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Review Article

Remediation technologies for heavy metal-contaminated water resources

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Abstract: Heavy metals, including arsenic, lead, cadmium, chromium, mercury, copper, nickel, and zinc, are common contaminants in global water resources. Their occurrence stems from both natural geogenic and anthropogenic sources, such as industrial, mining, or urban activities. Heavy metals can be found in groundwater due to geogenic mobilization and leaching from ore deposits. They can also be found in streams and lakes impacted by mine drainage, industrial effluents, agricultural runoff, and urban stormwater. Elevated concentrations pose risks to human health and ecosystems, necessitating monitoring, remediation, and the safe management of generated residuals. A variety of technologies exist for heavy-metal removal. The selection and use of these technologies depend on contaminant concentration, speciation, and available resources. In this review article, the latest technologies for heavy-metal removal are presented and discussed. The availability and maturity of each technique, energy demand, management of generated residual, environmental impact, and recommended applications are discussed. Algal bioremediation and constructed wetlands are the most sustainable techniques due to their ecosystem benefits, carbon capture, and lowest energy consumption, while the most efficient industrial techniques are membrane technologies and ion-exchange systems due to their high metal selectivity and purity; however, the main restrictions are high cost and an energy-intensive nature. The most distinctive approach involves hybrid systems, which offer a more resilient and sustainable alternative by integrating complementary mechanisms that enhance flux stability, improve selectivity, and reduce energy consumption, such as the combination of Reverse Osmosis with Membrane Distillation (RO-MD) and Reverse Osmosis with Pressure Retarded Osmosis (RO-PRO). The hybrid approach, in various sequences, enhances efficiency, scalability, and ecological restoration.

Keywords: Adsorption; Electrocoagulation; Membrane technology; Algal bioremediation; Hybrid treatment systems.

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Introduction

Heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), copper (Cu), nickel (Ni), and zinc (Zn) are common pollutants found in groundwater, surface water including streams and lakes, coastal waters, and wastewaters (Agrawal et al., 2021; Jagaba et al., 2024). Their presence depends on both natural geochemical processes and human activities, such as mining, industrial operations, agriculture, urban runoff, and improper waste disposal (Daripa et al., 2023). The concentrations of these metals vary significantly by region and the nature of the specific metal (Jagaba et al., 2024; Liu et al., 2026; Xu et al., 2026). For example, groundwater contaminated with arsenic exposes tens of millions to hundreds of millions of people to unsafe levels (Podgorski and Berg, 2020).

It is essential to treat waters contaminated with heavy metals. They pose significant risks because they are persistent, non-biodegradable, and bioaccumulative. The harmful effects depend on their concentration, exposure pathway, and chemical form (Khalef et al., 2022; Hassan et al., 2025). Long-term exposure to arsenic is linked to skin lesions, cancers, cardiovascular disease, and

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diabetes (Garcia-Vargas and Cebrian, 2023). Arsenic is especially toxic in its inorganic forms, such as arsenite and arsenate. As a neurotoxin, lead impairs cognitive development in children, reduces IQ, and causes behavioral disorders. It also damages the kidneys and cardiovascular system and impairs blood formation. Meanwhile, cadmium causes kidney dysfunction, skeletal damage, and cancer. It bioaccumulates in the kidneys and liver (Prakash and Verma, 2021; Garcia-Vargas and Cebrian, 2023).

Methylmercury is highly neurotoxic and affects brain development in fetuses and children. It causes sensory impairment, tremors, and cognitive decline (Chamoli and Karn, 2024; Zafar et al., 2024). Cr (VI) is highly toxic and carcinogenic. It causes lung cancer and nasal, kidney, and liver damage (Hossini et al., 2022). Nickel can trigger allergic dermatitis and respiratory problems, and is classified as a carcinogen in some forms (Genchi et al., 2020). Copper (Cu) and zinc (Zn) are essential trace elements; however, at high concentrations, Cu causes gastrointestinal distress and liver and kidney damage, and Zn interferes with nutrient uptake in aquatic life (Naz et al., 2023).

These heavy metals cause bioaccumulation and biomagnification in the ecosystem. Metals like mercury, cadmium, and lead accumulate in organisms and biomagnify along the food chain, affecting fish, birds, and humans who consume them. Heavy metals are toxic to plankton, fish, and benthic organisms; they also disrupt reproduction and growth (Azar and Vajargah, 2023). Zinc and copper interfere with gill function in fish, leading to reduced oxygen uptake (Kwong, 2024). Mercury bioaccumulates in fish tissues, creating health risks for predators, including humans (Oros, 2025). For soil ecosystems, heavy metals bind to soil and affect microbial diversity and activity, reducing soil fertility and impairing decomposition and nutrient cycling (Naz et al., 2022). In the long term, contamination creates toxic hotspots where sensitive species disappear, only tolerant species survive, reducing biodiversity (Zhao et al., 2020; Agarwal et al., 2024).

Various technologies can be employed to treat contaminated waters, including physical, chemical, and biological methods. In this study, the latest technologies are exhibited and compared, including coagulation and precipitation, and nature-based solutions such as constructed wetlands and phytoremediation. Each treatment method has its own advantages and disadvantages concerning cost, effectiveness for specific metals and their species, energy and chemical consumption, residual waste, and overall environmental impact. In most practical scenarios, the best approach strikes a balance between using locally available and simple solutions, such as adsorption with low-cost, locally sourced materials or constructed wetlands suitable for resource-limited areas, and implementing higher-performance technologies such as nanofiltration or ion exchange for more centralized or industrial-scale applications. Finally, the availability of a selected technique, environmental impact, and energy demand are summarized for all discussed techniques.

1 Current global contamination status

Heavy metal accumulation in water streams and groundwater arises primarily from anthropogenic activities such as industrial discharges, agricultural runoff, and mining, alongside natural sources such as weathering of rocks and volcanic activity, as shown in Fig. 1. Surface water contamination by heavy metals is spatially patchy and strongly correlated with land-based anthropogenic activities, such as mining districts, industrial zones, and urban watersheds. These areas show elevated dissolved and particulate-bound metal loads (Taka et al., 2022). The United Nations Environment Programme (UNEP) highlights that global chemical pollution, including from metals, affects monitored sites in regional studies, causing chronic effects at many sites (Travnikov et al., 2020). Quantitative prevalence varies by metal and basin; aggregated global inventories are incomplete due to limited monitoring coverage in many regions. (Wong, 2025).

Urban stormwater and runoff often contain Pb, Zn, Cu, and Cd released from traffic, brake and tire wear, and building materials. These values can reach concentrations in the mg/L range during concentrated storm events or effluents from metal-processing facilities (Popick, 2022). Representative background concentrations of arsenic in low-impact groundwater typically range from 1 μg/L to 10 μg/L. Hotspot groundwater and mine-impacted waters often show concentrations ranging from tens to hundreds of μg/L, or higher in extreme cases (Irunde et al., 2022). Pristine surface and groundwaters usually have concentrations of lead, cadmium, copper, and zinc below 1 μg/L, whereas industrial discharge concentrations vary from tens to thousands of μg/L (i.e., 0.01–10+ mg/L), depending on the source (Hunt and Voulvoulis, 2020; Tunioli, 2025). Fig. 2 shows a schematic of

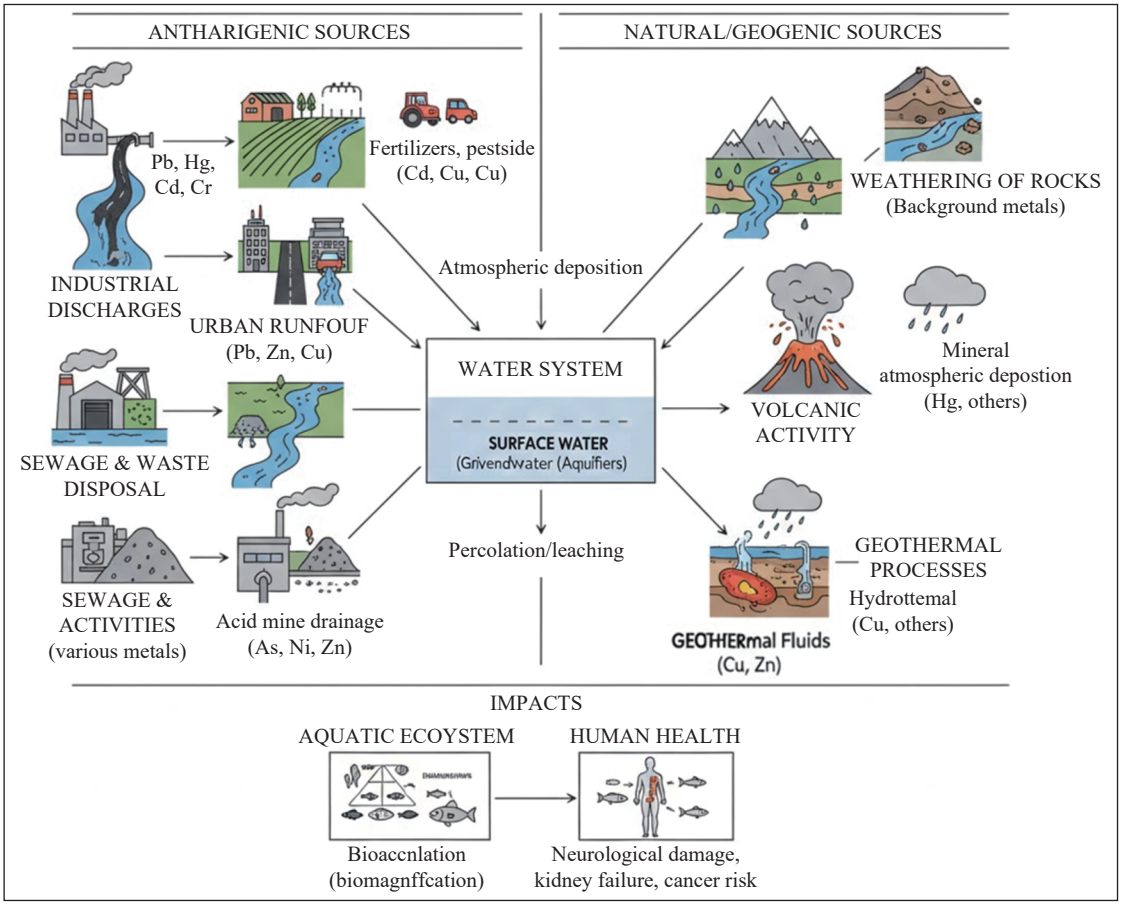


Fig. 1 Global heavy metal contamination sources and pathways

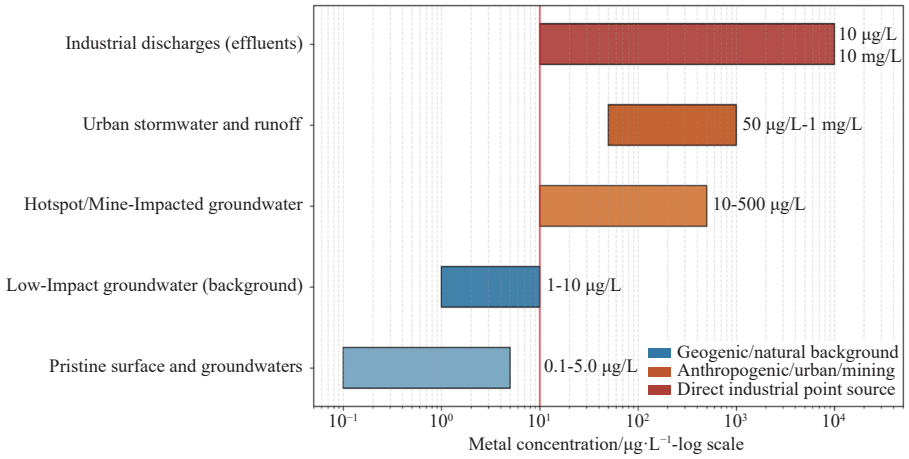


Fig. 2 The concentration ranges by sources of arsenic accumulation in water bodies

concentration ranges by sources of arsenic accumulation in water bodies (Ali et al., 2019; MacDonald et al., 2021; Irunde et al., 2022).

Certain aquifers naturally contain elevated concentrations of geogenic metals, especially arsenic and manganese (Kushawaha and Aithani, 2021). Global assessments estimate that about 94 million to 220 million people are exposed to high arsenic in groundwater in hotspot regions, such as South Asia and parts of East Asia (Guo et al., 2024). Observational studies in countries with extensive monitoring, such as the United States, detected arsenic at levels above 1 µg/L in nearly half of the wells sampled within parts of principal aquifers, exceeding the WHO and US EPA arsenic maximum allowable concentration of 10 µg/L in several percent of wells nationally (Singh et al., 2024). These patterns indicate that groundwater often carries dissolved heavy metals when geology or redox conditions mobilize them. Table 1

Table 1 Major heavy metals, their main sources, human health effects, and environmental impacts

Heavy metals	Main sources	Effects on human health	Environmental impact	References
Arsenic (As)	Natural rocks, mining, pesticides, and contaminated groundwater	Skin diseases, cancer, cardiovascular diseases, and diabetes	Groundwater pollution and its toxicity to aquatic organisms	Azar and Vajargah, (2023); Daripa et al., (2023); Garcia-Vargas and Cebrian, (2023); Guo et al., (2024)
Lead (Pb)	Batteries, paints, vehicle emissions, and industrial wastewater	Neurotoxicity, impaired cognitive development, reduced IQ in children, and kidney, heart, and blood vessel damage	Bioaccumulation and toxicity of aquatic organisms	Prakash and Verma, (2021); Popick (2022); Azar and Vajargah, (2023); Garcia-Vargas and Cebrian, (2023)
Cadmium (Cd)	Mining, fertilizers, electroplating, and industrial wastewater	Kidney damage, bone disorders, and cancer risk	Soil toxicity and reduced microbial activity	Prakash and Verma, (2021); Naz et al., (2022); Daripa et al., (2023)
Mercury (Hg)	Coal combustion, mining activities, and industrial effluents	Acute neurotoxicity, cognitive decline, sensory impairment, and developmental disorders caused by methylmercury	Biomagnification through aquatic food chains and accumulation in fish tissues	Chamoli and Karn, (2024); Zafar et al., (2024); Oros, (2025)
Chromium (Cr VI)	Tanneries, textile industries, electroplating, and industrial waste	Cancer, liver, and kidney damage	Toxic to aquatic organisms and plants	Hossini et al., (2022); Azar and Vajargah, (2023)
Nickel (Ni)	Metallurgical industries, mining operations, and battery manufacturing	Skin allergies, respiratory problems, and carcinogenic effects	Toxic effects on aquatic ecosystems	Genchi et al., (2020); Naz et al., (2022)
Copper (Cu)	Industrial waste, pipe corrosion, and agricultural runoff	Gastrointestinal distress and liver and kidney damage at elevated exposure levels	Reduced oxygen uptake in fish	Naz et al., (2023); Kwong, (2024)
Zinc (Zn)	Galvanizing processes, municipal and industrial wastewater, and traffic-related sources	Gastrointestinal effects at excessive concentrations and metabolic disturbances	Toxic to fish and aquatic organisms	Popick, (2022); Naz et al., (2023); Kwong, (2024)

summarizes the major heavy metals, their main sources, and their effects on human health and the environment, providing a simple overview of the most common heavy metal pollutants discussed above.

2 Remediation technologies

A variety of technologies exist for heavy-metal removal, selected depending on concentration, speciation, and resources. These technologies include adsorption using biochar, iron oxides, activated carbon, and zeolites; Coagulation and precipitation; Membrane technologies; Ion exchange and electrochemical processes; Constructed wetlands and phytoremediation; and microalgae-based bioremediation. These techniques are shown in Fig. 3.

2.1 Adsorption for heavy metal removal

Adsorption is a surface-based separation process in which dissolved heavy metal ions in water bind to the surface of a solid adsorbent (Alprol, 2024). It relies on physical interactions via van der Waals forces and electrostatic attraction, as well as chemical interactions through complexation, ion exchange, and surface precipitation (Aljamali et al., 2021). The effectiveness depends on the surface area, pore structure, and functional groups present on the adsorbent (An et al., 2022). The mechanism of adsorption for heavy metals is based on electrostatic attraction. As illustrated in Fig. 4, this attraction occurs by ion exchange, surface complexation, or surface precipitation. In the ion exchange mechanism, metal cations replace those of the adsorbent surface, such as the replacement of Na^+ on a zeolite framework by a heavy metal ion, Pb^{2+} (Senila et al., 2022). The surface complexation mechanism (chemisorption) occurs for heavy metals, particularly for As(V) and As(III) binding to iron oxides, by transferring the metal molecule into stable inner-sphere complexes with oxygen-rich functional groups, such as OH^-, $COOH^-$, and Fe^{3+}-OH (Navarathna et al., 2020). This is especially relevant at pH values above the point of zero charge (Tan et al., 2021; Zhang et al., 2023). The surface precipitation mechanism occurs at higher concentrations or pH values, where metal hydroxides or carbonates precipitate directly onto

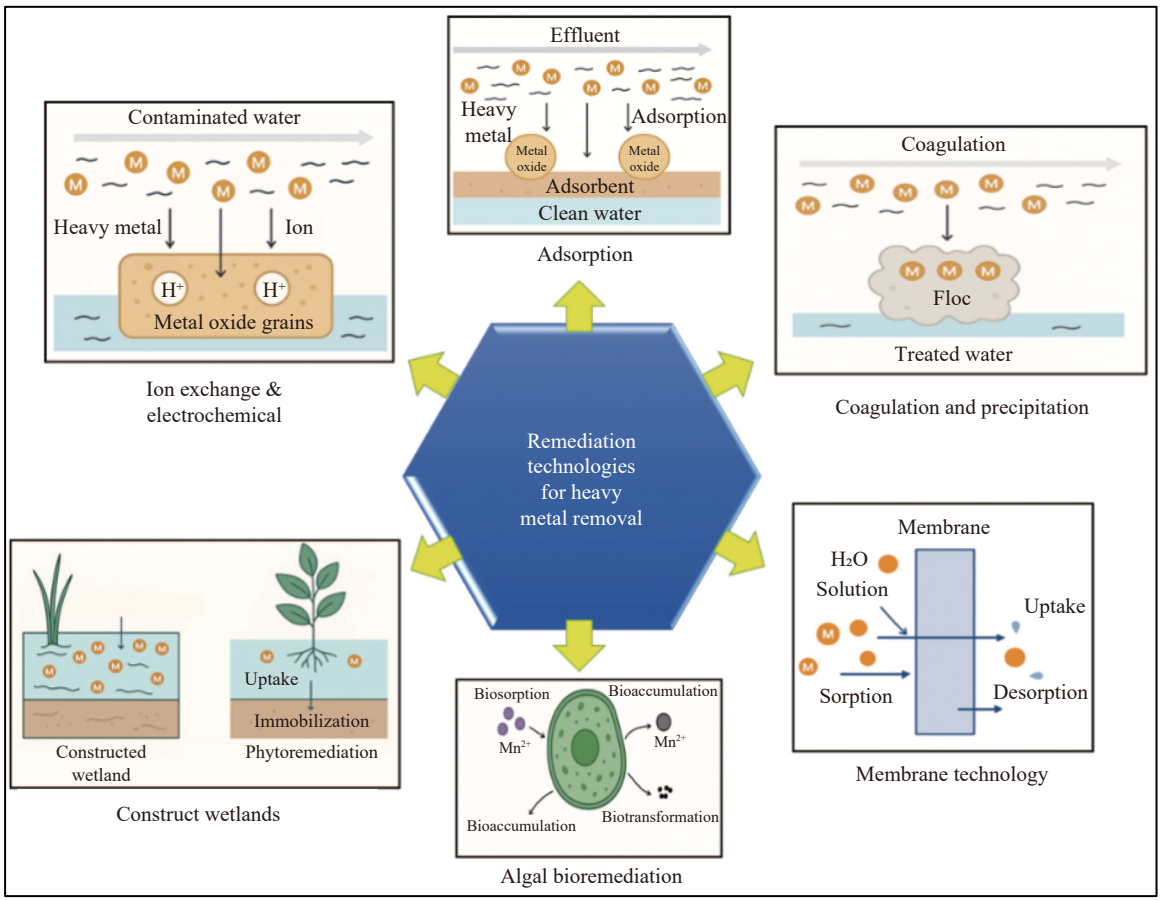


Fig. 3 The recent techniques for heavy-metal removal from contaminated water resources

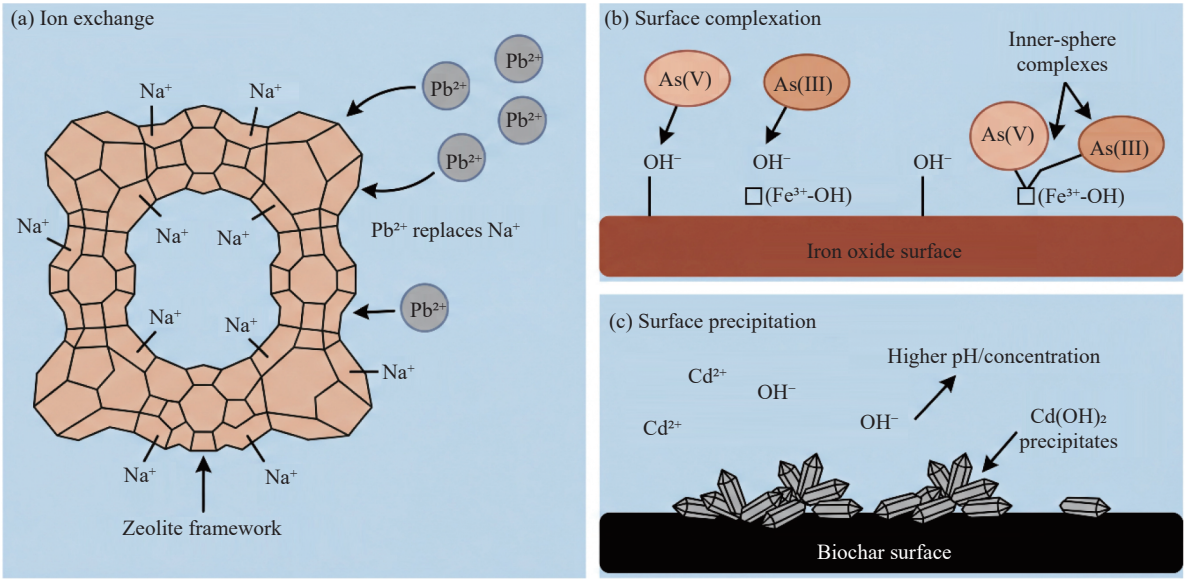


Fig. 4 Adsorption mechanism by (a) ion exchange, (b) surface complexation, (c) surface precipitation

the adsorbent surface, such as $Cd(OH)_2$ precipitating on the biochar surface (Raji et al., 2023).

The type of adsorbents utilized depends on the heavy metal, the applied technique, and the adsorbent source. The most commonly used adsorbents are biochar, iron oxides, activated carbon, and zeolites. The porous structure of biochar and its abundant oxygen-containing groups enhance its effectiveness for adsorption via electrostatic attraction, ion exchange, surface complexation, and precipitation. It can be regenerated at low cost, enhancing its ability to adsorb heavy metals

(Joseph et al., 2021; Khare et al., 2021). Iron oxides have a high affinity for arsenic via surface complexation with Fe^{3+} and hydroxyl groups. These oxides are effective over a wide pH range, but especially strong under neutral to acidic conditions. They can be used in a granular form as granular ferric hydroxide, incorporated into filters, or as coatings on membranes and biochar (Sun et al., 2024).

Activated carbon is effective for ion exchange and physical adsorption due to its large surface area, which exceeds 1,000 m^2/g (Heidarinejad et al., 2020). Adsorption efficiency can be enhanced by impregnating activated carbon with metal oxides. Zeolites are aluminosilicate minerals that possess a strong cation-exchange capacity due to negatively charged AlO_4 tetrahedra balanced by Na^+, K^+, or Ca^{2+} (Kordala and Wyszkowski, 2024). An iron oxide-silica nanocomposite provides adsorption capacities of 50 mg/g for Pb^{2+} and 240 mg/g for methyl orange. The key feature of this adsorbent is the superparamagnetic property of its mesoporous silica coating, which provides a large surface area (Gallo-Cordova et al., 2020). Using cellulose and $FeCl_3$ enhances the removal capacity of Cr(VI) to 95.9 mg/g (Zhou et al., 2021), and jackfruit peel and potassium ferrate enhance the ion adsorption capacity of Cu^{2+} to 61.3 mg/g in seawater (Wen et al., 2022).

Heavy-metal removal efficiency depends on the technique, metal valency, feed concentration, pH, contact time, and type and amount of adsorbent. Some of these conditions and their impact on removal efficiency are summarized in Table 2. In general, adsorption technology is easy to design and operate; its low cost stems from the use of natural resources, and it has high selectivity, such as iron oxide for arsenic and zeolite for cations. Assessing the cost of preparing adsorbents is necessary to determine the feasibility of scaling up (Mahmoud et al., 2021). This technology is scalable and environmentally friendly; most of these adsorbents cost between 1 USD/mol and 200 USD/mol on a lab scale, depending on the use of bioresources, and they can be regenerated or disposed of with minimal impact (Ighalo et al., 2022). The operating cost range is 4.5 USD/m^3 to 6.4 USD/m^3 of treated water on pilot scale; however, it should be accompanied by one or more techniques to coagulate the adsorbent and separate it (Mokhtar et al., 2024). The main limitation of this technology is the need for adsorbent regeneration; however, natural resources or adsorbents derived from agricultural waste would overcome this limitation. The potential issue of spent adsorbent disposal still needs to be studied for each specific adsorbent type.

2.2 Coagulation and precipitation

Coagulation–precipitation is a widely used method for remediating heavy-metal-laden wastewater, combining chemical precipitation with coagulation and flocculation, as shown in Fig. 5. The initial chemical precipitation phase converts dissolved ionic metal species into insoluble precipitates, primarily hydroxides, carbonates, or sulfides, enabling their separation via sedimentation or filtration (Pohl, 2020). While hydroxide precipitation remains the most common approach, its efficacy is governed primarily by pH. Optimal precipitation thresholds are metal-specific; for instance, lead achieves maximum precipitation within a pH range of 9–10, whereas copper requires a more moderate range of 8–9. Furthermore, certain contaminants necessitate a reductive

Table 2 Removal efficiencies utilizing different types of adsorbents on a lab scale

Adsorbent	Metal	Feed conc. (mg/L)	Contact time (h)	Adsorbent capacity (mg/g)	Adsorbent dose (g/L)	pH	Removal efficiency	Reference
Activated carbon derived from green algae *Spirogyra*	Cu^{2+}	200	0.3	98.82	0.1	5.28	95.09%	Djezzar et al., (2024)
Activated Carbon Produced from *Sargassum* ssp.	Cr^{6+}	60	24	46	1	5	65%	Alvarez-Galvan et al., (2022)
Activated Carbon Produced from *Sargassum* ssp.	Cr^{6+}	60	24	46	1	2	98%	Alvarez-Galvan et al., (2022)
Silica-coated $Cu_{0.5}Mg_{0.5}Fe_2O_4$ nanoparticles	Zn^{2+}	0.2	36	32.57	2.5	7	97%	Irfan et al., (2023)
Silica-coated $Cu_{0.5}Mg_{0.5}Fe_2O_4$ nanoparticles	Pb^{2+}	0.2	36	25.66	2.5	7	92%	Irfan et al., (2023)
Electrolytic manganese residue + distillers' grain biochar composite (EDB)	Sb^{3+}	50	24	11.5	2.5	7	60%	Wei et al., (2024)
	Sb^{5+}	50	24	8.4	2.5	7	40%	
	As^{3+}	50	24	16.5	2.5	7	84%	
	As^{5+}	50	24	18.5	2.5	7	90%	

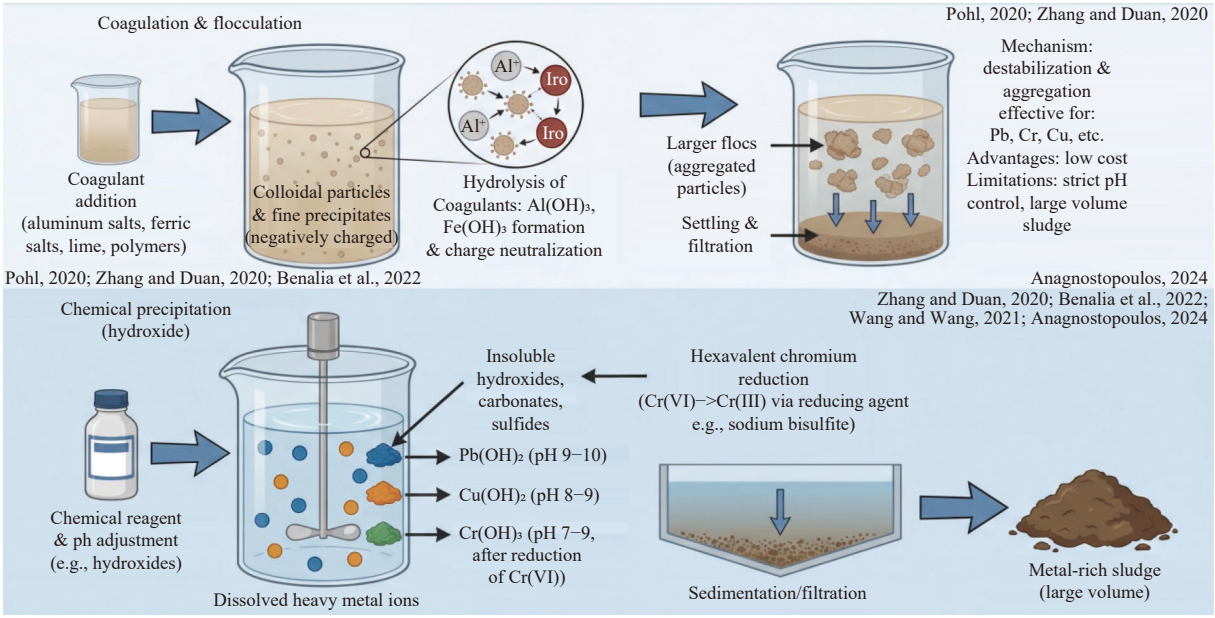


Fig. 5 Coagulation and precipitation mechanism for the treatment of water contaminated with heavy metals

pretreatment to mitigate toxicity and enhance precipitation potential, such as the reduction of hexavalent chromium to trivalent chromium (Zhang and Duan, 2020). Hexavalent chromium is characterized by high solubility and potency; thus, it must be reduced using agents like sodium bisulfite to form $Cr(OH)_3$, which precipitates within a pH interval of 7–9. Consequently, pH adjustment remains a critical parameter for maximizing hydroxide precipitation (Benalia et al., 2022).

After precipitation, the coagulation phase begins with the introduction of coagulants, such as aluminum or ferric salts, lime, or synthetic polymers. These agents destabilize colloidal suspensions and fine precipitates by neutralizing surface charges, thereby promoting the aggregation of particles into macroscopic flocs amenable to settling or filtration. The underlying mechanism involves the hydrolysis of the metallic coagulants, such as aluminum sulfate and ferric chloride, to form metal hydroxides such as $Al(OH)_3$ and $Fe(OH)_3$. These generated hydroxides either collide with heavy metals or act as scaffolds for the adsorption of metal hydroxide flocs (Wang et al., 2021). Although this dual-process technique demonstrates high removal efficiency of concentrated lead (Pb), chromium (Cr), and copper (Cu), its operational utility is inherently constrained by pH control and the prolific generation of large volumes of hazardous, metal-rich sludge (Anagnostopoulos, 2024).

From a techno-economic perspective, the fiscal viability of coagulation depends primarily on reagent selection and uptake capacity. In the case of chromium Cr^{6+} removal, ferric chloride ($FeCl_3$) and iron-based coagulants are widely preferred because of their high affinity toward chromate species and comparatively low chemical costs. Iron-based coagulation systems can achieve chromium removal efficiencies exceeding 95%–99% under acidic to near-neutral pH conditions, while maintaining operational expenditures comparatively low. However, higher iron dosages significantly increase sludge production, thereby elevating downstream handling and disposal costs (Sagar et al., 2026). Aluminum-based coagulants, although effective for certain wastewater treatment parameters, generally require larger dosages and exhibit lower uptake capacities, resulting in less favorable economic performance. In addition to reagent expenses, operational overheads such as energy consumption, mixing, maintenance, and sludge management substantially contribute to the overall treatment cost (Liu et al., 2023). Reported operating costs for coagulation-based chromium removal commonly range between 0.20 USD/m^3 and 1.10 USD/m^3 of treated wastewater, depending on influent concentration, reactor configuration, and treatment scale (Liu et al., 2023; Sagar et al., 2026). Overall, the total operating cost typically fluctuates between 0.90 USD and 1.30 USD per cubic meter of treated effluent (Loh et al., 2022). These cost estimates rely on scale-up assumptions based on lab-scale results.

2.3 Membrane technologies

Membrane-based separation technologies have

emerged as efficient and versatile approaches for the removal of heavy metals from various aqueous systems, including surface water, groundwater, industrial effluents, and mine drainage. Among these, Ultrafiltration (UF), Nanofiltration (NF), and Reverse Osmosis (RO) have attracted considerable attention due to their distinct separation mechanisms and performance characteristics. Ceramic membranes are primarily used in the UF range, with increasing research aimed at extending their use into NF regimes.

The interaction between membrane characteristics and the physicochemical properties of metal species controls the removal performance of membrane systems. High-pressure processes such as RO have the highest removal efficiencies (> 90%) for a wide range of metals, while NF offers selective removal, particularly for divalent ions (70%–90%). UF is generally limited to dilute solutions and operates through indirect mechanisms such as complexation and colloidal retention. Consequently, pilot-scale validation remains essential for optimizing system performance under real-world conditions (Chen et al., 2023; Shoshaa et al., 2023).

UF has a limited ability to remove free ionic metals such as Pb^{2+} and Cu^{2+} without chemical conditioning, since pH adjustment is required to modify water chemistry, which leads to lower selectivity compared to NF and RO (Alardhi et al., 2020; Siagian et al., 2021). A sorbent-assisted UF system removed Pb^{2+}, Cu^{2+}, Zn^{2+}, and Ni^{2+} effectively via adsorption and precipitation/complexation, as well as through retention of insoluble species by UF. At pH 6, the removal sequence was $Pb^{2+} > Cu^{2+} > Zn^{2+} > Ni^{2+}$, with particularly high removal for Pb and Cu due to precipitation and complex formation. The removal efficiency of UF ranges from 80%–92% (Alkherraz et al., 2020; Çelebi et al., 2020). Hybrid UF with sorbents can broaden removal to dissolved ions at a lower cost (Fuks et al., 2022; Fuks et al., 2023). CAPEX encompasses the acquisition of membrane modules; the UF module costs 2,106 EUR and the RO module 205 EUR, with total water production costs of 0.316–0.630 EUR/m^3 for UF and 0.256–0.470 EUR/m^3 for RO, notwithstanding the lower operating pressure of the UF (Pérez et al., 2022).

NF combines size exclusion and Donnan exclusion. Hydrated heavy metal ions larger than the NF pore size are rejected by size exclusion. The charged NF membranes repel multivalent cations such as Pb^{2+} and Cr^{3+} more strongly than monovalent ions such as Na^{+} and K^{+} according to the Donnan exclusion mechanism (Tang and Bruening, 2020). Rejection may reach 80%–99% for most divalent and trivalent heavy metals. The pressure required for NF ranges from 4 bar to 30 bar, which is less than RO, thus more energy-efficient. However, it is less effective for monovalent contaminants, sensitive to fouling and scaling, and has a higher cost compared to UF or adsorption-based materials (Jakhar et al., 2023). Replacing RO with NF membranes in reclamation applications can yield annual cost savings of 55,000 USD to 187,000 USD (i.e., a saving range of 0.03–0.08 USD/m^3 of treated water) due to lower pressure operation (Devaisy et al., 2023).

The membrane Isoelectric Point (IEP) corresponds to the pH at which the membrane surface exhibits zero net charge (zero zeta potential). At pH values above the IEP, the membrane surface becomes negatively charged, enhancing the electrostatic repulsion of anions such as AsO_4^{3-} and CrO_4^{2-}. Conversely, at pH values below the IEP, the membrane surface becomes positively charged, favoring the repulsion of cations such as Pb^{2+} and Cu^{2+}. Therefore, ion rejection depends on the relationship between feed pH, membrane surface charge, and ion speciation.

A ceramic membrane is made of inorganic materials such as alumina, zirconia, or titanium dioxide. It operates across MF, UF, and NF ranges depending on membrane's pore size. Heavy-metal removal occurs via size exclusion of metal colloids, surface adsorption, or surface modification. Incorporating sawdust to replace 2% of clay in ceramic membrane fabrication enhances the removal efficiency of Pb^{2+}, Cu^{2+}, and Cd^{2+} to 99% (Ali et al., 2017). Meanwhile, treating the membrane surface with polyamide 6 (PA6) raises the rejection from 80% up to 99.97% (Azzam et al., 2025). A fabricated Fe-doped zeolite-coated porous clay ceramic membrane shows strong rejection of Pb^{2+}, Cu^{2+}, Cd^{2+}, and Hg^{2+} from synthetic wastewater (Khalil et al., 2025). The main advantages of ceramic membranes are their superior chemical, thermal, and mechanical stability compared to polymeric membranes, as well as their long lifespan, resistance to cleaning chemicals, and tolerance to high temperatures, features that make fouling more reversible through backwashing or chemical regeneration (Jiang et al., 2022). However, the CAPEX of ceramic membranes ranges from 500 USD/m^2 to 3,000 USD/m^2 compared to polymeric membranes, which range from 20 olymeric membranes, which range from 20 USD/m^2 to 400 USD/m^2.

Despite their effectiveness, membrane systems are constrained by techno-economic challenges. Operating costs (OPEX) typically range from 4.5

USD/m^3 to 6.4 USD/m^3, with energy consumption representing a major contributor, particularly in RO systems (1–10 kWh/m^3). In contrast, UF and MF operate at lower pressures and offer improved energy efficiency. However, membrane fouling remains a critical issue, leading to increased maintenance, chemical cleaning, replacement costs, and disposal challenges associated with accumulated salts and backwash streams (Ahmed et al., 2024; Dawam et al., 2025; Gao et al., 2025; Panagopoulos and Michailidis, 2025; Zulu et al., 2025; Gopal et al., 2026). A detailed synthesis of these critical metrics is presented in Table 3.

2.4 Ion-exchange

Ion-exchange removes dissolved ionic species by replacing heavy metal ions in contaminated water with ions bound to the functional groups of a solid polymer (resin) or inorganic exchanger such as zeolite (Barman et al., 2023). A typical ion-exchange reaction shows the replacement of the bound ion (Na^+) with a sulphonate functional group by a metal ion (M^+), as follows:

$$R-SO_3^-Na^+ + M^{+2} \leftrightarrow R-SO_3^-M^+ + Na^+$$

The process is reversible, and the resin can usually be regenerated with an acid or salt solution to restore exchange capacity (Qasem et al., 2021; Carolin et al., 2023). Ion exchange has been reported to achieve high removal efficiencies ranging from 90% to 99% for Pb^{2+}, Cu^{2+}, Ni^{2+}, Cd^{2+}, and other cationic heavy metals when properly selected and operated. The ion-exchange technique depends fundamentally on the acidity of the exchange media. The main types of media are synthetic polymeric resins, namely Strong-Acid Cation (SAC) resins, such as sulfonated polystyrene; Weak-Acid Cation (WAC) functionalized with carboxylic acid; and chelating resins functionalized with iminodiacetic acid, thiol, or oxime groups, which exhibit high selectivity for particular metals, such as Cu^{2+}, Pb^{2+}, and Hg^{2+}. SAC resins are applicable over a wide pH range, including highly acidic conditions, while WAC resins are inactive below pH 4; and chelating resins are essential for the selective recovery of heavy metals (Sgreccia et al., 2024).

Table 3 Systematic evaluation of membrane technologies for heavy metal removal

Parameter	UF (0.01–0.1 μm Polymeric membrane)	NF (0.5–2 nm Polymeric membrane)	RO (0.1–0.5 nm Polymeric membrane)	Ceramic membrane (UF/NF)
Treatment efficiency (metal rejection)	Less than 10% rejection, and 90%–99% by surface modification	90%–99% rejection of divalent heavy metals, and lower efficiency (30%–70%) for monovalent	99% rejection for all dissolved metals	Its performance is similar to UF; surface modification is necessary to achieve 85%–99%
Operating pressure (bar)	1–5	5–20	10–80	Similar to UF, while a hollow fiber membrane behaves as NF
Energy consumption (kWh/m^3)	0.1–0.4	0.3–1.0	0.5–2.0 for brackish water,	0.2–1.0
OPEX (USD/m^3)	0.5–1.5	2–6	3–10	1.5–4
Applicable contaminant concentrations (mg/L)	1–500	10–500	>1,000 High concentration requires high pressure	1–1,000 depending on pore size and surface modification
Selectivity	None without surface modification	Charge-based selectivity as divalent and monovalent	Reject all solutes	Tunable via surface modification
Fouling resistance	Requires frequent cleaning due to its susceptibility to biofouling	Similar to UF	High fouling tendency, extensive pretreatment is required	Fouling is reversible and easier to clean
Lifetime (years)	3–7	5–7	5–7	10–20
Scale-up potential	A capacity of >10,000 m^3/d is widely used in water treatment	A capacity of >100,000 m^3/d is widely used in municipal wastewater treatment	A capacity of >500,000 m^3/d is widely used in desalination	A capacity of >100,000 m^3/d is widely used in industrial wastewater treatment
Recommended application	As a pretreatment before NFor RO	Polishing after chemical precipitation or divalent heavy metals removal	Final polishing, and capable of removing monovalent, arsenic, and Cr(IV)	Aggressive waste streams, such as low pH, high temperature, and oily contaminated water

Several operating conditions affect the removal efficiency; media configuration is the main factor, and it is in turn affected by pH. Jasim and Ajjam (2024a, b) reported, on a lab scale, the use of 2.6 g of Lewatit S 1568 resin to treat water contaminated with Cu^{2+}, and Ni^{2+} at concentrations of 150–300 mg/L, and 20–40 mg/L, respectively; and at pH ranges of 4–6 and 5–6, respectively, with a rotation speed of 99 rpm for 35 min. Under these conditions, the treatment efficiency was 99% for both contaminants. Purolite C100 resin was used to treat a solution containing 50 mg/L to 150 mg/L of Cu^{2+}, and Pb^{2+} at a pH range of 3–12, and a contact time of 30–90 min. Under these conditions, the treatment efficiency of Cu^{2+} was 94%, while that for Ni^{2+} was 93% (Jasim and Ajjam, 2024a, b). The optimal pH for chelating resins to remove Cu^{2+} and Pb^{2+} is 4 to 6, while the optimal pH for chelating Ni^{2+} and Zn^{2+} is 5 to 6. Meanwhile, the optimal pH range for Fe^{3+} removal is 2–4, as Fe^{3+} hydrolyzes above pH 4; hence, lower pH is preferred (Benalla et al., 2022; Jasim and Ajjam, 2024a, b).

Inorganic exchangers, such as natural or synthetic zeolites, layered double hydroxides, and ion-exchanging clays, are used for their thermal and chemical tolerance. The most commonly used configuration is the fixed-bed column. It is usually arranged as a series of two or more treatment columns as a lead-lag configuration. In this series, the lead unit treats the influent raw water to remove most contaminants; the lag unit receives the partially treated effluent as a polishing stage, as illustrated in Fig. 6 (Ellis, 2023). Longer contact times increase the removal and loading capacity per pass. Column design uses Empty-Bed Contact Time (EBCT) and breakthrough curves to size columns and schedule regenerations (Vukojević Medvidović and Svilović, 2023).

Regeneration is an important consideration, owing to the cost of the resin and the difficulty of safe metal disposal. A common regeneration method involves treating the resin with a saturated NaCl solution. A saturated NaCl solution typically contains approximately 26.4% (w/w) NaCl at room temperature, which is the maximum concentration of NaCl that can dissolve in water at that temperature (Reda Hamed and Abdallah, 2024). This regeneration did not change the exchange capacity of the resin; however, safe disposal remains an unresolved issue (Benalla et al., 2022; Abin-

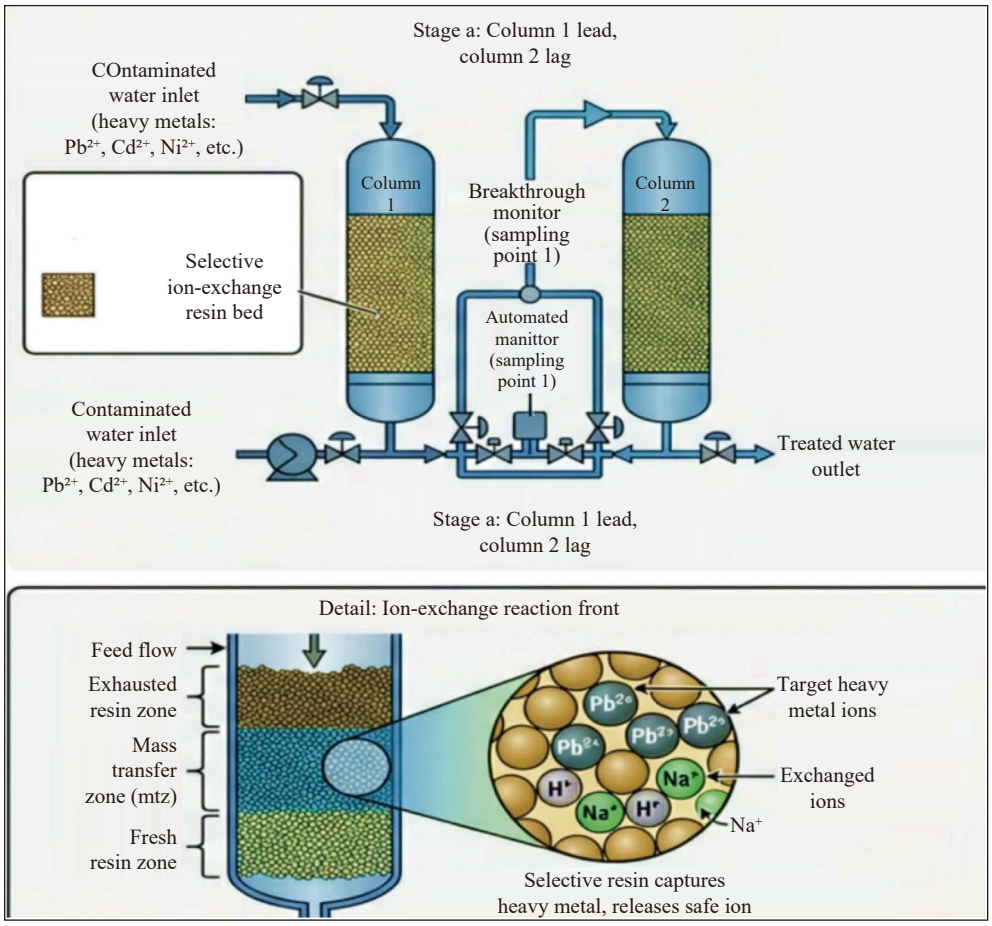


Fig. 6 Lead-lag configuration system for the ion-exchange technique

Bazaine, 2024). Direct energy data are limited for standard ion exchange; however, the regeneration method, named Adjacent Bed Electrically Regenerated Ion-exchange (ABERI), consumes 0.38 kWh/m^3 on a lab scale. In this method, the resin is regenerated by H^+ and OH^- ions produced from a pair of electrodes installed on both sides of the resin bed (He et al., 2020). The cost of ion exchange systems depends on their design and influent conditions. Ion exchange exhibits the lowest levelized costs among the discussed technologies, generally in the range of 0.08–0.21 USD/m^3 at pilot scale, as reported by the Danish Centre for Environment and Energy (Jasim and Ajjam, 2024a, b; Massenberg, 2025).

2.5 Electrochemical techniques

Electrochemical techniques include electrocoagulation (EC), electrodeposition, and electrodialysis (ED), in which ion-separation membranes are driven by an electric field, as shown in Fig. 7.

2.5.1 Electrocoagulation

Electrocoagulation uses sacrificial anodes, typically iron or aluminum, immersed in the water and connected to an external direct current (Yasri et al., 2020). The metal of the anode dissolves electrochemically, producing metal ions, which are hydrolyzed to form metal hydroxides that act as in-situ coagulant flocs (Li et al., 2023). These flocs adsorb and enmesh heavy metals and suspended particles. Simultaneously, hydrogen evolution at the cathode produces bubbles that float flocs to the surface. EC thereby combines coagulation, flotation, and oxidation or reduction (Paknia et al., 2025).

The type of electrode, electrode spacing, orientation, and current distribution affect efficiency. Multiple electrodes, arranged in monopolar or bipolar configurations, are used in scale-up (Arenas et al., 2020; Rajaei and Haverkort, 2020). The metal dissolution rate, which determines coagulant generation, is proportional to current density following Faraday's law. The removal efficiency increases with time and current, but energy consumption rises accordingly (Fotovat and Hosseini, 2023). EC often works well across a range of pH, but may require pH adjustment for some metals, as observed by Kim et al. (2020) for the removal of Cr, whose removel efficiency was 95% at pH 5 when using iron anodes, compared with 35% when using aluminum anodes. Conductivity influences cell voltage and energy consumption, as low conductivity waters may require salt addition (Thakur and Kumar, 2024). This technique has a compact footprint and rapid treatment times. However, energy consumption is significant at high current or in low-conductivity waters. The recovered residual takes the form of metal-rich hydroxide sludges, as experimentally demonstrated by Kim et al. (2020) for the treatment of artificial wastewater contaminated with Cr, Ni, Cu, and Zn: As the current density increased (1–2–4 mA/cm^2) and the voltage increased correspondingly (1.85–4.52–6.95 V) at a constant electrolyte concentration of 0.10 M, the sludge generated per volume of treated wastewater increased (0.68–1.04–1.34 kg/m^3), and the energy consumed per volume of treated wastewater increased (0.37–1.36–2.78 kWh/m^3).

2.5.2 Electrodeposition

This approach is used for metal recovery from industrial wastewater. It uses electrical potential to reduce metal ions at a cathode into their elemental

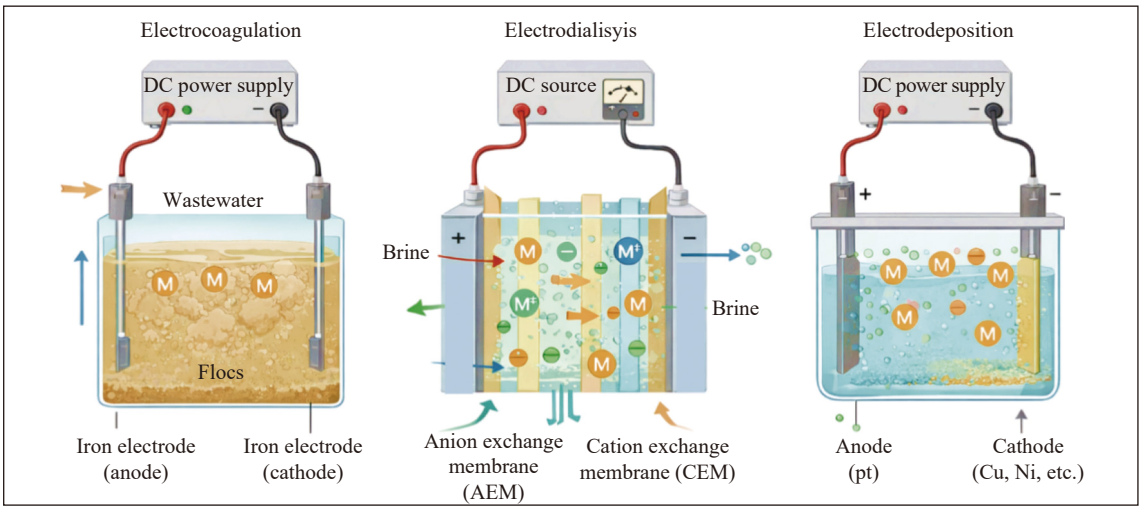


Fig. 7 Electrochemical water treatment

form, plating the metal onto electrode surfaces, or producing less soluble compounds that precipitate near electrodes. The process directly removes dissolved ions rather than forming flocs, so it is applicable for very low concentrations (Kuleyin and Uysal, 2020).

The applied potential, current density, and cathode material are the most important key parameters of this technique. In addition, the solution composition, pH, complexing agents, stirring rate, and deposition selectivity affect process efficiency; some examples at the lab scale are shown in Table 4 (Delgado et al., 2021). In this method, the deposited metals can be harvested and potentially reused, thereby increasing the recovery of high-value metals. However, this approach requires control of side reactions such as hydrogen evolution, and competing metal deposition, as well as careful cathode maintenance (Roy et al., 2022).

2.5.3 Electrodialysis

Electrodialysis uses anion- and cation-exchange membranes, arranged between electrodes; an applied DC field drives cations towards the cathode and anions towards the anode, transporting ions through selective membranes into concentrate compartments while producing a desalinated dilute stream. For heavy metals, ED can separate and concentrate ionic metals from dilute streams and is used for brine concentration or metal recovery (Eti et al., 2021). This technique is suitable for continuous operation, offering low fouling and modular scalability; however, pretreatment is often needed for waters containing multivalent ions. Adding conductive particle beds to increase the active surface area forms 3D electrodes, enhancing mass transfer and removal rates for complex mixtures (Min et al., 2021). The similarities and differences among the electrochemical techniques are summarized in Table 5.

The total operating cost of the EC technique estimated by El-Sadaawy et al. (2025) is about 0.97 USD/m^3 for treating water contaminated with hexavalent chromium under the conditions of 20 mg/L Cr^{6+}, pH 2, 0.5 g NaCl, 750 rpm stirring, nine iron electrodes, and 43.4 A/m^2 current density, providing 99% removal within 7 min on a lab scale. Bakry et al. (2024) estimated the operating cost of EC for treating real wastewater spiked with heavy metals (Pb, Cd, Zn, Ni, Cr, Mn, Cu, each at 50 mg/L). The cost analysis results, on a lab scale, for EC at current densities of 5 mA/cm^2, 15 mA/cm^2, and 25 mA/cm^2 were in the ranges of 0.02–0.35 USD/m^3, 0.09–1.02 USD/m^3, and 0.17–2.33 USD/m^3, respectively, indicating that the cost depends on the current density and the properties of the feed. However, the available data are for EC at lab scale and must be validated at larger scales to enable informed decision-making

Table 4 Some factors affecting electrodeposition of Cu^{2+} from contaminated water

Feed conc. (g/L)	Stirring speed (rpm)	Electrode material	Current density	pH	Temp (°C)	Removal (%)	Cost and energy consumption	Reference
0.5	3 m/s	Anode: RuO_2-coated Ti tube Cathode: Pure Ti sheet	12 A/dm^2	1	-(1)	97.4%	Energy consumption 5.6 kWh/kg	Ning et al., (2019)
9.07	1,000	Anode: Ruthenium, Iridium, titanium net Cathode: Graphite	75 mA/cm^2	2	15	88%	-(1)	Gu et al., (2020)
10	700	Platinum electrodes	2 A	1.8	24	98%	Constant voltage operation has an estimated cost of 1.43 EUR/kg Cu.	Santaolalla et al., (2020)
0.0318–19.0638	700 for catholyte	Anode: Zinc mesh Cathode: Copper	1 mA/s·cm^2	4–6	18–23	90%	Energy density of 4.9 kWh/m^3, Power density of 546 W/m^2	Wang et al., (2020)
0.43	70	Anode: Hollow cylindrical platinum mesh Cathode: Copper	190 mA	1.74	37	33.59%	-(1)	Morais Nepel et al., (2020)
0.001	-(1)	Anode: Saturated calomel electrode (SCE), Cathode: Reticulated glassy carbon (RVC)	0.5 V	3	40	91.3%	-(1)	Xie et al., (2026)
1	1,000	Anode and cathode plates: Iridium-, tantalum-, and titanium plates	75 mA/cm^2	4	21	94.53%	-(1)	Xu et al., (2025)

Note: (1) Not mentioned

Table 5 Comparison of electrochemical techniques

Aspect	Electrocoagulation	Electrodialysis	Electrodeposition
Definition	The sacrificial electrodes generate coagulant species in situ, removing contaminants	A membrane-based electrochemical separation process using an electric field, which selectively transports ions through ion-exchange membranes	An electrochemical process where dissolved metal ions are reduced and deposited as solid metal on an electrode surface
Principle	DC dissolves the metal of the electrodes to form metal hydroxide, which adsorb the pollutants	The electric potential drives cations and anions through selective membranes toward opposite electrodes, separating ions from water.	Metal cations gain electrons at the cathode and are reduced to elemental metal
Materials	Iron or aluminum electrodes	Ion-exchange membranes; electrodes (Ti, graphite, stainless steel)	Cathode (stainless steel, copper, graphite); anode (inert or sacrificial).
Target metals	Pb, Cr, Cd, Cu, Zn, Ni, As	Pb, Cd, Cu, Cr, Ni, Zn, As (ionic species)	Cu, Ag, Ni, Zn, Cd, Pb (mainly recoverable metals)
Removal efficiency	80%–99% depending on current density and pH	70%–99% for dissolved ionic metals	90%–99% for metals suitable for electrodeposition
Energy consumption	Increases with current density	0.3–5 kWh/m^3	highly dependent on metal concentration
Cost, USD/m^3	0.02–3.2	0.25–1.2	Rarely reported; evaluated based on metal recovery value
Environmental impact	Sludge disposal is required	Membrane production and electricity footprint impact the environment	Favorable if metal recovery offsets impact
Applications	Industrial wastewater, mine drainage, mixed heavy-metal streams	Brackish water, selective metal removal, polishing step	Metal plating wastewater, mining effluents, and metal recovery systems

on this technology. The operating cost of the ED technique is in the range of 0.25–1.20 USD/m^3 with a possible 30% reduction via integration with the reverse electrodialysis (RED) (Balogun et al., 2024).

2.6 Constructed wetlands

Constructed wetlands (CWs) are a nature-based solution used for heavy metal removal from contaminated water bodies such as streams, lakes, groundwater, and mine drainage. For groundwater remediation, ex-situ techniques are used, especially the pump-and-treat technique, in which pumping wells extract contaminated groundwater to the surface for treatment in CWs. CWs are engineered systems designed to mimic natural wetland functions, using a combination of substrate, vegetation, and microbial communities to treat wastewater, stormwater, or contaminated natural waters. Depending on design, they can be surface-flow, subsurface horizontal-flow, or subsurface vertical-flow wetlands (Wu et al., 2023).

This technique involves several mechanisms depending on the type of heavy metal and the presence of microorganisms. Heavy metals may be suspended in sediments or adsorbed to substrate materials such as gravel, soil, sand, and organic matter. In another mechanism, metals precipitate as insoluble hydroxides, such as $Fe(OH)_3$, carbonates such as $PbCO_3$, and sulfides such as CdS (Majumdar et al., 2020). The plants used in CWs, such as Phragmites australis and Typha latifolia, absorb metals into their roots, stems, or leaves. Sulfate-reducing bacteria, such as Proteobacteria, Firmicutes, and Acidobacteria, promote the precipitation of metals as metal sulfides in the soil (Abbas et al., 2025).

CWs remove heavy metals with high efficiency, often exceeding 90% for many metals such as Cd, Cu, Pb, and Zn. Removal rates vary by substrate and design; waste-derived substrates such as date palm fiber and eggshells achieved 92.6%-98.7% removal for As, Cr, Cd, Pb, Fe, Zn, Cu, and Ni in vertical-flow systems (Rabbi et al., 2025). Hydraulic Retention Times (HRT) typically range from 3 d to 14 d per cycle for over 90% removal in vertical-flow wetlands. The first-order removal rate constant for Zn is 0.23/h in a coke-based wetland and 0.12/h in a gravel-based wetland with >90% removal efficiency (Bao et al., 2025; Porras-Socias et al., 2024).

CWs are cost-effective and low-maintenance because treatment occurs naturally with minimal energy input. The reliance on ecosystem biodiversity and limited chemical inputs enhances the sustainability of this technique; however, removal efficiency may be lower than that of advanced

physicochemical methods for high-strength wastewater. The main drawback is biomass disposal, as the harvested plants contain toxic metals and require safe disposal or incineration (Breil et al., 2022). The operating cost of this technique depends strongly on the conditions of the surrounding area and the type of plants; it has been reported as 1.25 USD/m^3 in São Paulo, Brazil, and 6.17 USD/m^3 at a facility in Lake Manzala, Egypt (Wibowo et al., 2022).

2.7 Algal bioremediation

Algal bioremediation is the process of using photosynthetic microorganisms (such as Chlorella, Scenedesmus, Spirulina, and Anabaena) to remove, immobilize, or transform heavy metals in water (Goswami et al., 2022). For groundwater remediation, ex-situ techniques are used, especially the pump-and-treat technique, in which pumping wells extract contaminated groundwater to the surface for treatment with microalgae. Microalgae have cell walls rich in functional groups (carboxyl, hydroxyl, sulfate, amine, and phosphate) that bind heavy metal ions via electrostatic attraction and complexation (Spain et al., 2021). The process involves several biological and physicochemical pathways, typically divided into three main mechanisms: Biosorption, bioaccumulation, and biotransformation.

The biosorption process does not require metabolic energy. It occurs rapidly when metal ions bind to functional groups on the algal cell wall, mainly polysaccharides and proteins (Gu and Lan, 2024). The bioaccumulation process depends on metabolism; metal ions are transported across the cell membrane and sequestered within vacuoles or organelles, often complexed with phytochelatins or metallothioneins. It requires living algal cells and takes longer than biosorption (Danouche et al., 2021). For example, Chlorella vulgaris accumulates Cd^{2+} and Pb^{2+} intracellularly by forming Cd phytochelatin complexes, which detoxify the metals within the cytoplasm. Biotransformation occurs through oxidation, reduction, or precipitation of metals into less toxic or insoluble forms (Chu et al., 2022a). For example, Spirulina platensis can reduce Cr(VI) to Cr(III), decreasing toxicity (Nath et al., 2024), while *Anabaena* sp. can precipitate metals as carbonates or sulfides. Removal efficiencies are highest under optimal pH and light conditions (Hossain and Okino, 2024). Table 6 illustrates some algal strains and their typical removal efficiencies of specific heavy metals. Microalgae-based bioremediation is a low-cost, sustainable, and environmentally friendly approach, but it is sensitive to operating conditions and often limited in scalability. Combining it with other systems like constructed wetlands or immobilized reactors enhances stability and performance (Goswami et al., 2022; El-Sheekh et al., 2025). The operating cost of the treatment pilot in Giza, Egypt (El-Mekkawi et al., 2021), is 0.12 USD/m^3 of treated water. This cost was 0.12 EUR/m^3 of treated water at facilities in Almeria and Cadiz, Spain (Kohlheb et al., 2020).

3 Comparing the availability of the used techniques

The range of available techniques allows the selection of a suitable option based on the concentration of the feed stream, the effectiveness of separation, the ease of sludge disposal, the cost, and the environmental impact. A comparative evaluation of adsorption, coagulation, membrane filtration, and electrocoagulation is summarized in Table 7.

Quantitatively, while coagulation–precipitation is a robust benchmark for bulk decontamination, achieving removal efficiencies of 90%–99.9%, it is

Table 6 Some of the algal strains used to remove heavy metals

Metal	Algal species	Operation conditions	Removal efficiency	Reference
Pb^{2+}	Chlorella vulgaris	Initial inoculum 1mg/L, pH 6 at 30°C Ca-alginate immobilized algal cells, algal dosage of 3 g/L, pH 5, 30 min at room temperature.	93.2% 90%	Manzoor et al., (2020) Kwarciak-Kozłowska, and Sławik-Dembiczak (2021); Yadav et al., (2022)
Cd^{2+}	Scenedesmus obliquus	Initial Cd^{2+} conc 3.0 mg/L, algae conc of 0.8 g/L, 2 h, pH = 6.0	92.7%	Ma et al., (2021)
Al^{3+}	Spirulina platensis	Treated microalgae with sulphuric acid enhances the metal removal at pH 6 for 40 min, initial adsorbent conc of 2.5 g/L, at room temperature, initial metal conc of 50 mg/L	55% for untreated microalgae 95% for treated microalgae	Almomani and Bhosale, (2021)
Cr(VI)	Anabaena variabilis	Initial inoculum 2 mg/L, after 48 h at pH 7.5 at 25°C for 48 h.	75%–91%	Hossain and Okino, (2024)

Table 7 Comparative evaluation of heavy metal removal technologies

Dimensions	Adsorption	Coagulation and precipitation	Membrane filtration (NF/RO)	Electrocoagulation
Treatment efficiency (%)	95–99 (Effective even at low concentrations)	90–99.9 (Ideal pH, high concentrations)	>99 (Can reach less than 0.1 mg/L)	90–99 (Improves at low concentrations)
Effective concentration range	Effective for low to very low concentrations (Less than 1 to 10 mg/L)	Best for medium to high concentrations (more than 10 to 50 mg/L)	Effective for all concentrations (especially low concentrations)	Medium to high (Better than chemical coagulation at low concentrations)
Operating cost (USD/m^3)	1–5 (Depending on the adsorbent types/regeneration)	0.9–1.3	2–10	1–4
Energy consumption (kWh/m^3)	Low to moderate (0.1–0.5)	Very low (0.05–0.2)	High (0.5–2)	Moderate to high (1–5)
Chemical/reagent consumption	Moderate (Adsorbent replacement/regeneration)	High (Lime, Fe/Al salts)	Low (Mainly cleaning chemicals)	Low to moderate (Electrode consumed)
Sludge/by-product generation	Low (spent adsorbent)	High (Metal hydroxide sludge)	Low solids waste produces concentrated brine	Medium (Dense, mineral-rich sludge)
Sludge treatment cost	Low to moderate	High	Moderate (brine disposal)	Moderate
Process complexity	Moderate (adsorbent material management)	Low (simple operation)	High (pressure systems, fouling control)	Moderate (requires electrical control)
Sensitivity to pH	Moderate	High (critical parameter)	Low to moderate	Moderate
Scalability/Industrial maturity	Good (widespread)	Excellent (well-established)	Excellent (industrial but capital-intensive)	Growing (from pilot to industrial scale)
Key advantages	High efficiency at low concentrations	Low cost, simple, and effective for bulk removal	Highest separation efficiency	No need to add chemicals; generates a coagulant on-site
Key limitations	Cost of adsorbent/regeneration	High sludge, poor performance at low concentrations	High cost, fouling, energy consumption	Energy consumption, electrode consumption

significantly limited in reaching ultra-low residual concentrations due to thermodynamic solubility equilibrium, which often restricts effluent levels to above 0.1 mg/L (Shammas et al., 2021; Fei and Hu, 2023). Conversely, adsorption-based approaches using activated carbon, biochar, or engineered nanomaterials exhibit superior performance in the removal of trace contaminants (<1 mg/L), reaching 95%–99% removal efficiency due to high specific surface areas and strong interfacial affinities (Raji et al., 2023; Bayar et al., 2024). However, the commercial scalability of adsorption is often limited by sorbent saturation and the complexity of regeneration, positioning it as an ideal polishing stage rather than a primary treatment for high-strength wastewater (Twizerimana and Wu, 2024).

Ceramic membranes and UF are inexpensive for removing particulates and colloids as a pretreatment step (Staszak and Wieszczycka, 2023; Castro and Abejón, 2024). The advanced membrane separation technologies of nanofiltration and reverse osmosis provide the most stringent purification, frequently achieving rejection rates exceeding 99% and effluent concentrations as low as 0.01–0.1 mg/L (Dawam et al., 2025). Nevertheless, these systems are characterized by substantial energy demands (0.5–2 kWh/m^3) and significant capital expenditures (2–10 USD/m^3), compounded by technical challenges such as membrane fouling and the management of concentrated brine streams.

Ion-exchange columns selectively remove ionic species using synthetic polymeric resins and natural zeolites. Expensive chelating resins are designed for the selective removal of trace heavy metals. Electrocoagulation (EC) dissolves Fe or Al anodes to generate a coagulant. Electrodialysis (ED) uses electrically driven ion transport across ion-exchange membranes. These technologies are widely used at pilot and industrial scales, particularly for metal-rich effluents, electroplating, and mining. EC units are compact and relatively simple; in contrast, ED requires specialized membranes and power electronics (Chu et al.,

2022b; Ayach et al., 2024). Electrocoagulation emerges as a promising hybrid alternative, enabling in-situ coagulant generation and achieving competitive removal efficiencies of 90%–99% (Ammar et al., 2023). While it often produces less voluminous sludge, its widespread adoption is hindered by the cost of electrode consumption and high energy requirements (1–5 kWh/m^3), particularly when treating highly concentrated streams (Twizerimana and Wu, 2024).

The comparative analysis underscores that coagulation–precipitation remains the most practical solution for the bulk treatment of high-strength industrial wastewater. This method offers distinct advantages in cost and scalability. However, its performance is fundamentally restricted by limitations in sludge generation and the removal of metals at low concentrations. Consequently, recent studies increasingly advocate combining bulk removal high-performance separation technologies such as adsorption or membrane filtration to optimize both economic performance and environmental sustainability in the management of heavy metal contamination (Fei and Hu, 2023).

The parameters affecting the constructed wetlands and algal bioremediation differ from those of other technologies. They require a large land footprint, operate at low feed concentrations, and have longer treatment times than other technologies. Besides operating costs (OPEX), the valorization of the harvested plants (in CWs) or algae is a major barrier, as their accumulated heavy metals prevent their use for animal feed or as fertilizers. However, these two techniques are low-tech, suitable for decentralized and rural settings, and use local materials and plants, ensuring high availability and sustainability, especially where land is available (Sridhar et al., 2020; Muzioreva, 2023).

From an environmental perspective, adsorption requires low energy to operate; the main environmental concern is the handling and disposal (or regeneration) of spent sorbents that concentrate metals. Spent adsorbent can sometimes be regenerated (chemical desorption), thermally treated, or used for metal recovery; however, regeneration produces a concentrated metal stream or chemical waste that must be managed (El Messaoudi et al., 2024). Adsorption reduces dissolved metal bioavailability rapidly, lowering immediate ecological and human exposure risk. However, if spent sorbents are disposed of improperly, metals can remobilize and re-contaminate soils or waterways; in addition, some regeneration chemicals, such as strong acids and bases, have their own disposal impacts (Sindhj and Cordeiro, 2025).

Coagulation generates metal-rich sludge, which must be dewatered and disposed of or stabilized. Sludge volume can be large and is the primary environmental problem (landfill demand, leachability). Chemical manufacture and transport add to life-cycle impacts, but per-m^3 operational energy is modest compared with pressure-driven membranes. Natural or "green" coagulants are being studied to reduce the footprint, but conventional inorganic coagulants remain the standard choice (Giannakoudakis et al., 2024). Coagulation is effective at reducing bulk metal loads and is suitable for high-strength industrial streams. However, mismanaged sludge disposal can create secondary contamination hotspots; residual coagulant in effluent can affect aquatic chemistry if overdosed (Zhang et al., 2020).

NF and RO require pumps and safe management or disposal of the rejected brine, which is often the limiting environmental and regulatory factor. If brine is released untreated, it produces local contamination hot spots and acute ecological harm. In addition, powering these systems with fossil-derived electricity increases indirect greenhouse-gas impacts; fouling control requires chemicals with disposal implications. RO achieves the highest removal efficiencies (>95–99% for most metals) while NF often gives excellent rejection for multivalent metals with lower energy than RO, but both must plan for concentrate disposal (Elazhar et al., 2021). Ceramic membranes have lower lifecycle impacts in harsh conditions because of their longer life and tolerance of strong oxidative cleaning. They enable robust treatment of difficult industrial streams, reducing metal loads entering ecosystems. Their durability reduces module replacement waste, but their manufacturing footprint and the disposal of spent ceramic elements and coated layers should be considered. Overall, ceramics can lower environmental impact, whereas polymeric membranes require frequent replacement or extensive pretreatment (Gruskevica and Mezule, 2021).

Ion exchange regeneration produces a small-volume, concentrated brine (acidic or saline) that contains the removed metals; managing, regenerating, or treating this brine is the main environmental and operational challenge. Energy demands are moderate (pumping), but chemical consumption for regeneration (acids, salts) adds to life-cycle impacts. When metal recovery is feasible, the process is economically attractive (Boyer et al., 2021). The major operational footprint of electrochemical processes is energy demand. EC produces a metal hydroxide sludge similar to that

from chemical coagulation, while ED produces recoverable solid metal, concentrating metals in the concentrate streams (Mourdikoudis and Dominguez - Benetton, 2025).

Constructed wetlands and phytoremediation require very low energy, as they depend on solar energy, and provide co-benefits, such as enhanced biodiversity. The main environmental concerns are the land area required, seasonal variability in performance due to temperature variation, and the accumulation of metals in sediments and biomass, which require safe harvesting and safe disposal. Long-term stabilization of metals in sediments can be effective but must be monitored to avoid re-mobilization under changing redox or pH conditions (Horne, 2020). Recent work explores adding adsorbent layers to wetlands to improve removal while reducing land requirements. Some algae strains can reduce Cr(VI) to Cr(III), thereby reducing toxicity (Shang et al., 2025). Microalgae bioremediation requires low energy as it is sunlight-driven; however, more controlled photobioreactors require electricity and CO_2. Biomass harvest and safe disposal are critical; if biomass is left in the environment, it could reintroduce metals (Vishnu et al., 2024). The main risks are algal toxins, if blooms form, and biomass disposal; metal-tolerant strains sometimes contain higher intracellular metal burdens that require careful handling (Reed and Gadd, 2024). The environmental impact of the technologies is illustrated in Fig. 8.

In summary, membrane processes generate less solid waste than conventional methods such as coagulation–precipitation. Nevertheless, challenges remain related to brine disposal and chemical residues, particularly in large-scale applications. Although membrane systems are inherently modular and scalable, operational complexity and membrane degradation can limit long-term performance (Ramachandran and Sathishkumar, 2023; Osman et al., 2024; Azmi et al., 2025). A systematic framework is therefore required for technology selection, incorporating water quality assessment, process efficiency, energy demand, economic feasibility, and waste management considerations. Pilot scale studies and continuous monitoring are essential to ensure reliable operation and scalability (Castro and Abejón, 2024; El-Shahat et al., 2025; Farfán Chilicaus et al., 2025; Acquaye, 2026; Senanayake et al., 2026).

4 Hybrid technique

UF membranes and ceramic membranes are ineffective for the direct removal of dissolved metal ions. Instead, removal occurs via indirect pathways such as polymer-assisted ultrafiltration and colloidal filtration (Bhowmick et al., 2022; Azzam et al., 2025; Khalil et al., 2025). These systems operate at low pressures of 1 bar to 5 bar, offering high energy efficiency and reduced fouling, so they are widely used as pretreatment for NF and RO. Under optimized conditions, removal efficiencies can reach 80%–92%, particularly in hybrid or sorbent-assisted systems (Siagian et al., 2021; Fuks et al., 2022; Fuks et al., 2023; Siddique et al., 2023; Volkov and Polyakov, 2023; Soto, 2025).

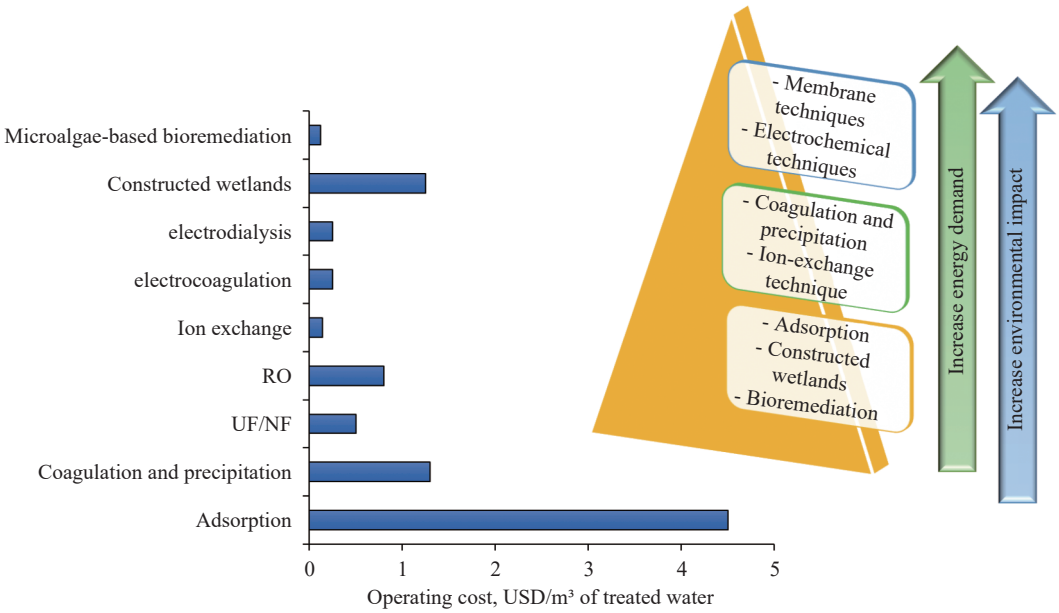


Fig. 8 Comparing OPEX and the environmental impact of the techniques

NF membranes operate at moderate pressures of 4 bar to 30 bar, offering lower energy consumption and reduced operational costs compared to RO, which operates at a pressure range of 10–80 bar (Tang and Bruening, 2020; Thabo et al., 2021; Devaisy et al., 2023; Jakhar et al., 2023).

The main challenges faced by NF and RO are their energy demand and sensitivity to fouling, which necessitates extensive pretreatment and, in some cases, limit their applicability (Lumami et al., 2022; Heiranian et al., 2023; Kapepula and Luis, 2024). Therefore, hybrid membrane systems have been developed to overcome the limitations of single-stage processes by enhancing performance, reducing fouling, and improving energy efficiency through reduced fouling-induced pressure buildup. A common configuration is UF pretreatment before RO; UF removes suspended solids, colloids, and natural organic matter (NOM), significantly reducing RO fouling and improving flux stability (Anis et al., 2019; Pakdaman et al., 2025).

Advanced hybrid systems that combine Membrane Distillation (MD), or Pressure Retarded Osmosis (PRO) with RO, forming RO-MD and RO-PRO, can reduce specific energy consumption from 2.28 kWh/m^3 for standalone RO to 0.67–1.75 kWh/m^3, achieving up to 40%–70% energy savings under optimized conditions (Tsai et al., 2022), while conventional UF-RO systems typically achieve 10%–30% savings (Gomaa et al., 2025). Similarly, NF-RO systems offer a high flux of 37–41 L/m^2·h with > 99% rejection efficiency, demonstrating strong operational performance (Tariqi et al., 2025). Reducing the frequency of chemical cleaning, lowering maintenance requirements, and extending membrane lifespan all improve economic efficiency.

Coupling membrane processes with adsorption or microfiltration further enhances pollutant removal while mitigating fouling through synergistic mechanisms (Song et al., 2025). Table 8 summarizes a comparative evaluation of conventional and hybrid membrane systems. Hybrid configurations offer a more resilient and sustainable alternative by integrating complementary mechanisms that enhance flux stability, improve selectivity, and reduce energy consumption.

Accordingly, the selection between conventional and hybrid systems should be based on a holistic assessment of feedwater characteristics, treatment objectives, and economic constraints. While conventional systems remain suitable for relatively simple applications, hybrid systems are better suited for complex industrial effluents and high-strength wastewater, representing a shift toward more sustainable application-specific treatment strategies. In this context, membrane technologies generally provide a flexible platform for heavy metal removal. RO ensures maximum rejection, NF balances selectivity and energy demand, UF serves as an effective pretreatment step, and ceramic membranes offer enhanced durability under harsh operating conditions. Future research should therefore focus on mitigating fouling, reducing energy requirements, and advancing hybrid-system integration to improve overall sustainability and cost-effectiveness.

5 Scientific challenges

A thorough understanding of process mechanisms is important for optimizing treatment effectiveness. Despite significant progress in developing treatment technologies for heavy-metal-contaminated water, several scientific uncertainties remain in the mechanistic understanding at multiple scales. Adsorption and biosorption mechanisms are still simplified in models; surface chemistry, ion competition, and biomineral interactions are not fully resolved under real wastewater conditions. Limited data exist on the kinetics of metal speciation shifts, such as the conversion of Cr(VI) to Cr(III), and As(III) to As(V) during coupled physical-biological treatments. This hampers the prediction of the long-term stability and mobility of residual metals, real-field performance, and regeneration efficiency.

One of the challenges affecting membrane performance is interference from co-contaminants. Complex wastewaters contain organics, salts, and nanoparticles that affect membrane selectivity, bioavailability, and microbial uptake, but these cross-effects are poorly quantified. Scale-dependent performance is another challenge; laboratory efficiencies rarely translate to field scale because of variations in hydraulic residence time, pH buffering, and temperature fluctuations in natural systems, which makes the study of process mechanisms during scale-up essential. Heavy metals in water are a global but spatially heterogeneous problem. A broad toolkit exists, and nature-based solutions stand out for availability and low environmental impact in many low-resource or diffuse-pollution contexts, while membrane and ion-exchange approaches are preferred when stringent removal goals and centralized treatment justify higher energy and operational complexity. In hybrid-system integration, the interaction mechanisms between combined processes remain poorly quantified; most research is conducted at the lab

Table 8 Comparative evaluation of conventional and hybrid membrane systems

Criterion	Conventional Membrane Systems (UF/NF/RO)	Hybrid Membrane Systems (UF–RO, NF–RO, Adsorption–UF)	Key Limitation
Removal efficiency	High (RO: 95%–99%; NF: 70%–99%; UF: Indirect removal)	Very high (often ≥ 99% due to combined mechanisms)	Hybrid systems may show diminishing returns at very low contaminant concentrations
Selectivity	Limited (UF), Moderate (NF), Broad (RO)	Enhanced selectivity via combined size exclusion, adsorption, and electrostatic interactions	Process optimization is required to avoid over-treatment and inefficiency
Fouling tendency	High in NF/RO due to NOM, colloids, and scaling	Significantly reduced (UF pretreatment removes foulants)	Fouling not fully eliminated; secondary fouling may occur in pretreatment units
Flux stability	Declines over time due to fouling	Improved stability with slower flux decline	Performance depends strongly on upstream process control
Energy consumption	RO: 1–10 kWh/m^3	Reduced by (10%–30)% (UF–RO); up to (40%–70)% in advanced hybrids (RO–MD/PRO)	Energy savings depend on system design and may not be realized in poorly optimized systems
Operating pressure	High (RO: 10–80 bar; NF: 4–30 bar)	Lower effective pressure due to improved feed quality	Additional pumping may be required for multi-stage systems
Chemical consumption	High (Frequent cleaning required)	Reduced (Lower cleaning frequency)	Chemical use may shift to the pretreatment stage rather than being eliminated
Membrane lifespan	Limited due to fouling and scaling	Extended due to reduced fouling load	Lifespan improvement depends on proper maintenance and operation
Operational cost (OPEX)	4.5–6.4 USD·m^{-3}	Reduced by (15%–35)% depending on configuration	Savings may be offset by increased system complexity and control requirements
Capital cost (CAPEX)	Moderate (Single unit)	Higher (multi-unit integration required)	High initial investment may limit adoption in small-scale applications
Process complexity	Relatively simple operation	More complex (Requires optimization and integration)	Requires skilled operation, monitoring, and control systems
Scalability	High (Modular systems)	High, but requires system integration expertise	Scale-up may introduce operational instability if not properly designed
Environmental impact	Lower sludge than conventional treatment, but produces brine	Reduced chemical usage but still produces brine; better overall sustainability	Brine management remains a critical challenge
Suitability for complex wastewater	Limited performance due to fouling	Highly suitable (Handles high turbidity and mixed contaminants)	Performance sensitive to fluctuations in feed composition
Typical applications	Desalination, polishing, low turbidity water	Industrial wastewater, mine drainage, high fouling streams	Application-specific design required

scale and does not account for the variations that occur during scale-up.

6 Technological bottlenecks

The transition from laboratory-scale performance to sustainable industrial or decentralized application faces notable technological constraints. Regeneration efficiency and the safe disposal of metal-loaded sorbents remain a challenge, reducing sorbent capacity and producing secondary metal-laden brines. In membrane technologies, membrane fouling, high operational pressure, and brine disposal remain major barriers to cost-effective and environmentally safe operation. Hybrid pre-coagulation or electro-assisted systems enhance separation but increase complexity.

In ion-exchange resins, selectivity and regeneration chemistry are limited for mixed-metal streams; strong acids or salts used for regeneration create concentrated waste that requires further treatment. In electrochemical processes, high energy demand and electrode passivation constrain scalability, particularly in low-conductivity waters. In nature-based systems, wetlands, algae, and phytoremediation rely on biological metabolism and environmental conditions. Metal accumulation in biomass and seasonal performance variability limit consistent long-term operation. Safe biomass management and monitoring of metal remobilization are required.

Optimization strategies are essential for practical process application. NF and RO achieve 99% rejection but consume 0.5–2 kWh/m^3, require a CAPEX 2–10 USD/m^3, and face severe fouling and concentrated-brine management challenges. This bottleneck, arising from operational complexity, maintenance, chemical cleaning, and infrastructure requirements, limits adoption in low-income countries. The hybrid of RO-MD and RO-PRO is proposed to reduce energy and improve sustainability, but their operational stability and economics remain uncertain. The main bottleneck of coagulation and electrocoagulation is sludge-management infrastructure. The sludge generation rate of such a process ranges between 0.68 kg/m^3 and 1.34 kg/m^3, which requires a proper risk-mitigation analysis before these methods are suitable for developing countries. The main bottleneck of the adsorption process is the regeneration of the adsorbent material; this may be addressed by using natural materials, such as rice husk, followed by landfill disposal of the spent adsorbent, an approach that also applies to the algae produced in algal bioremediation and the plants grown in CWs.

The selection of a suitable technique depends on water chemistry, target concentrations, climate, metal recovery, waste management resources, and allowable energy consumption and OPEX. As a practical recommendation, ion exchange is suitable when selective polishing is needed; it is appropriate for municipal and industrial polishing and for the recovery of valuable metals. Electrocoagulation is appropriate for high-load industrial streams such as mining and plating effluents; it is versatile for multi-contaminant streams and can achieve reduction or oxidation in situ. Electrodeposition is best where metal recovery has economic value for reuse, while electrodialysis is useful for concentrating dilute metal streams for recovery or when desalination with selective ion removal is required. Both constructed wetlands and phytoremediation represent sustainable, low-cost, environmentally friendly strategies for heavy metal removal.

7 Groundwater hydrogeochemical constraints and their consequences for remediation technologies

Groundwater remediation presents unique hydrogeochemical challenges that differ substantially from those encountered in surface waters and industrial waters. Temperature, redox conditions, background water chemistry, and naturally occurring dissolved constituents significantly affect the performance of physical, chemical, and biological treatment technologies (Kanel et al., 2023). Consideration of groundwater-specific conditions is essential for realistic technology assessment and implementation. Groundwater matrices have distinct characteristics: Lower temperature, commonly ranging from 10°C to 20°C, and anoxic conditions. Lower temperatures reduce the rate of adsorption, precipitation, oxidation-reduction reactions, and microbial metabolism (Sun et al., 2024). For example, the release of arsenic depends on redox and pH conditions.

Arsenic leaches under anoxic conditions due to the dissolution of arsenic-bearing iron minerals in the aquifer. It is also released from iron and aluminum hydroxides under oxidizing conditions and high pH. As(III) is difficult to remove and should be oxidized to As(V) for optimal arsenic removal in situ (Navarathna et al., 2020). The most common oxidants for As(III) are chlorine, hydrogen peroxide, ozone, permanganate, manganese dioxide, persulfate, and potassium ferrate. However, the residual oxidant concentration should not exceed the maximum permissible limit (1 mg/L) (Amiri et al., 2022). UV and ozone oxidize 96% As(III) to As(V) within 10 min; however, both require high energy inputs. Biological remediation technologies are particularly sensitive because microbial growth and enzymatic activity decrease substantially at lower temperatures; therefore, microbial metal transformation becomes slower under groundwater conditions (Krylova, 2022; Liu et al., 2025).

Naturally occurring geogenic ions constitute another major challenge. Groundwater frequently contains elevated concentrations of Ca^{2+}, Mg^{2+}, Fe^{2+}, and Mn^{2+}, which compete with target contaminants for adsorption and ion-exchange sites. These competing ions reduce the adsorption capacity and selectivity of sorbents and resins (Mangarengi et al., 2022). Calcium and magnesium, typically present at higher concentrations than heavy metals, can occupy active sites and diminish removal efficiency (Lin et al., 2023). Similarly, dissolved iron and manganese interfere with ion-exchange processes and may accelerate media exhaustion, increasing operational costs and regeneration frequency (Cheng et al., 2023).

Membrane technologies also face important groundwater-specific limitations. Dissolved Fe^{2+} and Mn^{2+} can oxidize and precipitate within membrane systems, causing fouling and permeability decline. In addition, hardness ions such as Ca^{2+} and Mg^{2+} promote mineral scaling, particularly in

reverse osmosis and nanofiltration systems (Shi et al., 2022). These phenomena increase transmembrane pressure requirements, elevate energy consumption, shorten membrane lifespan, and necessitate frequent cleaning. Consequently, pretreatment steps such as oxidation, filtration, and softening are often required before membrane application.

Besides hydrogeochemical conditions, the selection of groundwater remediation techniques is based on the location of treatment, specifically whether an in-situ or ex-situ approach is used. The in-situ approach involves treating the contaminated water within the aquifer, while the ex-situ approach involves pumping the contaminated groundwater out for surface treatment. The in-situ technologies include injection, permeable reaction barriers, air sparging, and thermal treatment. In-situ injection uses chemical methods to convert groundwater contaminants into harmless substances. Oxidizing or reducing reagents are injected into the contaminated groundwater: Oxidizing agents enhance the dissolved oxygen content and promote the oxidation and decomposition of organic compounds; while reducing agents transform or degrade pollutants (Liu et al., 2025).

Microbial agents are also suitable for in-situ injection, provided that appropriate strains are selected and amendments are added to alter environmental conditions and enhance their growth. For example, anaerobic microorganisms such as sulfate-reducing bacteria achieved high removal efficiencies of 99.03% and 99.79% for SO_4^{2-} and Fe^{2+}, respectively, under conditions of 1,500 mg/L initial concentration, pH 7, and a treatment time of 12 h (Geng et al., 2025).

The second in-situ approach is the permeable reactive barrier, which involves installing a permeable barrier filled with reactive material. Common configurations include continuous reactive walls and funnel-and-gate systems (Kończak et al., 2022). Continuous reactive walls are used for mild groundwater contamination, while funnel-and-gate systems are used for severe contamination. A permeable reactive barrier was applied in Elizabeth City, North Carolina, USA, to treat contaminated groundwater. Over three years, an influent Cr(VI) concentration of 3 mg/L was reduced to almost zero (Zhang et al., 2022).

Air sparging is the third type of in-situ approach; it uses shafts to establish an air injection-extraction system that injects air below the water table, where pollutants are transferred from the liquid to the gas phase and then pumped out. The factors affecting this technique are the gas flow rate and the gas pressure (Teng et al., 2025). Air sparging typically takes at least 12 h; by contrast, steam-injection thermal treatment of contaminated groundwater reduces the treatment time to minutes while maintaining high removal efficiency (Cheng et al., 2024).

The ex-situ pump-and-treat technique is widely used; several pumping wells are installed to extract contaminated groundwater to the surface, where it is remediated by chemical, physical, and microbiological methods, then discharged to the distribution network or recharged underground. This technique was applied to treat 4,475 m^3 of groundwater contaminated by arsenic, benzene, ethylbenzene, carbon tetrachloride, and chloroform at a relocated chemical plant in Shanghai; 33 pumping wells were used at a rate of 150–200 m^3/d, and the water was treated using primary sedimentation, advanced oxidation, and coagulation and sedimentation (Liu et al., 2024). Schematic diagrams of in-situ and ex-situ approaches for treatment of contaminated groundwater are shown in Fig. 9, representing the most widely used techniques (Liu et al., 2024).

In-situ technologies generally offer lower energy demands, reduced infrastructure requirements, and minimal disturbance to aquifer systems. However, their effectiveness may be constrained by aquifer heterogeneity, limited reagent distribution, and slower treatment rates. In contrast, ex-situ pump-and-treat systems provide greater operational control and treatment flexibility but require continuous groundwater extraction, pumping energy, long-term maintenance, and higher lifecycle cost and carbon footprint. Therefore, technology selection for groundwater remediation should be based on realistic subsurface hydrogeochemical conditions rather than laboratory performance. Site-specific evaluation of temperature, redox status, competing ions, fouling potential, and aquifer characteristics is critical for optimizing remediation performance.

8 Emerging research directions

Recent research trends indicate several promising avenues to overcome current limitations of hybrid and synergistic systems. These include the integration of physical, chemical, and biological units, for example, combining adsorption with membrane systems. Integrating electrocoagulation with algae, or wetlands with biochar, improves selectivity, reduces energy use, and enhances resilience under

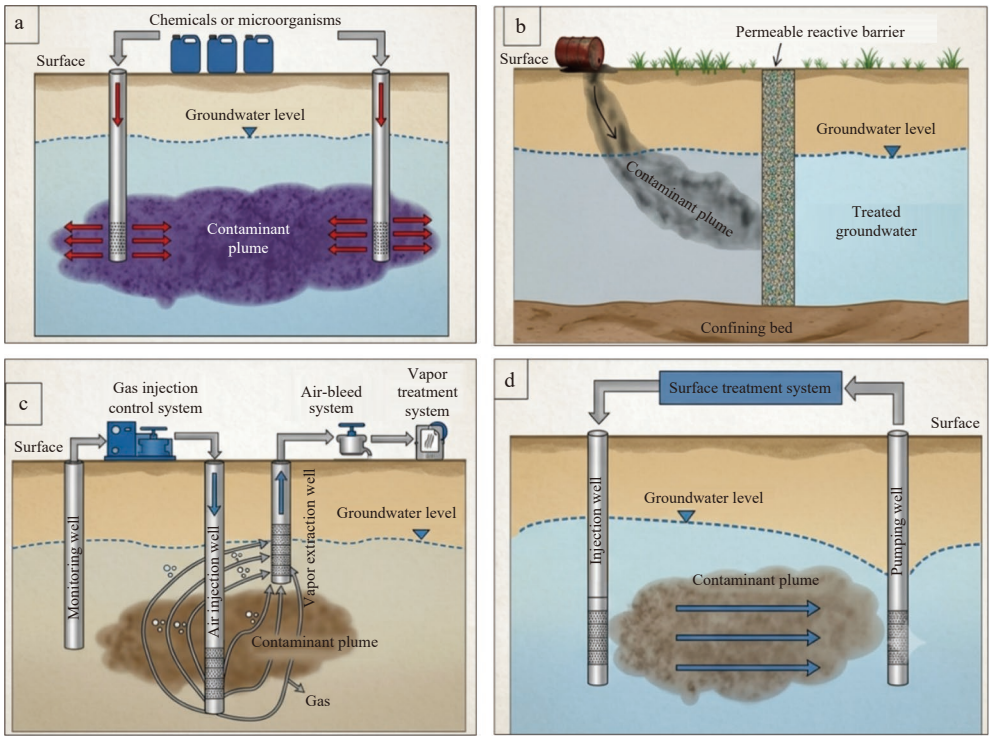


Fig. 9 Schematic diagrams of in-situ and ex-situ approaches for the treatment of contaminated groundwater

Notes: (a) in-situ injection, (b) in-situ permeable reactive barrier, (c) in-situ air sparging, (d) ex-situ pump and treat technique (Liu et al., 2024)

variable loading conditions. The goals of this direction are to reduce fouling, improve metal selectivity, minimize sludge generation, optimize energy recovery, and enable AI-assisted selective recovery for process optimization. The limitations of nanostructured and bio-inspired materials could be overcome by the development of Graphene Oxide membranes (GO), Metal-Organic Frameworks (MOFs), and biochar-nanoiron composites, which enhance selectivity and recyclability for specific metals such as Pb, As, and Cr. Metal recovery and reuse, particularly for Cu, Ni, and Zn, add economic value. Machine learning models for adsorption and membrane fouling prediction are emerging tools for real-time optimization of multi-stage treatment systems.

GO membranes consist of stacked nanosheets that form nanochannels with highly tunable spacing. Their functional groups, hydroxyl, epoxy, and carboxyl groups, enable selective adsorption and ion coordination. Several emerging directions for surface-functionalized GO membranes exist, such as Hg selectivity via thiol-modified GO, Cu and Ni affinity via amine-functionalized GO, and Li separation via layered GO composites (Hoa, 2026; Moradi - Choghamarani and Ghorbani, 2026; Wang et al., 2026). The main barriers to this technology are membrane instability under extreme pH and prolonged operation, high susceptibility to biofouling, the cost of high-quality graphene production, and long-term environmental safety due to nanoparticle release. Current research is focused on crosslinking, polymer-GO composites, and ceramic-support GO membranes.

MOFs, as emerging nanostructured separation materials, have strong potential to simultaneously achieve ultra-high selectivity, fast ion transport, lower energy consumption, resource recovery, and compatibility with circular and carbon-neutral treatment systems. These materials are especially promising for the selective removal and recovery of As, Cr, Pb, Hg, Cu, Li, Co, and Rare Earth Elements (REEs). MOFs can be chemically engineered for specific metals; for example, sulfur-containing ligands are suitable for Hg^{2+}, and carboxyl coordination for Pb^{2+} (Newar et al., 2026). However, despite excellent lab-scale performance, commercialization remains limited by economic barriers, such as expensive organic ligands and energy-intensive fabrication. A major limitation is hydrolytic instability; some MOFs degrade in acidic wastewater, alkaline conditions, and high ionic-strength environments. Their long-term performance in real wastewater therefore remains a critical, unresolved concern.

In this review, the discussed technologies are applied to pollutant removal; however, a critical remaining issue is the recovery of the metal

content from the discharge. The bioaccumulation of heavy metals in algae (algal bioremediation) or plants (CWs) could be used in biofuel production. Metals can be electrodeposited, recovered as reusable solids, and reintegrated into manufacturing chains. Lithium extraction efficiency exceeds 80% (Roy et al., 2022), Cu recovery ranges from 95%–99%, and Ni recovery reaches 90% (Djezzar et al., 2024; Xu et al., 2025).

Adsorbent regeneration is the key challenge for adsorption. Adsorption should be designed not only for high adsorption capacity, but also for selective desorption, metal recovery, and adsorbent recyclability. For an economically feasible process, the number of regeneration cycles must exceed 10, capacity retention must exceed 80% after regeneration, and metal desorption efficiency must exceed 90% (El Messaoudi et al., 2024). The critical issues for membrane separation are fouling, scaling, energy efficiency, and brine disposal. Therefore, emerging membrane directions are the selective ion separation and zero-liquid-discharge systems. Biomass-derived carbon adsorbents are increasingly important because they use waste biomass, sequester carbon, and support circular economy models. Carbon-neutral systems increasingly aim for minimal sludge, maximal water reuse, closed-loop recovery, and zero-liquid discharge. GO/MOF hybrid membranes support high water recovery, selective ion concentration, and reduced waste generation.

Strategically important targets are shifting towards the recovery of Li and Ni for batteries and electronic industries, Co for energy storage, rare earth elements for electronics and clean energy, Cu for high economic recovery value, U for nuclear fuel cycle, and gold and silver electronic waste recovery. Thus, future systems increasingly prioritize the selective recovery rather than bulk removal. Important future research directions include anti-fouling GO membranes to improve membrane durability, water-stable MOFs and hybrid GO-MOF composites to enhance selectivity, AI-assisted membrane design to optimize separation performance, green synthesis methods to reduce carbon footprint, biomass-derived graphene materials to support sustainable manufacturing, selective Li/REE recovery to strengthen critical mineral economy, and solar-power separation systems to enable low-carbon operation. Circular economy and life cycle assessment are two essential tools for evaluating the feasibility of any of the proposed techniques, considering energy used, carbon footprint, and residual management. Such assessments can guide technology policy and direct investment toward sustainable remediation frameworks.

9 Conclusion

Heavy metal contamination of water resources remains a global challenge affecting groundwater, surface water, industrial effluents, mining-impacted waters, and wastewater systems. This review comprehensively evaluated the major remediation technologies currently available for heavy metal removal, comparing their treatment efficiency, technological maturity, energy requirements, residual generation, environmental impacts, scalability, and suitability for different water matrices. The analysis demonstrates that no single technology can satisfy all treatment objectives, as performance depends on contaminant characteristics, water chemistry, regulatory requirements, operational constraints, and sustainability goals. The comparative assessment reveals clear strengths and limitations among the reviewed technologies. Adsorption remains one of the most versatile and cost-effective approaches, particularly when low-cost and waste-derived sorbents are employed. Ion exchange and membrane technologies consistently achieve the highest removal efficiencies, but are associated with higher capital costs, energy consumption, and fouling potential. Electrocoagulation offers rapid and effective treatment for a broad range of contaminants, but requires optimization of energy use and sludge handling. Biological approaches provide environmental co-benefits; however, their performance is constrained by their large land footprint. Hybrid treatment systems improve operational resilience and reduce the limitations of individual technologies. For groundwater remediation, the geochemical characterization is essential for deciding the treatment approach; therefore, several engineering aspects should be considered in future remediation projects, especially those involving groundwater. First, the physical and chemical characteristics of the contaminated water, and the hydrogeochemical characteristics of the groundwater, should be defined. Second, pilot-scale testing should be conducted before full-scale implementation to verify performance under realistic operating conditions. Third, hybrid treatment scenarios should be considered to optimize the technology-selection framework. Fourth, energy consumption, residual management, life-cycle impacts, and technoeconomic performance should be evaluated. The future of heavy metal remediation is expected to rely increasingly on integrated, resource-efficient,

and sustainable treatment systems that combine high removal performance with reduced environmental impacts.

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