical and radiological toxicity (Wang et al., 2021; Zhu et al., 2023). Uranium mainly attacks the kidneys, the site of chemical action, resulting in nephrotoxicity with tubular damage and renal failure (Liu et al., 2025). Bone accumulation, liver dysfunction and possible carcinogenic effects have also been linked to chronic exposure (Liu et al., 2024; Kong et al., 2026). Radiologically, uranium is an emitter of alpha particles, which despite their poor penetration can be very destructive to biology when ingested (Xie et al., 2023). The presence of uranium levels in groundwater that are over the safe limits has been reported in various regions around the world such as parts of

Asia and Africa, raising the issue of serious concern about the health of the people (Zhang et al., 2024; Liu et al., 2024).

In order to curb such risks, the World Health Organization, and the United States Environmental Protection Agency have come up with guideline values of uranium in drinking water (Wang et al., 2021). The WHO recommends $30 \mu\text{g/L}$, while the US EPA sets a maximum contaminant level of $30 \mu\text{g/L}$ (Zhang et al., 2024; Liu et al., 2025). Even with these standards, a lot of communities, especially those in low- and middle-income nations, still use untreated groundwater sources that have a higher concentration of uranium that may surpass these levels (Xie et al., 2023).

Different technologies have been invented over the past decades to extract uranium in water, such as ion exchange, membrane filtration, chemical precipitation and adsorption (Zhang et al., 2024). Among them adsorption-based techniques have received much attention because of the simplicity of operation, cost-effectiveness, and versatility (Kong et al., 2026; Liu et al., 2024). However, traditional materials usually have drawbacks, including a low selectivity when used in the presence of other competing ions, low efficiency when used at different pH, and difficulties in their regeneration and for large-scale use (Zhu et al., 2023). This has led to an increasing requirement of innovative materials and processes that can attain high removal efficiency, and also be selective and scalable in realistic environmental conditions (Liu et al., 2025).

Here, new materials like functionalized biochar, carbon nanomaterials, metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and novel polymeric adsorbents have demonstrated good performance in the uranium remediation (Liu et al., 2025; Zhang et al., 2024). The materials have the ability to provide tunable surface chemistry, high surface area, and increased binding affinity toward uranyl ions, making them attractive to next-generation water treatment technologies (Kong et al., 2026; Liu et al., 2024).

Hence, the aim of this review is to review and analyze advanced materials and processes to

remove uranium in water, specifically their mechanisms of operation, selectivity to uranium in the presence of more complex aqueous environments, and scalability to large-scale operation. Combining the latest developments and determining the current challenges, the work tends to underline the perspectives of the future research and make contributions to the creation of efficient, sustainable, and practical solutions to treat uranium-contaminated water.

2. Methodology

This review employed a narrative synthesis approach to analyze the new developments in materials and processes in the area of uranium removal in aqueous systems, with special attention to the mechanisms, selectivity, and scalability.

The review focuses on identifying and evaluating progressive materials like carbon-based adsorbents, biochar, aerogels, metal-organic frameworks (MOFs), covalent organic frameworks (COFs), polymeric materials, and nanocomposites as well as the mechanisms that drive uranium removal. Literature has been chosen to represent both the pioneering research and the most recent advancements that have led to better removal efficiency, selectivity in complex aqueous matrices and scalability.

2.1 Literature Search

The extensive literature search was carried out in the reputable scientific databases, such as PubMed, Scopus, Web of Science, and Google Scholar. The search strategy was a combination of keywords and Boolean operators to get the relevant publications. The keywords that were used included uranium removal in water, uranyl adsorption sequences, high-capacity materials in removing heavy metals, biochar uranium adsorption, MOFs in extracting uranium, selective adsorption of U(VI), and scalable technologies in the treatment of water.

To focus on the latest developments in the field of material science and environmental remediation, the search focused on recent articles (2020-2025). There were no geographical restrictions and it was feasible to synthesize findings globally about uranium contamination

and remediation measures. Gray literature sources were considered to improve the scope and topicality of the review. These included technical reports, policy documents and guidelines of agencies like the World Health Organization and the United States Environmental Protection Agency.

Relevant experimental works assessing the uranium adsorption capacity, kinetics, isotherms and regeneration performance of different materials were incorporated. Pilot-scale and field-based studies were also taken into account where possible to determine the practical feasibility and scalability of the technologies suggested.

2.2 Synthesis of Data

The synthesis process aimed to integrate findings from diverse sources into a coherent and structured narrative highlighting key advances and challenges in the field. The selected literature was categorized into major thematic areas based on recurring concepts and research focus.

Findings from the literature were critically analyzed and synthesized to identify patterns, relationships, and knowledge gaps. Emphasis was placed on comparing material performance, understanding underlying mechanisms, and evaluating the practicality of implementation in real-world water treatment systems.

3. Advanced Materials and Processes

Advanced materials are key to the removal of uranium in water since they not only have high surface areas but also structures and functional groups that strongly bind uranium ions (Mei et al., 2023; Sun et al., 2023). These materials are designed to be effective even when the concentration of uranium is low, as well as when other ions are present in the water and competing against uranium (Chen et al., 2023; Dai et al., 2024).

3.1 Metal-Organic Frameworks (MOFs) and Covalent Organic Frameworks (COFs)

MOFs consist of porous networks of metal ions or clusters connected through organic molecules

(Mei et al., 2023; Cao et al., 2024). The number of pores can be increased or decreased and the surfaces can contain groups attracting uranium (Sun et al., 2023). MOFs have very large surface areas, most exceeding 1000 m²/g, and thus a great number of uranium ions can bind at once (Hou et al., 2024). Examples are ZIF, UiO and MIL series (Cui et al., 2023). To enhance water stability, scientists tend to incorporate magnetic particles or alter the linkers (Zhu et al., 2024; Huang et al., 2025).

For instance, Fe₃O₄@ZIF-8 reaches a q_{max} of 523.5 mg/g at pH 3 (Dai et al., 2024). The uranium is primarily held to the material by coordination between the atoms of zinc and the atoms of uranyl ions (UO₂²⁺) and hydrogen bonding. It is quick and can be removed from water by means of a magnet and reused (Sun et al., 2023).

COFs are analogous, except that strong covalent bonds between organic building blocks are employed in place of metal nodes (Chen et al., 2023). They create well-structured pores which are not easy to collapse in water and can conduct uranium ions rapidly (Mei et al., 2023). Among them is a TAPM-DHBD COF, providing a q_{max} of 955.3 mg/g over a pH range of 2–10 and it is still operative after 6 cycles of reuse (Cui et al., 2023). It is a coordination mechanism that is bidentate with nitrogen and oxygen atoms surrounding the uranyl ion (Hou et al., 2024; Cao et al., 2024).

MOFs and COFs are advanced useful materials as their pore sizes can be designed to be size-exclusive and their linkers to be selective (Cao et al., 2024; Hou et al., 2024). Nonetheless, certain MOFs tend to lose structure in the presence of strong acid or high salt content and their production may be expensive when large quantities are required (Mei et al., 2023). New efforts are directed at stabilizing them and simplifying their manufacture (Chen et al., 2023; Huang et al., 2025).

3.2 Carbon-based Materials

Graphene Oxide (GO) and Reduced Graphene Oxide (rGO). GO is a single sheet made of carbon saturated with oxygen groups like carboxyl, hydroxyl and epoxy (Dai et al., 2024;

Hou et al., 2024). These groups confer negative charge on GO which attracts positively charged UO₂²⁺ ions by electrostatics and coordination (Cui et al., 2023). GO is inexpensive, simple to prepare and disperses in water (Sun et al., 2023; Mei et al., 2023). rGO is the reduced form; it retains some oxygen groups but becomes more conductive and stable (Zhu et al., 2024).

An advanced example is the combination of GO with graphene oxide nanoribbons and chitosan (GO/GONRs/CS) (Chen et al., 2023). It reaches a q_{max} of 1208.85 mg/g. Oxygen and amino groups form strong complexes with uranium (Zhu et al., 2024). The aerogel has a high pH range, and displays high hydrophobicity, beneficial in practical wastewater (Mei et al., 2023). GO materials are highly kinetic and may accumulate or become nonselective in the presence of large numbers of competing ions (Sun et al., 2023). This is fixed by functionalizing them with amidoxime or polymers and enhances real-world performance (Zhu et al., 2024; Huang et al., 2025).

3.3 MXenes and Other 2D Materials

MXenes are 2D peeled layers of transition-metal carbides or nitrides. They possess –OH, –O, and –F surface groups, are highly conductive, as well as radiation resistant. Uranium is removed through ion exchange, inner-sphere complexation and occasionally reduction (Sharma et al., 2022). To ensure that uranium moves freely between layers, interlayer spacing can be adjusted by adding ions or molecules (Gandhi et al., 2024; Hussain et al., 2025).

A 3D/2D MnO/MXene heterostructure has a capacity of 862.1 mg/g with 99.7% removal and extremely fast kinetics- over 90% uptake in less than 20 seconds (Mahmoud et al., 2023; Yusan et al., 2024). The presence of the layered structure and oxygen vacancies result in numerous active sites. They involve chemisorption and hydrogen bonding. They are also proven to be functional in seawater with MXenes functionalized with amidoxime; capture is accelerated by the electric field or photothermal effect of sunlight. Theoretical q_{max} of 595.3 mg/g by DFT calculations of

pristine $\text{Ti}_3\text{C}_2(\text{OH})_2$ (He et al., 2023; Hussain et al., 2025).

MXenes have advantages of being fast and stable in radioactive environments, but pure MXenes can restack and lose surface area (Mahmoud et al., 2023; Yusan et al., 2024). Composites solve this (Sharma et al., 2022). Simple washing has good reusability (usually 5 or more cycles) (Gandhi et al., 2024; Hussain et al., 2025). Next-generation designs concentrate on bigger aerogels or membranes (Ahmed et al., 2023; Tian et al., 2025).

3.4 Nanomaterials: Magnetic, Functionalized Polymers, Amidoxime-Based, and Hierarchical Hydrogels

Magnetic nanomaterials are commonly Fe_3O_4 cores with functional shells, which allow scientists to remove the adsorbent with a magnet. This negates filtration which consumes a lot of energy (Yusan et al., 2024). A single magnetic amidoxime-functionalized composite is capable of high capacity and rapid separation whilst maintaining selectivity in complex water (Ahmed et al., 2023; He et al., 2023).

Amidoxime-based materials and functionalized polymers incorporate the amidoxime group ($-\text{C}(\text{NH}_2)=\text{NOH}$) that forms a stable five-membered ring with UO_2^{2+} . This provides a good selectivity even with vanadium or carbonate (Tian et al., 2025). Amidoxime hydrogels are able to swell in water and reveal additional sites. Faster release and reuse of temperature-sensitive polyamidoxime hydrogel (PAOU) is based on ion-imprinting.

Hierarchical hydrogels add macro-, micro-, and nanopores in one structure (Hussain et al., 2025; Tian et al., 2025). This solves slow diffusion in thick materials (He et al., 2023). The HTC-PAO hydrogel, for example, has a honeycomb triple-channel design (Ahmed et al., 2023; Tian et al., 2025). In natural seawater it reaches 14.69 mg/g

after 35 days with no extra energy—2.4 times better than simple microporous versions (Hussain et al., 2025). Laminar flow through large channels and fast diffusion in small pores explain the gain (He et al., 2023; Ahmed et al., 2023). It regenerates 5 times with $\text{Na}_2\text{CO}_3/\text{H}_2\text{O}_2$ and resists biofouling (Tian et al., 2025; Hussain et al., 2025). Another hierarchically porous polyamidoxime/ZIF-8 hybrid aerogel hits 741.6 mg/g in lab tests (Ahmed et al., 2023; Tian et al., 2025). PVPA-PAO hydrogel achieves 43.89 mg/g in concentrated seawater after 24 days. These materials balance high capacity in lab water with realistic performance in seawater (Ahmed et al., 2023; Tian et al., 2025).

Advantages include low cost and easy scaling (Hussain et al., 2025; Ahmed et al., 2023). Limits are biofouling in long-term marine use and lower capacity in very dilute solutions unless pores are optimized (Tian et al., 2025; He et al., 2023).

3.5 Hybrids and Composites

Hybrids combine the best traits of different materials (Hussain et al., 2025; Ahmed et al., 2023). A GO-COOH/UiO-66 composite gives 188.3 mg/g at pH 6–9 through synergy between GO's oxygen groups and MOF pores (Mahmoud et al., 2023; Yusan et al., 2024). Magnetic hybrids add easy recovery (Sharma et al., 2022; Gandhi et al., 2024). MXene/MOF or amidoxime/MXene composites boost selectivity and speed (Hussain et al., 2025; Ahmed et al., 2023). One nZVC/ Ti_3C_2 nanocomposite uses reduction plus adsorption for high efficiency in wastewater (Tian et al., 2025; He et al., 2023).

Hybrids often show better reusability (5–8 cycles) and work in real matrices because one component handles stability while another provides binding sites (Hussain et al., 2025; Ahmed et al., 2023). They represent the future for scalable systems (Tian et al., 2025; He et al., 2023).

Table 1. Performance comparison of selected advanced materials for U(VI) adsorption
(representative recent examples; capacities from batch tests unless noted)

Material	Type	q_{\max} (mg/g)	Optim al pH	Kinetics	Reusabil ity (cycles)	Key Mechanism	Notes
Fe ₃ O ₄ @ZIF-8	MOF (magneti c)	523.5	3	Fast	Good	Coordinatio n, H- bonding	Easy magnetic separatio n
TAPM-DHBD COF	COF	955.3	2–10	Chemisorpt ion	6	Bidentate coordinatio n	Broad pH range
COFs/GO/CH aerogel	COF-GO hybrid	1191	6	Pseudo- second- order	5	Inner- sphere complexatio n	Wastewa ter tested
GO/GONRs/CS aerogel	GO- based	1208.85	Wide	Pseudo- second- order	Multiple	Chemisorpti on	High capacity
3D/2D MnO/MXene	MXene composit e	862.1	–	>90 % in 20 s	Good	Chemisorpti on, reduction	Ultra- fast
HTC-PAO hydrogel	Hierarchi cal amidoxi me	14.69 (seawat er, 35 d)	Natura l	Diffusion- enhanced	5	Chelation	Real seawater, scalable
Polyamidoxime/ ZIF-8 aerogel	Hybrid hydrogel	741.6	–	Fast	Good	Synergistic sites	Lab high capacity

4. Removal Processes

Several processes can remove uranium from water (Li et al., 2022; Ye et al., 2022). Adsorption stands out as the most common and practical method today (Liao et al., 2024). Other approaches include electrochemical methods, membrane filtration, photocatalysis, bioremediation, and hybrid systems (Xing et al., 2023; Qin et al., 2023). Each process has its strengths and limits depending on the uranium concentration, water type, and goal (removal

only or recovery for reuse) (Al Saadi et al., 2026; Zhang et al., 2024).

4.1 Adsorption

Adsorption is the predominant method since it is easy, inexpensive and can be used at extremely low concentrations of uranium (Li et al., 2022; Liao et al., 2024). During adsorption, the uranium ions (primarily UO₂²⁺) are bound to the surface or the inside of the pores of solid materials (Huang et al., 2025). More complex

materials including MOFs, COFs, graphene oxide composites, MXenes and amidoxime-containing hydrogels frequently deliver high loads (hundreds of mg/g in laboratory) and rapid uptake (Zhang et al., 2024; Huang et al., 2025). The process is efficient in batch or column configurations and does not require much energy

(Li et al., 2022). It is popular among researchers in extracting contaminated groundwater as well as seawater (Liao et al., 2024; Zhang et al., 2024). But in real water, performance is deteriorated by the presence of competing ions and regeneration is required with repeated use (Li et al., 2022; Huang et al., 2025).

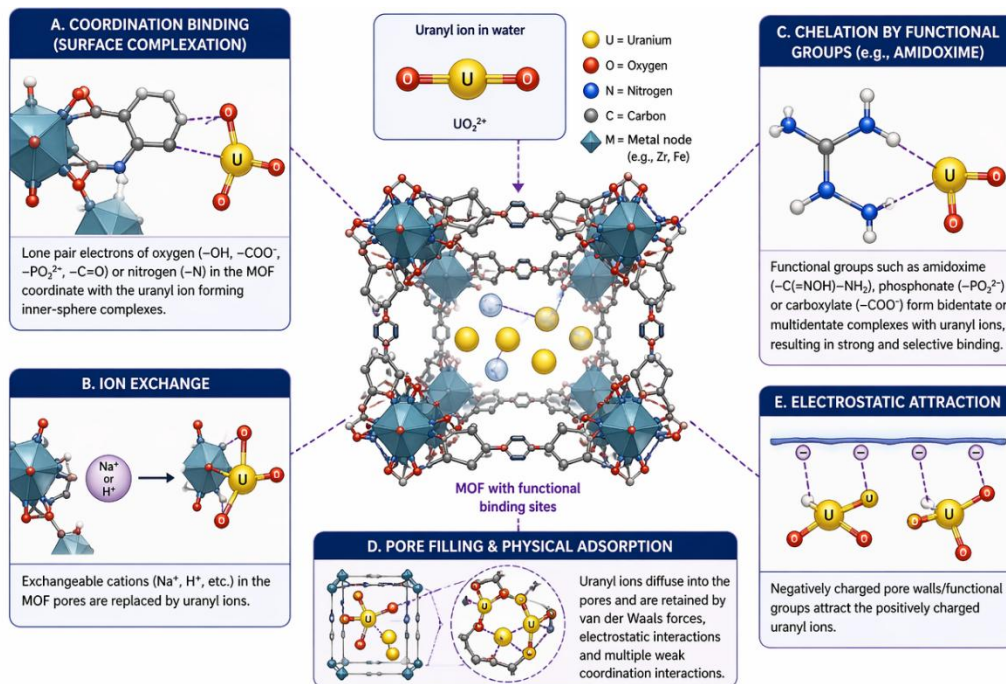


Figure 1: Mechanisms of uranium adsorption by MOFs

4.2 Electrochemical Processes

Active alternatives include electrosorption and electrocatalytic reduction which are electrochemical processes (Ye et al., 2022; Ye et al., 2023). The techniques use the voltage to propel uranium to electrodes or to reduce U(VI) to less soluble species (Ye et al., 2022). One of them involves adsorption in combination with electrocatalysis of amidoxime-functionalized materials with atomically dispersed indium (Ye et al., 2023). Electrochemical techniques have the potential to enhance selectivity and allow direct recovery, but they use energy and need stable electrodes that cannot be easily corroded

in salty or radioactive water (Ye et al., 2022; Al Saadi et al., 2026).

4.3 Membrane Filtration

Membrane filtration employs the special membranes to isolate uranium and allow clean water to go through (Xing et al., 2023; Xing, 2022). In certain cases these membranes are able to reject more than 95% of uranium (Xing et al., 2023). Nanofiltration or reverse osmosis membranes operate either by size exclusion or charge repulsion (Xing, 2022; Zhang et al., 2024). Continuous operation and high throughput are the key benefits (Xing et al.,

2023). But membrane tends to be contaminated (organic or mineral deposition), high pressure is required, and there is discharge of concentrates (Xing, 2022; Al Saadi et al., 2026). Combinations of filtration and adsorption layers demonstrate superior performance and reduced fouling (Zhang et al., 2024; Al Saadi et al., 2026).

4.4 Photocatalysis

Photocatalysis is the method of using light to activate compounds that reduce or oxidize uranium (Qin et al., 2023). Light can be used to produce photo-generated electrons, which can reduce soluble U(VI) to insoluble U(IV), and the latter can be removed more easily (Qin et al., 2023; Ye et al., 2022). Some designs of recent COF-based or semiconductor materials do this without additional chemicals (Zhang et al., 2024). Photocatalysis is appealing because of its sunlight utilization and the possibility of concomitant destruction of organic contaminants (Qin et al., 2023; Al Saadi et al., 2026). Difficulties are slow kinetics in low-light, radiation stability of catalysts, and good contact between light, catalyst and water (Qin et al., 2023).

4.5 Bioremediation

Bioremediation involves the use of microbes, algae or plants to remove or process uranium (Liao et al., 2024). Bacteria may either reduce U(VI) to U(IV) or biosorb on their cell wall (Ye et al., 2022). This method is environmentally friendly and cheap when high amounts of low-level contamination are involved (Al Saadi et al., 2026; Zhang et al., 2024). Nonetheless, it is most often slow, pH and temperature sensitive, and less active in high-salinity and toxic conditions (Li et al., 2022; Qin et al., 2023). It can be accelerated by combining biology with materials (bio-composites).

4.6 Hybrid Systems

Hybrid systems are systems in which two or more processes are combined to address the weaknesses that are present in each process (Zhang et al., 2024; Al Saadi et al., 2026). This

can be adsorption-electrochemical platforms, photo-assisted membranes, or material-enhanced bioreactors (Ye et al., 2023). The hybrids tend to provide better efficiency, selectivity and easy recovery of uranium. They are one of the bright perspectives of real-world applications where the individual processes do not suffice (Al Saadi et al., 2026; Zhang et al., 2024).

5. Mechanism of Uranium Removal

Knowledge of the mechanisms enables researchers to come up with improved materials and determine performance in various waters (Thakur et al., 2022; Zhou et al., 2022). The primary uranium removal mechanisms are coordination/chelation, ion exchange, electrostatic attraction, reduction and hydrogen bonding (Li et al., 2025; Tian et al., 2023). They are frequently in combination (Chen et al., 2022). Sophisticated characterization methods like X-ray photoelectron spectroscopy (XPS), fourier-transform infrared spectroscopy (FTIR) and extended X-ray absorption fine structure (EXAFS) give good indication of what occurs at the molecular level (Guo et al., 2025; Ye et al., 2022).

5.1 Coordination and Chelation

Much of the advanced material relies on the most important mechanism which is coordination or chelation (Tian et al., 2023; Li et al., 2025). Amidoxime ($-C(NH_2)OH$) and other functional groups create stable rings with the uranyl ion (UO_2^{2+}) (Thakur et al., 2022). The uranium is bidentately or η^2 bound by the nitrogen and oxygen atoms to form a powerful inner-sphere complex (Zhou et al., 2022; Guo et al., 2025). This is the reason behind the high affinity and selectivity of amidoxime-based hydrogels and polymers (Li et al., 2025; Tian et al., 2023). Uranium is frequently coordinated to two axial oxygen atoms and equatorial oxygen or nitrogen of the functional groups, as indicated by EXAFS data (Ye et al., 2022). XPS validates changes in binding energies of O 1s and N 1s following uptake of uranium and FTIR shows new U–O or variations in C=N and N–O vibrations (Chen et al., 2022; Guo et al., 2025).

5.2 Ion Exchange

The process of ion exchange happens between uranium species displacing other ions on the surface of the material or within pores (Chen et al., 2022; Thakur et al., 2022). In layered materials (MXenes or layered double hydroxides), the uranyl carbonate or hydroxide complexes replace the interlayer anions (such as nitrate) (Zhou et al., 2022). This is a rapid and reversible mechanism that helps in regeneration (Li et al., 2025; Tian et al., 2023). It is optimal over some pH values in which uranium is anionic complex (Guo et al., 2025; Ye et al., 2022).

5.3 Electrostatic Attraction

Initial contact is brought about by electrostatic attraction (Thakur et al., 2022; Zhou et al., 2022). A large number of materials have negative surface charge at neutral or slightly alkaline pH, which attracts the positively charged UO_2^{2+} (Li et al., 2025). This is supported by Zeta potential and pH-edge experiments (Tian et al., 2023; Chen et al., 2022). But the forces of electrostaticity alone are feeble and less specific than coordination (Guo et al., 2025).

5.4 Reduction

The soluble U(VI) is reduced to less mobile U(IV) (Ye et al., 2022; Guo et al., 2025). In photocatalytic process or electrocatalytic process, uranium is reduced by the electrons, precipitating as oxides or hydroxides (Tian et al., 2023). Certain materials (such as oxygen vacancies in MXenes) are partially reduced even during adsorption (Li et al., 2025; Zhou et al., 2022). In situ Raman and XAS assists in monitoring the transformation of U(VI) to intermediate U(V) or end product U(IV) (Ye et al., 2022; Guo et al., 2025). Uranium remains as U(VI) following binding in most cases of adsorption-dominant binding (Thakur et al., 2022).

5.5 Hydrogen Bonding

The other mechanisms are supported by hydrogen bonding (Chen et al., 2022; Tian et al., 2023). It is a complex between hydroxyl or

amine groups of the material and oxygen atoms of uranyl (Zhou et al., 2022). Broadening or shifting of OH and NH bands typically occurs in FTIR after adsorption (Li et al., 2025; Guo et al., 2025).

6. Scalability and Practical Challenges

The translation of high-tech materials used in laboratory tests is crucial to a practical effect (Wang et al., 2025; Arora et al., 2026). Even though a variety of materials perform well in the small batch tests, a variety of challenges occurs when translating lab into field (Lin et al., 2026). These are mass transfer constraints, high cost of production, regeneration challenges, long-term stability, biofouling in natural waters, energy usage and the necessity to evaluate life-cycle comprehensively (Kong et al., 2026; Al Saadi et al., 2026).

6.1 Mass Transfer Limits and Hierarchical Design Solutions.

Mass transfer often limits uranium uptake in thick or dense adsorbents (Wang et al., 2025; Lin et al., 2026). Diffusion of Uranium ions needs to occur between the bulk solution and the inner pores of the material (Kong et al., 2026). This is slow in traditional microporous hydrogels, particularly when the thickness of the material is more than a few millimeters (Arora et al., 2026). This minimizes efficient capacity and complicates large scale implementation (Bales et al., 2023).

This challenge is met by hierarchical structures (Wang et al., 2025; Kong et al., 2026). The bioinspired honeycomb triple-channel polyamidoxime (HTC-PAO) hydrogel is one of the successful examples (Arora et al., 2026). It has big millimeter-scale honeycomb channels with high flow of water, sub-millimeter transverse channels and natural micropores (Lin et al., 2026).

6.2 Costs in Synthesis and Operation

The greatest hurdle to mass adoption is production cost (Arora et al., 2026; Wang et al., 2025). The synthesis of certain MOFs and COFs

can take complex synthesis paths that use costly precursors and controlled conditions and are thus challenging to scale up (Iroegbu et al., 2025). Conversely, more basic approaches like freeze-thaw cycles, hydrothermal treatment or biological foaming (with yeast or ice templates) maintain the cost of hydrogels and aerogels lower (Kong et al., 2026). The present estimates of extracting seawater uranium with advanced amidoxime materials are in the range of 200 to 400 dollars per kilogram of the extracted uranium (Wang et al., 2025). These costs might be lower than those of conventional land mining, although they remain higher than that, as reusability and scale of production is improved (Arora et al., 2026; Kong et al., 2026).

6.3 Stability, Biofouling, and Environmental Durability

Long-lasting stability involves chemical resistance (pH fluctuations, high salinity), mechanical and radiation resistance (Arora et al., 2026; Wang et al., 2025). MXenes are typically radiation tolerant, and strong hydrogel networks do not degrade in flowing water (Kong et al., 2026).

Biofouling is a major problem in the marine environment (Lin et al., 2026; Bales et al., 2023). The surface can readily become covered with algae, bacteria and biofilms, which block uranium-binding sites, and performance declines rapidly over time (Arora et al., 2026). New designs have been designed to include antibacterial properties or antifouling to counter this problem (Wang et al., 2025; Kong et al., 2026). An example is how one PVPA-PAO composite hydrogel recorded a rate of 99.94 in antibacterial and a small decrease in capacity in open seawater than in filtered water (Lin et al., 2026).

7. Case Studies and Performance Benchmarks

Recent experimental works and pilot demonstrations offer useful standards of the performance of advanced materials in realistic conditions. These case studies are not limited to idealized laboratory tests but consider materials

in simulated seawater, natural seawater, concentrated brine and polluted groundwater.

7.1 Hydrogels in Natural Seawater with Hierarchy.

One such notable example is the HTC-PAO honeycomb triple channel hydrogel. It had a uptake capacity of 14.69 mg/g in 35 days in natural seawater with a uranium concentration of about 3.3 $\mu\text{g/L}$ and no external energy source. This was 2.4 times more compared to conventional microporous polyamidoxime materials. The thick 10 mm format worked effectively due to optimized mass transfer. The material was also shown to be selective to competing ions and could be repeatedly regenerated (5 times) maintaining much of its capacity.

This bioinspired hierarchical triple-channel polyamidoxime (HTC-PAO) adsorbent was developed in a study by Wang et al. (2025), which also achieved precisely these results. Their experiment demonstrated that the synergistic laminar flow (Reynolds number ≈ 922.5) and optimized diffusion pathways were achieved by the interlocked millimeter-scale honeycomb channels, sub-millimeter transverse channels, and intrinsic micropores. The improved mass transfer was proven by simulations in COMSOL, allowing the material to retain high performance at 10 mm thickness. Wang et al. (2025) also emphasized the advantages of the material with high ion selectivity, multiple-cycle reusability, and economical benefits to deploy on a large scale in the ocean.

7.2 Performance in Concentrated Seawater Brine

The PVPA-PAO composite hydrogel, recently reported by Wang et al. (2025), demonstrates strong performance in concentrated seawater brine (e.g., solar saltworks or desalination plants), achieving an adsorption capacity of 43.89 mg/g after 24 days. This enhanced performance is attributed to the anti-polyelectrolyte effect, which inhibits shrinkage under high-salinity conditions and preserves binding sites, resulting in significantly higher

capacity compared to conventional PAO hydrogels (~10 mg/g). In addition, the material exhibits very high antibacterial activity (99.94) and minimal capacity loss (6.29) in open (unfiltered) seawater relative to filtered conditions, indicating strong resistance to biofouling and highlighting its suitability for practical marine applications.

7.3 Groundwater Remediation

Phosphate-modified activated carbons have been found to be of practical use in the treatment of contaminated groundwater. Aluminum- and calcium-phosphate-modified versions extracted 94-99% of uranium in real groundwater samples in 5-30 minutes. Uranium levels were found to decrease to less than the WHO limit of 30 µg/L even in the presence of interfering anions like bicarbonate and fluoride. These materials were promising with capacities of 24.5 to 58 mg/g at a neutral pH and were therefore useful in the point area applications in mining regions.

Kuntaiah et al. (2025) synthesised aluminum-phosphate-modified activated carbon (Al-AC) and calcium-phosphate-modified activated carbon (CP-AC) and applied it to actual groundwater samples. The adsorption capacities of 24.5 mg/g in the case of Al-AC and 58 mg/g in the case of CP-AC were found in neutral pH where more than 94% of the removal took place within just 5 minutes. In real contaminated groundwater with typical interfering anions such as bicarbonate and fluoride, both materials decreased uranium levels to less than 30 µg/L (the WHO limit) and thus showed excellent potential in practice in mining-impacted areas.

7.4 Future trends to enhance better sustainability

Sustainability can be enhanced by making materials using renewable feedstocks (e.g., chitosan-based hybrids), with multiple reuse cycles, and low-energy operation. The integration of biodegradable materials and the ability to recycle all materials at end-of-life will add to the environmental profile. Detailed LCA, assessments of toxicity in natural waters, and designs with high performance and low

ecological footprint should also be considered in future research.

Finally, efficient regeneration, minimal operational effects, and the increasing interest in considering the full effects of life cycles all make advanced materials a promising avenue to a cleaner water and more sustainable management of nuclear resources.

8. CONCLUSION

Uranium extraction out of the water plays a crucial role in protecting the environment and ensuring nuclear fuel sustainability. MOFs, COFs, graphene oxide composites, MXenes and amidoxime-based hydrogel have demonstrated impressive developments. These materials can eliminate uranium well, by coordination, ion exchange, electrostatic attraction and reduction. They provide high capacities, rapid kinetics and enhanced selectivity when they are in the presence of competing ions such as sodium, calcium and vanadium. Just as recent case studies show real-world potential. Triple-channel polyamidoxime hydrogels with hierarchies are useful in uptake in natural seawater without added energy, whereas composites can be used in concentrated brine and groundwater. Massive marine experiments also substantiate that adsorption is the most practical technology towards seawater extraction. Mass transfer and biofouling problems are overcome by regeneration and hierarchical design, which aid reusability and reduced costs. Yet, the issues of scalability, long-term stability, energy consumption and overall life-cycle effects remain. The areas of low-cost synthesis, antifouling, hybrid electrochemical systems, and extensive pilot deployments should be the focus of future studies. As material engineering and process integration continue to improve, these technologies will be able to offer cleaner water, minimize radioactive pollution and tap into the huge reserves of uranium in the ocean. In the end, they will make nuclear energy safer and the energy future of the world more sustainable.

List of Abbreviations

AI – Artificial Intelligence
 BET – Brunauer–Emmett–Teller
 CDC – Centers for Disease Control and Prevention
 CNTs – Carbon Nanotubes
 COFs – Covalent Organic Frameworks
 FTIR – Fourier Transform Infrared Spectroscopy
 GO – Graphene Oxide
 HCO_3^- – Bicarbonate Ion
 IIPs – Ion-Imprinted Polymers
 ICP-MS – Inductively Coupled Plasma Mass Spectrometry
 ICP-OES – Inductively Coupled Plasma Optical Emission Spectroscopy
 Kd – Distribution Coefficient
 Langmuir Model – Langmuir Adsorption Isotherm Model
 ML – Machine Learning
 MOFs – Metal–Organic Frameworks
 NF – Nanofiltration
 NIH – National Institutes of Health
 pH – Potential of Hydrogen
 PSD – Pore Size Distribution
 R^2 – Coefficient of Determination
 RO – Reverse Osmosis
 SEM – Scanning Electron Microscopy
 TEM – Transmission Electron Microscopy
 U – Uranium
 U(IV) – Tetravalent Uranium
 U(VI) – Hexavalent Uranium
 UO_2 – Uranium Dioxide
 UO_2^{2+} – Uranyl Ion
 UV–Vis – Ultraviolet–Visible Spectroscopy
 WHO – World Health Organization
 XPS – X-ray Photoelectron Spectroscopy
 XRD – X-ray Diffraction

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