

REVIEW



Advances in nanotechnology for heavy metal removal from contaminated water sources

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ABSTRACT

Heavy metal contamination in water sources poses significant threats to human health and ecological systems due to the toxic, non-biodegradable, and persistent nature of these pollutants. Traditional remediation techniques such as chemical precipitation, ion exchange, and filtration often suffer from limitations in selectivity, efficiency, and sustainability. Recent advances in nanotechnology have revolutionized water treatment approaches by introducing a wide range of nanomaterials with enhanced surface properties, high adsorption capacities, and tunable functionalities. This review critically examines the role of various nanomaterials-including carbon-based nanostructures, metal and metal oxide nanoparticles, nanocomposites, layered double hydroxides (LDHs), hydrogels, and nanosponges-in the adsorption and removal of heavy metals such as lead, cadmium, mercury, chromium, and arsenic from aqueous systems. Special emphasis is placed on adsorptive membrane systems that integrate nanomaterials to achieve synergistic removal mechanisms through enhanced surface interactions, porosity, and functional group availability. Furthermore, the review discusses key parameters influencing removal efficiency, recent case studies demonstrating real-world applications, and the challenges related to nanomaterial toxicity, stability, and regeneration. By synthesizing recent findings, this review provides comprehensive insights into the potential of nanotechnology to develop next-generation, sustainable water purification systems.

KEYWORDS

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Introduction

Access to clean and safe water remains one of the foremost global challenges in the face of rapid industrialization, urban expansion, and population growth. Among various contaminants, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) represent a critical class of pollutants due to their non-biodegradable nature, toxicity, and ability to bioaccumulate in aquatic ecosystems and the human body [1]. Chronic exposure to these metals, even at trace levels, has been linked to severe health disorders including neurological, renal, hepatic, and carcinogenic effects [Table 1].

Conventional wastewater treatment technologies-such as chemical precipitation, coagulation, ion exchange, reverse osmosis, and membrane filtration-have been widely applied for heavy metal removal. However, these methods often suffer from insufficient selectivity, high operational cost, sludge generation, pH sensitivity, and secondary pollution risks. Consequently, the search for innovative, efficient, and sustainable solutions has accelerated in recent years [2].

Nanotechnology has emerged as a transformative platform in environmental remediation due to the unique physicochemical characteristics of nanomaterials. These include high surface-area-to-volume ratios, tunable pore sizes, functional group versatility, enhanced reactivity, and strong adsorption affinities, enabling them to effectively target and

sequester a broad spectrum of heavy metals from contaminated water sources [3]. Various types of nanomaterials-such as carbon-based nanostructures (e.g., graphene oxide, carbon nanotubes), metal and metal oxide nanoparticles (e.g., iron oxide, titanium dioxide), nanocomposites, and layered double hydroxides (LDHs)-have demonstrated remarkable potential in enhancing adsorption capacity, selectivity, and recyclability for water purification applications [4].

Notably, the integration of nanomaterials into adsorptive membrane systems offers a dual advantage: combining physical separation with chemical adsorption. These hybrid membranes exhibit improved water permeability, mechanical strength, and heavy metal retention capacity, making them promising candidates for next-generation water treatment systems [5].

This review aims to provide a comprehensive overview of the recent advancements in nanotechnology-enabled strategies for heavy metal removal from aqueous environments. It covers the mechanisms of metal adsorption, classification and characteristics of nanomaterials, factors influencing removal performance, and comparative analysis with conventional methods. Additionally, the review explores real-world applications, challenges, and future prospects for implementing nanotechnology in large-scale, sustainable water treatment infrastructures [6].

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Table 1. Overview of major heavy metals in water: Sources, toxicity, and who permissible limits.

Heavy Metal	Common Sources	Toxic Effects	WHO Permissible Limit (mg/L)
Lead (Pb ²⁺)	Batteries, metal plating, fertilizers, paints	Neurotoxicity, anemia, developmental disorders, kidney failure	0.01
Cadmium (Cd ²⁺)	Electroplating, pigments, battery manufacturing, plasticizers	Renal dysfunction, bone damage, carcinogenic effects	0.003
Mercury (Hg ⁺)	Pulp/paper industries, chlor-alkali plants, agriculture, coal combustion	Neurological damage, kidney failure, teratogenic effects	0.001
Arsenic (As ^{3+/5+})	Groundwater, pesticides, metal smelting	Carcinogenic, liver and skin damage, cardiovascular and neurological disorders	0.01
Chromium (Cr ⁶⁺)	Leather tanning, dye manufacturing, electroplating	Mutagenic, liver and kidney damage, respiratory issues	0.05
Nickel (Ni ²⁺)	Electroplating, stainless steel, batteries	Dermatitis, lung and nasal cancers, respiratory failure	0.07
Copper (Cu ²⁺)	Corroded plumbing, industrial effluents	Gastrointestinal distress, liver and kidney damage	2.0
Zinc (Zn ²⁺)	Galvanization, paint industries, fertilizers	Nausea, vomiting, interference with iron and copper metabolism	3.0

Mechanisms of Heavy Metal Removal Using Nanomaterials

The exceptional physicochemical properties of nanomaterials—such as high surface-to-volume ratios, tunable surface functionalities, and reactive sites—have enabled their effective use in heavy metal remediation. The removal of heavy metals by nanomaterials operates through several distinct mechanisms, which may act independently or synergistically depending on the material type and system configuration. The key mechanisms are described below:

Adsorption

Adsorption is the most widely exploited mechanism for heavy metal removal using nanomaterials. It involves the adherence of metal ions onto the surface of nanostructures via physical or chemical interactions. Nanomaterials like graphene oxide, carbon nanotubes (CNTs), metal oxides (e.g., Fe₃O₄, TiO₂), and nanocomposite membranes provide abundant active sites, facilitating efficient metal ion capture. Factors such as surface area, pore size, pH, and functional group availability critically influence adsorption efficiency [7].

Ion exchange

Certain nanomaterials, particularly layered double hydroxides (LDHs) and functionalized polymeric nanocomposites, facilitate ion exchange, wherein heavy metal ions in solution are replaced with benign ions from the nanomaterial matrix (e.g., Na⁺, Ca²⁺) [8]. This process is selective and is often enhanced by the presence of surface functional groups like carboxyl, amine, or phosphate.

Surface complexation

This mechanism involves the formation of coordination bonds between metal ions and functional groups on the nanomaterial surface. The affinity and geometry of these complexes depend on the metal ion species and the electron-donating groups on the nanostructure (e.g., –OH, –COOH, –NH₂) [9].

Precipitation and co-precipitation

In precipitation-based removal, heavy metals react with counter ions or functional moieties to form insoluble hydroxides, sulfides, or carbonates that deposit on the nanomaterial or are filtered out. Co-precipitation occurs when nanomaterials serve as nucleation sites, aiding the aggregation of metal precipitates [10].

Reduction and redox reactions

Some nanomaterials (e.g., nano zero-valent iron, nZVI) can chemically reduce toxic metal ions to less soluble or less toxic oxidation states. This redox mechanism is especially effective for contaminants like Cr(VI), which is reduced to Cr(III), and As(V) to As(III) [11].

Electrostatic attraction

For charged nanomaterials, electrostatic forces play a significant role in the attraction and immobilization of oppositely charged metal ions. The surface charge of nanomaterials can be manipulated by pH or functionalization to enhance selectivity and binding strength [12].

Photocatalysis and advanced oxidation

Certain nanomaterials, particularly TiO₂ and ZnO, exhibit photocatalytic properties that enable them to degrade metal-organic complexes or oxidize metal species under UV or visible light. This mechanism is less common but effective in systems combining removal with detoxification [13].

Types of Nanomaterials for Heavy Metal Removal

Nanomaterials applied for the remediation of heavy metal-contaminated water are characterized by their high surface area, tunable surface chemistry, and superior reactivity. These materials can be classified based on their composition and structural attributes. This section outlines the principal categories of nanomaterials used in heavy metal removal, highlighting their properties, mechanisms, and relevant applications.

Carbon-based nanomaterials

Carbon-based nanomaterials-such as graphene oxide (GO), reduced graphene oxide (rGO), carbon nanotubes (CNTs), and activated carbon nanofibers-have been extensively explored due to their large surface area, π -electron-rich frameworks, and capacity for chemical modification [14].

- Graphene oxide and rGO are rich in oxygen-containing groups (e.g., $-\text{COOH}$, $-\text{OH}$, $-\text{epoxy}$) that facilitate adsorption and surface complexation with metal ions like Pb^{2+} , Cd^{2+} , and Hg^{2+} .
- CNTs, both single-walled and multi-walled, provide high mechanical strength and conductivity, and functionalization enhances their dispersibility and metal affinity.

Metal oxide nanoparticles

Metal oxides such as iron oxides (Fe_3O_4 , Fe_2O_3), titanium dioxide (TiO_2), zinc oxide (ZnO), and manganese oxide (MnO_2) have demonstrated significant adsorption and redox capabilities.

- Iron oxide nanoparticles exhibit magnetic properties allowing for easy separation after treatment. They have a high affinity for arsenic, chromium, and lead ions [15].
- TiO_2 and ZnO not only adsorb heavy metals but also act as photocatalysts under UV or visible light to degrade metal-organic complexes.

Zero-valent metal nanoparticles (nZVI)

Nanoscale zero-valent iron (nZVI) is widely recognized for its ability to reduce and immobilize heavy metals through redox reactions and co-precipitation.

- nZVI reduces Cr(VI) to Cr(III) and facilitates its subsequent adsorption or precipitation.
- However, bare nZVI particles tend to agglomerate and oxidize, so surface stabilization using polymers or carbon matrices is often necessary.

Layered double hydroxides (LDHs)

LDHs are anionic clays composed of positively charged layers and interlayer anions. Due to their anion-exchange capabilities, LDHs are effective in removing oxyanion-form heavy metals like arsenate, chromate, and selenite [16].

- The substitution of metals in the brucite-like layers (e.g., $\text{Mg}^{2+}/\text{Fe}^{3+}$) allows tunability of surface charge and interlayer chemistry.

Polymeric Nanocomposites

Natural polymers (e.g., chitosan, alginate) and synthetic polymers (e.g., polyacrylamide, polyethyleneimine) are often combined with nanoparticles to enhance mechanical strength and improve sorption performance [17].

- These materials offer multiple functional groups ($-\text{NH}_2$, $-\text{OH}$, $-\text{COOH}$) that interact with metal ions via chelation or electrostatic forces.
- Polymeric membranes embedded with nanoparticles exhibit both size-exclusion and adsorption mechanisms.

Metal-organic frameworks (MOFs)

MOFs are porous crystalline structures composed of metal ions and organic linkers. Their high porosity and customizable pore environments make them attractive for selective heavy metal adsorption.

- MOFs such as Zr-based UiO-66 and Fe-based MIL-101 have shown promising results for Hg^{2+} , Pb^{2+} , and Cu^{2+} removal [18].

Nanosponges and hydrogels

Nanosponges are porous 3D networks, often based on cyclodextrins or other polymers, that can capture both organic and inorganic pollutants.

- Hydrogels incorporate functional groups capable of swelling in water and binding to heavy metals via ion exchange or surface complexation [19].

Factors Influencing the Performance of Nanomaterials in Heavy Metal Removal

The efficiency and selectivity of nanomaterials in removing heavy metal ions from contaminated water depend on a wide array of physicochemical and operational parameters. Understanding these influencing factors is crucial for the rational design and optimization of nanomaterial-based water treatment systems.

Surface area and porosity

One of the most defining characteristics of nanomaterials is their high surface-area-to-volume ratio, which significantly enhances the number of available active sites for adsorption and interaction with metal ions. Materials with large surface areas, such as graphene oxide, carbon nanotubes, and mesoporous metal oxides, allow greater accessibility for contaminant binding. Additionally, porosity-especially meso- and microporosity-affects the diffusion and entrapment of metal ions. The pore structure must be engineered to ensure that it allows metal ions to access internal surfaces without hindering mass transfer [20].

Surface functional groups

The nature and density of functional groups on the nanomaterial surface play a pivotal role in determining their adsorption capacity and metal-binding specificity. Functional groups such as $-\text{COOH}$, $-\text{OH}$, $-\text{NH}_2$, and $-\text{SH}$ provide reactive sites for complexation, chelation, ion exchange, and electrostatic interaction. Functionalization of nanomaterials-either through chemical modification or grafting-can significantly enhance their selectivity toward particular heavy metal species [21]. For example, amine-functionalized graphene oxide shows superior binding to lead and copper ions due to its ability to form coordination complexes.

Particle size and morphology

Particle size influences both the surface reactivity and dispersion stability of nanomaterials. Smaller particles offer higher surface-to-volume ratios and thus more active sites. However, they may also be prone to agglomeration, which reduces their effective surface area and performance. Nanomaterials with controlled and uniform morphology-such

as spherical nanoparticles, nanorods, or nanoflakes-often demonstrate more predictable and consistent behavior in adsorption and catalysis applications [22]. Morphological control is particularly important in ensuring optimal dispersion within polymer matrices in nanocomposite membranes.

pH of the solution

The pH of the aqueous environment significantly affects both the ionization state of surface functional groups on nanomaterials and the speciation of heavy metals in solution. At lower pH, protonation of functional groups may reduce their ability to bind cationic metals due to electrostatic repulsion or competition with H^+ ions. Conversely, at higher pH values, deprotonation enhances negative surface charge, promoting adsorption of positively charged metal ions through electrostatic attraction [23]. Optimal pH conditions vary depending on the target metal and nanomaterial used; for instance, maximum adsorption of Cr(VI) by iron oxide nanoparticles generally occurs in acidic conditions, whereas Pb(II) adsorption by graphene oxide is favored in near-neutral to slightly basic pH [24].

Contact time and adsorption kinetics

The interaction time between nanomaterials and contaminated water affects the extent of metal removal. Most nanomaterials exhibit rapid adsorption kinetics due to their high reactivity and surface accessibility. However, equilibrium times vary based on particle dispersion, concentration gradients, and the type of heavy metal involved [25]. Understanding the kinetics-whether it follows pseudo-first-order, pseudo-second-order, or intraparticle diffusion models-helps in scaling up for continuous-flow systems and optimizing treatment time.

Initial metal ion concentration

The initial concentration of metal ions in the solution influences the driving force for mass transfer and adsorption onto the nanomaterial surface. At low concentrations, metal ions are efficiently captured by the available surface sites. However, at higher concentrations, saturation may occur, reducing removal efficiency unless additional adsorbent is introduced. This parameter is critical for designing systems intended to treat industrial effluents with variable contaminant loads [26].

Dispersion and stability in aqueous media

The dispersibility of nanomaterials in water directly affects their accessibility to metal ions. Materials that agglomerate or sediment rapidly will exhibit lower effective surface area and reduced performance. Surface modification with hydrophilic polymers or surfactants can improve colloidal stability, particularly in complex wastewater matrices. Additionally, ensuring stability over a wide pH range and ionic strength is essential for real-world applications [27].

Temperature

Temperature can influence both adsorption capacity and reaction kinetics. In some cases, increased temperature enhances the mobility of metal ions and the activity of surface sites, leading to improved removal efficiency. However, for certain nanomaterials or adsorbates, elevated temperatures may reduce adsorption due to the exothermic nature of the process.

Thermodynamic analysis (e.g., Gibbs free energy, enthalpy, and entropy changes) helps to evaluate whether the process is spontaneous and favorable under specific thermal conditions [28].

Regenerability and reusability

For sustainable and cost-effective applications, nanomaterials must be reusable over multiple adsorption-desorption cycles without significant loss of efficiency. Factors such as structural integrity, binding reversibility, and ease of regeneration (using acid, base, or salt solutions) determine their practical viability [29]. Materials like magnetic nanoparticles and functionalized polymeric nanocomposites often demonstrate excellent regeneration potential, enabling repeated use in batch or continuous treatment systems.

Interaction with co-existing ions

In real wastewater systems, various ions coexist, including competing heavy metals, alkali metals (e.g., Na^+ , K^+), and anions (e.g., Cl^- , NO_3^- , SO_4^{2-}). These species may compete with target contaminants for adsorption sites, alter the surface charge of the nanomaterials, or form complexes that influence the overall removal efficiency. Hence, selectivity and competitive adsorption behavior must be carefully considered during material design and testing [30].

Role of Adsorptive Nanocomposite Membranes in Heavy Metal Removal

Structure and Functionality of Adsorptive Nanocomposite Membranes

Adsorptive nanocomposite membranes (ANMs) have garnered considerable attention as an innovative and efficient solution for the removal of heavy metal ions from contaminated water sources. These membranes represent a hybrid system that combines the benefits of membrane separation with the adsorption capabilities of nanomaterials. The integration of nanostructures into polymeric matrices allows these membranes to simultaneously achieve physical filtration and chemical binding, resulting in a versatile platform for water purification [31].

Structurally, adsorptive nanocomposite membranes are composed of a base polymer such as polyvinylidene fluoride, polysulfone, or chitosan, which is embedded with or surface-modified using functional nanomaterials. These nanomaterials may include carbon-based compounds like graphene oxide or carbon nanotubes, metal or metal oxide nanoparticles such as iron oxide and titanium dioxide, layered double hydroxides, zeolites, and metal-organic frameworks [32]. The nanostructures introduce reactive surface sites and enhance the membrane's surface chemistry, enabling the efficient capture of heavy metal ions through mechanisms such as ion exchange, surface complexation, or electrostatic interaction.

Mechanisms of Heavy Metal Removal in ANMs

The removal of heavy metals in these membrane systems is governed by a combination of physicochemical mechanisms. Adsorption occurs at the functional sites on the nanomaterials, while the porous membrane matrix contributes to size-based

separation and retention. Electrostatic attraction between the charged nanomaterial surfaces and ionic metal species further enhances selectivity [33]. In some systems, nanomaterials like nanoscale zero-valent iron or iron oxide can facilitate redox or co-precipitation reactions, converting metal ions into less soluble or less toxic forms that are retained within the membrane matrix.

Key performance parameters

The performance of adsorptive nanocomposite membranes is closely linked to several key parameters. Hydrophilicity, for instance, enhances water permeability and reduces the likelihood of fouling. Pore size and porosity govern fluid transport and affect the accessibility of active sites within the membrane. Surface roughness can increase the effective surface area, while chemical functionalization directly influences the selectivity and binding capacity for specific heavy metals. Moreover, mechanical stability is critical for operational durability, especially under continuous flow conditions in filtration systems [34].

Nanomaterials used in ANM fabrication

A wide variety of nanomaterials have been employed in the fabrication of ANMs, each contributing unique properties. Carbon-based nanomaterials, such as graphene oxide and carbon nanotubes, provide high surface area and versatile chemical functional groups. When incorporated into membranes, these materials enhance both mechanical strength and metal ion binding affinity. Metal oxide nanoparticles like Fe_3O_4 and TiO_2 introduce magnetic or photocatalytic properties, along with active surface sites for heavy metal binding. Layered double hydroxides offer anion exchange capabilities and are particularly effective for removing metal species that exist in anionic forms, such as arsenate and chromate. Polymeric composites enhance flexibility, dispersibility, and biocompatibility, while materials like metal-organic frameworks contribute high porosity and customizable selectivity (Figure 1).

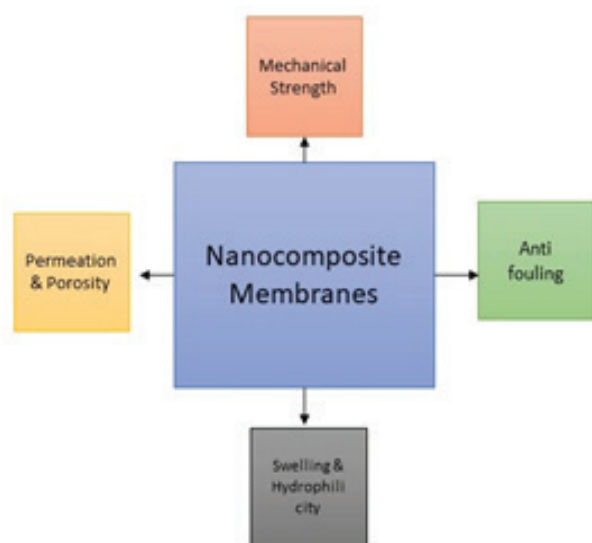


Figure 1. Key properties of nanocomposites for heavy metal removal.

Advantages over conventional membrane systems

Compared to conventional membrane systems, adsorptive nanocomposite membranes offer significant advantages. Traditional membranes often suffer from limited selectivity and are prone to fouling and pore blockage. In contrast, ANMs exhibit high specificity for metal ions due to their tailored surface chemistry. Their enhanced hydrophilicity and structural design reduce fouling, while the presence of nanomaterials improves adsorption capacity and enables regeneration. Furthermore, multifunctionality can be achieved by incorporating photocatalytic or antimicrobial agents, thus extending the membranes' application beyond mere filtration.

Comparative Analysis with Conventional Methods

Conventional techniques for the removal of heavy metals from water—such as chemical precipitation, ion exchange, membrane filtration, reverse osmosis, adsorption using activated carbon, and electrochemical treatments—have long been used in municipal and industrial wastewater treatment [35]. While these methods have proven effective to varying degrees, they are often associated with several limitations related to cost, efficiency, environmental sustainability, and long-term performance.

Chemical precipitation is one of the most widely used conventional methods due to its simplicity and low operational cost. It involves the transformation of dissolved heavy metal ions into insoluble forms, typically hydroxides or sulfides, by the addition of reagents such as lime, alum, or sulfide salts. However, this method is often ineffective for low-concentration metal ions and generates large volumes of toxic sludge, requiring further handling and disposal. Moreover, it lacks selectivity, making it less suitable for complex wastewater matrices containing multiple metal ions or organic contaminants [36].

Ion exchange methods are highly selective for certain metal ions and can achieve significant removal efficiencies. Synthetic resins with functional groups such as sulfonate or carboxylate are commonly employed in fixed-bed columns. However, these resins are expensive, sensitive to fouling, and often require regeneration using concentrated acids or bases, resulting in secondary waste streams and high operational complexity.

Reverse osmosis and nanofiltration are membrane-based techniques capable of removing a wide range of dissolved species, including heavy metals. These methods operate via size exclusion and charge repulsion, delivering high rejection rates. Nevertheless, their high energy demand, membrane fouling, and limited selectivity toward specific metal species restrict their widespread application in decentralized or resource-limited settings. Additionally, these systems often concentrate pollutants into brine streams, which require further treatment.

Activated carbon adsorption is another traditional approach, offering good removal efficiencies for a variety of organic and inorganic pollutants. However, its performance in heavy metal removal is relatively limited, especially for metals that do not strongly interact with carbon surfaces. Activated carbon is also costly to regenerate and prone to exhaustion under high contaminant loads [37].

In contrast, nanotechnology-based approaches-particularly nanomaterial-embedded membranes and nanosorbents-offer superior advantages. Nanomaterials exhibit high surface area, tunable pore structures, and modifiable surface chemistries that allow for targeted removal of a wide spectrum of heavy metals even at trace concentrations. Their mechanisms, such as redox transformation, surface complexation, ion exchange, and electrostatic attraction, provide enhanced performance over traditional methods. Moreover, nanomaterials can be designed to be multifunctional, integrating detection, removal, and even catalytic degradation within a single system.

Adsorptive nanocomposite membranes, in particular, provide a hybrid platform that combines membrane separation with the reactivity of nanoscale materials. Unlike conventional membranes that rely solely on size exclusion or pressure gradients, these systems actively bind metal ions through chemical interactions, leading to higher selectivity, reduced fouling, and potential for regeneration and reuse. Additionally, many nanomaterials, such as magnetic nanoparticles, can be easily recovered and recycled, addressing environmental concerns associated with nanomaterial leaching [38].

Despite their promise, nanotechnology-based systems are still evolving and face challenges such as potential toxicity, environmental persistence, scalability, and cost-effectiveness at industrial levels. However, with advancements in green synthesis methods, sustainable material design, and process optimization, nanotechnology is positioned to overcome the limitations of conventional systems and play a transformative role in future water treatment technologies.

Challenges and Future Prospects

Despite significant advancements in nanotechnology-based approaches for heavy metal removal from contaminated water sources, several critical challenges impede their widespread practical application. A major limitation lies in the scalability and reproducibility of nanomaterial synthesis methods. Many nanomaterials are fabricated under tightly controlled laboratory conditions that are often not feasible for large-scale production, thereby restricting their deployment in real-world water treatment infrastructures. Furthermore, the high cost associated with the synthesis of certain nanomaterials, especially those involving complex fabrication techniques or scarce precursors, presents a considerable economic barrier, particularly in low-resource settings.

Another pertinent challenge concerns the environmental safety and potential ecotoxicological impacts of nanomaterials. The environmental fate, transport mechanisms, bioaccumulation potential, and long-term toxicity of engineered nanomaterials in aquatic systems remain inadequately understood [39]. This knowledge gap raises concerns regarding secondary contamination and ecological risks, underscoring the necessity for comprehensive environmental risk assessments and the development of biocompatible, non-toxic nanomaterials. Strategies for efficient recovery, regeneration, and recycling of nanomaterials are equally critical to mitigate environmental release and ensure sustainable application.

Additionally, the operational stability and reusability of nanomaterials present technical challenges. Adsorbents often exhibit diminished removal efficiency after multiple regeneration cycles, which adversely affects their economic viability and practical utility. Enhancing the physicochemical stability and adsorption capacity retention through material engineering and surface functionalization is imperative to advance the practical deployment of these nanotechnologies.

Future research directions should emphasize the design and synthesis of multifunctional nanocomposites that integrate adsorption with complementary mechanisms such as photocatalytic degradation or antimicrobial activity, thereby expanding the functional scope of water remediation technologies. Integration of nanomaterial-based treatment systems with real-time monitoring and sensing technologies will facilitate dynamic process control and improved contaminant management [40].

Moreover, interdisciplinary collaboration involving materials science, environmental toxicology, engineering, and regulatory policy is essential to establish standardized protocols for nanomaterial evaluation, environmental impact assessment, and regulatory compliance. Such frameworks will ensure the safe, responsible, and effective implementation of nanotechnology-enabled water treatment solutions.

Conclusions

Nanotechnology has demonstrated considerable potential as an advanced strategy for the removal of heavy metals from contaminated water sources. Recent developments in the synthesis of diverse nanomaterials-such as metal oxide nanoparticles, carbon-based nanostructures, and functionalized nanocomposites-have enabled enhanced adsorption capacities, improved selectivity, and faster removal kinetics compared to conventional remediation techniques. These advancements underscore the ability of nanotechnology to address persistent challenges in heavy metal contamination across various environmental matrices.

Nonetheless, the practical application of nanomaterials is still limited by challenges including scalable and cost-effective production, material stability during repeated usage, and potential environmental risks associated with nanoparticle release. Comprehensive toxicological assessments and development of safe, eco-friendly nanomaterials are critical to mitigate these concerns. Additionally, optimizing regeneration processes to maintain adsorption efficiency over multiple cycles is essential for sustainable operation.

Future research should focus on designing multifunctional nanomaterials that integrate heavy metal adsorption with complementary functionalities, as well as incorporating real-time sensing capabilities for dynamic monitoring and control. Collaborative interdisciplinary approaches will be vital in establishing standardized safety protocols and regulatory frameworks to facilitate responsible deployment.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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