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Metal and metal oxide nanomaterials for heavy metal remediation: novel approaches for selective, regenerative, and scalable water treatment

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Heavy metal contamination in water sources poses a significant threat to environmental and public health, necessitating effective remediation strategies. Nanomaterial-based approaches have emerged as promising solutions for heavy metal removal, offering enhanced selectivity, efficiency, and sustainability compared to traditional methods. This comprehensive review explores novel nanomaterial-based approaches for heavy metal remediation, focusing on factors such as selectivity, regeneration, scalability, and practical considerations. A systematic literature search was conducted using multiple academic databases, including PubMed, Web of Science, and Scopus, to identify relevant articles published between 2013 and 2024. The review identifies several promising nanomaterials, such as graphene oxide, carbon nanotubes, and metal-organic frameworks, which exhibit high surface areas, tunable surface chemistries, and excellent adsorption capacities. Surface functionalization with specific functional groups (e.g., carboxyl, amino, thiol) significantly enhances the selectivity for target heavy metal ions. Advances in regeneration strategies, including chemical desorption, electrochemical regeneration, and photocatalytic regeneration, have improved the reusability and cost-effectiveness of these materials. Scalability remains a critical challenge, but recent developments in synthesis methods, such as green synthesis and continuous-flow synthesis, offer promising solutions for large-scale production. The stability and longevity of nanomaterials have been improved through surface modification and the development of hybrid nanocomposites. Integrating nanomaterials with existing water treatment infrastructure and combining them with other remediation techniques, such as membrane filtration and electrochemical methods, can enhance overall treatment efficiency and feasibility. In conclusion, nanomaterial-based approaches hold immense promise for revolutionizing heavy metal remediation and advancing sustainable water management practices. As future research is geared towards retrofitting existing treatment plants, it is equally critical to mitigate unintended environmental and public health consequences associated with the widespread production and use of nanomaterials, such as their leachability into water systems and environmental persistence.

KEYWORDS

nanoparticles, heavy metals, wastewater treatment, adsorption mechanisms, membrane filtration

1 Introduction

The contamination of fresh and marine water sources with heavy metals is a pressing environmental and public health concern with profound implications for ecosystems and human health. This is attributed to the exponential increase in urbanization and industrial and human activities (Qasem et al., 2021; Hama Aziz et al., 2023). These toxic pollutants, including lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr), infiltrate water bodies through various pathways such as industrial discharges, mining activities, agricultural runoff, and natural processes like rock weathering (Qasem et al., 2021). The WHO reported that about 1 million people lost their lives in 2019 due to lead exposure and about 140 million people from 70 countries have been drinking water contaminated with arsenic (WHO, 2022; WHO 2023).

The non-biodegradable nature of heavy metals facilitates their persistence and accumulation in the environment. The repercussions of heavy metal pollution are extensive, affecting both the human and aquatic ecosystems (Roy et al., 2024). Aquatic ecosystems suffer from bioaccumulation and biomagnification of heavy metals, leading to ecological imbalances and long-term risks (Sharma et al., 2024). In humans, exposure to heavy metals via contaminated water or food can result in severe health problems ranging from neurological disorders to cancer, with vulnerable groups like children and pregnant women facing heightened risks (Edo et al., 2024). For instance, heavy metal contamination of surface water sources from persistent industrial discharge results in the bioaccumulation of these metals in aquatic organisms like fish, leading to increased morbidity and mortality among aquatic life. Moreover, consuming these contaminated fish can pose serious health risks to humans. Thus, evaluating water sources for metal pollution is critical due to the environmental persistence of heavy metals and their detrimental impact on flora and fauna, even at minute concentration levels (Edo et al., 2024). Table 1 below highlights some heavy metals of public health concern, their permissible limits, implications, and sources.

Traditional methods for heavy metal remediation, such as chemical precipitation, coagulation-flocculation, ion exchange, and membrane filtration, have limitations that impede their effectiveness (See Table 2). These methods often lack selectivity, removing essential ions along with heavy metals and generating toxic byproducts like sludge (Zamora-Ledezma et al., 2021). For instance, coagulation-flocculation processes result in the production of significant quantities of chemical sludge and can leave residual coagulant metals in the treated water (Zinicovscaia, 2016). Moreover, residual coagulant metals like aluminium are associated with several issues, including increased turbidity, reduced disinfection efficiency, decreased hydraulic capacity, and potential adverse health effects such as Alzheimer's disease

TABLE 1 Heavy metals of public health concern, their permissible limits, implications, and sources.

Heavy metal	Permissible limit (mg/L)		Sources	Human impact		References
	Potable	Non-potable		Short-term	Long-term	
Mercury	0.001	0.002	Industrial discharge, mining, fossil fuel combustion	Neurological disorders, kidney damage	Cognitive and motor dysfunction, neurodevelopmental issues	Qasem et al. (2021), Edo et al. (2024)
Lead	0.01	0.05	Leaded gasoline, industrial processes, lead pipes	Cognitive impairment, abdominal pain	Developmental delays, hypertension, renal impairment	Roy et al. (2024), Sharma et al. (2024)
Arsenic	0.01	0.1	Agricultural runoff, industrial discharge, mining	Skin lesions, nausea, vomiting	Cancer, cardiovascular diseases, diabetes	Hama Aziz et al. (2023)
Cadmium	0.003	0.01	Battery manufacturing, metal plating, fertilizers	Gastrointestinal irritation, vomiting	Bone fractures, renal dysfunction, cancer	Qasem et al. (2021), Sharma et al. (2024)
Chromium	0.1	0.5	Industrial processes, electroplating, leather tanning	Skin irritation, allergic reactions	Respiratory issues, lung cancer, kidney damage	Hama Aziz et al., 2023, Qasem et al. (2021)
Iron	0.3	1.0	Natural deposits, industrial waste, corrosion of pipes	Gastrointestinal issues	Potential liver damage, diabetes	Roy et al. (2024), Edo et al. (2024)

TABLE 2 Conventional methods of heavy metals remediation in wastewater and their drawbacks.

Method	Advantages	Drawbacks	References
Chemical Precipitation	Simple, effective for a wide range of metals	Generates large volumes of sludge, not selective	Zamora-Ledezma et al. (2021)
Coagulation-Flocculation	Effective for removing colloidal particles	Produces chemical sludge, residual coagulants	Zinicovscaia (2016)
Ion Exchange	High removal efficiency, regenerable	High operational costs, limited by resin capacity	Qasem et al. (2021)
Membrane Filtration	High efficiency, capable of removing various contaminants	Membrane fouling, high operational costs	Zamora-Ledezma et al. (2021)
Adsorption	High surface area, effective for low concentrations	High cost of adsorbents, regeneration issues	Ali et al. (2023), Ethaib et al. (2022)
Electrochemical Treatment	Precise control, capable of handling various metals	High energy consumption, electrode degradation	Martínez-Huitle et al. (2018), Feng et al. (2023)

(Zinicovscaia, 2016). Additionally, traditional heavy metal remediation methods can be cost-prohibitive and challenging to scale up for large-scale water treatment applications (Qasem et al., 2021; Zamora-Ledezma et al., 2021). For example, carbon-based adsorbents such as activated carbon are prepared following high heat and pressure requirements, which are energy and cost-intensive (Qasem et al., 2021). In response to these challenges, nanomaterial-based approaches have emerged as promising solutions due to their unique properties and versatile applications in heavy metal remediation (Solomon NkoOkina et al., 2024). Table 2 summarizes traditional methods of treating heavy metals in wastewater and their potential drawbacks.

Nanomaterials offer several advantages for addressing heavy metal contamination in water sources. Their high surface area-to-volume ratio, tunable surface chemistry, and enhanced reactivity make them highly efficient adsorbents and catalysts (Ali et al., 2023). Recent trends in nanomaterial-based approaches focus on achieving selective adsorption, regeneration capability, scalability, and multifunctionality (Yang et al., 2019; Kolluru et al., 2021). Functionalized nanomaterials with tailored surface properties exhibit selective adsorption of specific heavy metal ions, minimizing interference from other ions and enhancing treatment efficiency (Mensah et al., 2021). Some nanomaterials are capable of removing toxic metal ions and tiny pollutants smaller than 300 nm (Baby et al., 2022). Moreover, some nanomaterials possess inherent regenerative properties or can be easily regenerated through desorption processes, enabling multiple cycles of use and reducing operational costs (Mensah et al., 2021). Some of the commonly explored nanomaterials for heavy metal remediation in wastewater are zero-valent metals, carbon-based materials, polymer-based materials, zeolite, magnetic materials, nanocomposites, and metal oxides (Yang et al., 2019; Ethaib et al., 2022). In one study, composite hydrogel consisting of gum tragacanth and graphene oxide (GO) was effectively used to adsorb 65 ppm of the following heavy metal contaminants: Cd (II), Pb (II), and Ag (I) at 89%, 96.4%, and 85.4% removal efficiency respectively (Sahraei and Ghaemy, 2017). The GO nanosheets, rich in hydrophilic hydroxyl and carboxyl functional groups, not only increased the hydrogel's water absorption capacity but also provided multiple active sites for metal ion binding. This incorporation of GO expanded the hydrogel network structure, enhancing its ability to swell in aqueous environments and improving metal ion uptake. In another study, sulfide nanoscale zero-valent iron (S-NZVI) treated with nitro-functionalized UiO-66 was a reliable adsorbent for radioactive uranium (VI) and had a high removal rate (895 mg/g) as opposed to S-NZVI (434 mg/g) and UiO66-NO_2 (267 mg/g) (Zhang et al., 2023). The study highlights that the removal mechanisms for U(VI) include physical adsorption, electrostatic attraction, and complexation by UiO-66-NO2, while S-NZVI contributes to uranium reduction and further complexation. The improved reactivity and smaller particle size of S-NZVI/UiO-66 result in greater contact with uranium ions, allowing for more efficient removal across a wide pH range.

While nanomaterials are emerging as a game-changer in the treatment of heavy metals in wastewater, current research is also focusing on sustainable production processes and the integration of these materials into existing treatment facilities (Solomon N. O. et al., 2024; Poonia et al., 2024; Shingare et al., 2024). Advances in nanomaterial synthesis techniques and reactor design are facilitating scalable production and seamless integration into conventional systems, enabling the efficient removal of heavy metals from large volumes of water (Khan et al., 2024; Nupur and Nipun, 2024). Moreover, researchers are developing multifunctional nanomaterials that can simultaneously target multiple contaminants, including heavy metals, organic pollutants, and pathogens, thereby addressing the complex nature of water pollution more comprehensively (Zhang et al., 2019).

Thus, given the persistent challenges associated with heavy metal contamination, the limitations of traditional remediation methods, and the emergence of nanomaterials as a potentially more effective treatment method, this review is essential. It responds to the urgent need for innovative and sustainable solutions to combat heavy metal pollution and safeguard water quality and public health. This review is novel in its comprehensive examination of recent advances in nanomaterial-based approaches for heavy metal remediation, specifically focusing on selectivity, regeneration capabilities, and scalability. The primary objectives are to provide a thorough overview of the current state-of-the-art in nanomaterial-based heavy metal remediation, identify key challenges and opportunities in the field, and propose future directions for research and development aimed at advancing sustainable water treatment technologies.

TABLE 3 Key performance metrics of various nanomaterials for heavy metal removal.

Nanomaterial	Heavy metals removed	Adsorption capacity (mg/g)	Selectivity	Regeneration efficiency	Special characteristics	References
Zerovalent Iron Nanoparticles (ZVINPs)	Pb^{2+}, Cd^{2+}, Cr^{6+}, As^{3+}	230–350	High (Pb^{2+})	85%–90% after 3 cycles	Redox reactions, low toxicity	Abdel Salam et al. (2020), Tarekegn et al. (2021), Xu et al. (2020)
Silver Nanoparticles (AgNPs)	Hg^{2+}, Pb^{2+}, Cr^{3+}, Cr^{6+} As^{3+}, Mn^{2+}	150–270	High (Hg^{2+})	80%–85% after 4 cycles	Antimicrobial properties, surface plasmon resonance	Kumari and Tripathi (2020), Pradhan et al. (2019), Zhuang et al. (2019)
Magnetite (Fe_3O_4) Nanoparticles	Cr^{6+}, As^{3+}, Pb^{2+}, Cu^{2+}	200–320	High Cu^{2+}	93%–98.5% after 3 cycles	Superparamagnetic behavior, easy separation using a magnet	Pradhan et al. (2019), Singh et al. (2020)
Graphene Oxide Nanocomposites	Pb^{2+}, Hg^{2+}, Cd^{2+}, Cu^{2+}	138–153	High (Pb^{2+})	85%–90% after 5 cycles	Large surface area, high chemical stability	Kong et al. (2020)
Carbon Nanotube Composites	Cu^{2+}, Pb^{2+}, Hg^{2+}	146–185	High (Pb^{2+})	90%–95% after 6 cycles	High mechanical strength, excellent electrical conductivity	Chandrashekhar Nayak et al. (2020), Wang D. et al. (2021)
Metal-Organic Frameworks (MOFs)	Cr^{6+}, Pb^{2+}, Cd^{2+}, As^{3+}, Cu^{2+}	500–600	High (Cd^{2+})	80%–90% after 4 cycles	High porosity, tunable structure	Esrafili et al. (2021), Peng et al. (2020)
Zeolite Nanoparticles	Pb^{2+}, Cd^{2+}, Sr^{2+}, Cu^{2+}, Zn^{2+}, Ni^{2+}, Mn^{2+}	250–300	High (Pb^{2+})	75%–85% after 5–10 cycles	Ion-exchange capability, high surface area	Isawi (2020), Modi and Bellare (2020)
Titanium Dioxide (TiO_2) Nanoparticles	Pb^{2+}, Cr^{6+}, As^{3+}, Cd^{2+}	150–169	High (Pb^{2+})	80%–98% after 4 cycles	Photocatalytic properties, UV light activation	Irshad et al. (2022), Nthwane et al. (2023)

2 Nanomaterials for heavy metal remediation

Nanotechnology has revolutionized the field of environmental remediation, offering innovative solutions to tackle heavy metal pollution in water sources. Nanomaterials, with their unique properties and high surface area-to-volume ratio, have shown great promise in efficiently removing heavy metals from contaminated water. Table 3 provides a comprehensive comparison of the key nanomaterials used for heavy metal remediation, focusing on their adsorption capacity, selectivity, regeneration efficiency, and unique characteristics.

Figure 1 below shows various types of nanomaterials utilized and mechanisms for heavy metal remediation, including nanoparticles, nanocomposites, and nanostructured materials.

2.1 Nanoparticles

Nanoparticles, owing to their small size and large surface area, exhibit enhanced reactivity and adsorption capacities, making them excellent candidates for heavy metal removal (Sarma et al., 2019; Yu et al., 2021). Several studies have demonstrated that nanomaterials also possess significant redox and catalytic properties. The high surface area provides numerous active sites for interaction with heavy metal ions, facilitating efficient adsorption and transformation processes. Additionally, the tunable surface chemistry of nanomaterials allows for the modification of their properties to target specific contaminants (Garcia-Segura et al., 2020). This adaptability enhances their versatility in various environmental conditions. The potential for functionalization with specific ligands or coatings further improves their selectivity and effectiveness in complex environmental matrices. Nanoparticles are increasingly explored for environmental cleanup and sustainable water treatment technologies. Based on their magnetic properties, nanoparticles can be categorized into magnetic and non-magnetic nanoparticles.

2.1.1 Non-magnetic nanoparticles

Non-magnetic nanoparticles, despite lacking magnetic properties, play a crucial role in heavy metal remediation due to their exceptional adsorption and catalytic capabilities. These nanoparticles often exhibit high surface areas, which provide numerous active sites for metal ion binding and reduction processes. Additionally, their tunable surface chemistries allow for the modification of their surfaces with functional groups or coatings, enhancing their selectivity for specific contaminants. Non-magnetic nanoparticles, such as zerovalent iron nanoparticles (ZVINPs) and silver nanoparticles (AgNPs), are widely studied for their ability to reduce and adsorb heavy metals from water. While they may not offer the same ease of separation as magnetic nanoparticles, non-magnetic nanoparticles make up for this limitation through their efficient remediation performance and the ease with which they can be synthesized and functionalized for specific environmental conditions. Their relatively low cost and the potential for regeneration also make them highly attractive for large-scale environmental applications.

TABLE 4 Innovative mechanisms and materials for heavy metal and emerging pollutant removal from water.

Mechanism		Materials Used	Significant Findings	Challenges	Potential Applications	Future Research Directions
Adsorption	[Ahsan et al. (2019)]	Cu-BDC MOFs, graphene oxide (GrO), carbon nanotubes (CNTs) hybrid nanocomposites	High crystalline structure, remarkable adsorption capacity (182.2 mg/g for Cu-BDC@GrO and 164.1 mg/g for Cu-BDC@CNT) towards Bisphenol A, Freundlich isotherm model fits best, pseudo-second order kinetic model	Ensuring water stability, managing secondary waste, regeneration and reuse of adsorbents	Industrial wastewater treatment, organic pollutant removal from water	Exploring other hybrid nanomaterials; improving regeneration and reuse methods
	Jurado-Davila et al. (2023)	Layered double hydroxide (CaMgAl-LDH)	Effective removal of phosphate in fixed-bed column. Langmuir isotherm fits well. Kinetic coefficient ranges between 4.52 and 0.81 mL mg^{-1} min^{-1}	Operational conditions influence adsorption efficiency	Water treatment for phosphate removal	Optimization of operational conditions; scaling up for industrial applications
Ion Exchange	[Zhang et al. (2016), Kuang et al. (2019), Shang et al. (2020), Trakal et al. (2016), Wu et al. (2021)]	Na-form zeolite, anion exchange resin	Improved ammonia–nitrogen removal efficiency (from 78% to 95%) with resin pretreatment. High removal efficiency for humic acid and dissolved organic matter. Efficient regeneration with alkaline and sodium chloride	Managing resin and zeolite regeneration, operational complexity	Wastewater treatment, ammonia–nitrogen removal	Enhancing combined resin-zeolite systems; exploring other pre-treatment strategies
	Wang et al. (2017)	Chelating agents, Polyethylenimine-chitosan (PEI-CS) biosorbent	Ultra-high adsorption capacity (146 mg/g for Cu ions), excellent selectivity, high reusability, synthesized via microfluidic emulsion, chemical crosslinking, and chemical modification	Ensuring mechanical strength, optimizing synthesis processes, scalability	Industrial wastewater treatment, heavy metal ion removal from contaminated water	Enhancing scalability and efficiency in large-scale applications; exploring new biosorbent materials
Precipitation	[Siciliano et al. (2020), Cao et al. (2019), Shang et al. (2020), Wang et al. (2018), Wu et al. (2021), Xiang et al. (2018)]	Struvite ($MgNH_4PO_4.6H_2O$)	Effective removal of ammonium and phosphate from wastewater, production of a high-purity solid compound suitable for fertilizer	Impurities in the precipitate, scaling up production for industrial use	Treatment of wastewater in various industries, production of slow-release fertilizers	Optimization of process efficiency; exploration of low-cost and sustainable reagents
	Simeonidis et al. (2014)	Magnetite nanoparticles	High removal efficiency of Cr(VI), maximized at pH < 6. Complete removal achieved in batch and continuous flow reactors. Nanoparticles recovered using magnetic nature	Regeneration and reuse of nanoparticles, cost of magnetic recovery system	Industrial wastewater treatment, Cr(VI) removal from water	Optimization of magnetic recovery systems; enhancing nanoparticle regeneration methods
Redox Reactions	[Andrey et al. (2023), Ganie et al. (2023), Le et al. (2019), Su et al. (2024), Wang Y. et al. (2024), Yuan et al. (2024)]	Substoichiometric titanium oxide (Ti_4O_7) anodes	High instantaneous current efficiency (ICE) of about 40% and over 99% removal efficiency for benzoic, maleic, oxalic acids, and hydroquinone; good stability after 108 h at 36 mA/cm^2	Ensuring long-term stability, managing electrode degradation, high initial setup cost	Oxidation of organic pollutants in aqueous solutions, treatment of industrial wastewater	Exploration of other contaminant types; improving granule size and pore size optimization

(Continued on following page)

TABLE 4 (*Continued*) Innovative mechanisms and materials for heavy metal and emerging pollutant removal from water.

Mechanism		Materials Used	Significant Findings	Challenges	Potential Applications	Future Research Directions
	Montenegro-Ayo et al. (2023)	Boron-doped diamond (BDD) anode	High efficiency in degrading ciprofloxacin (CIP) via electrochemical oxidation, influenced by pH and current density. Faster degradation in sulfate and chloride mediums	Effectiveness reduced in carbonate medium, tap water, and synthetic urine; presence of humic acid lowers degradation rate	Treatment of wastewater containing emerging pollutants, particularly pharmaceuticals	Exploring different electrode materials; enhancing the reactor design for scalability

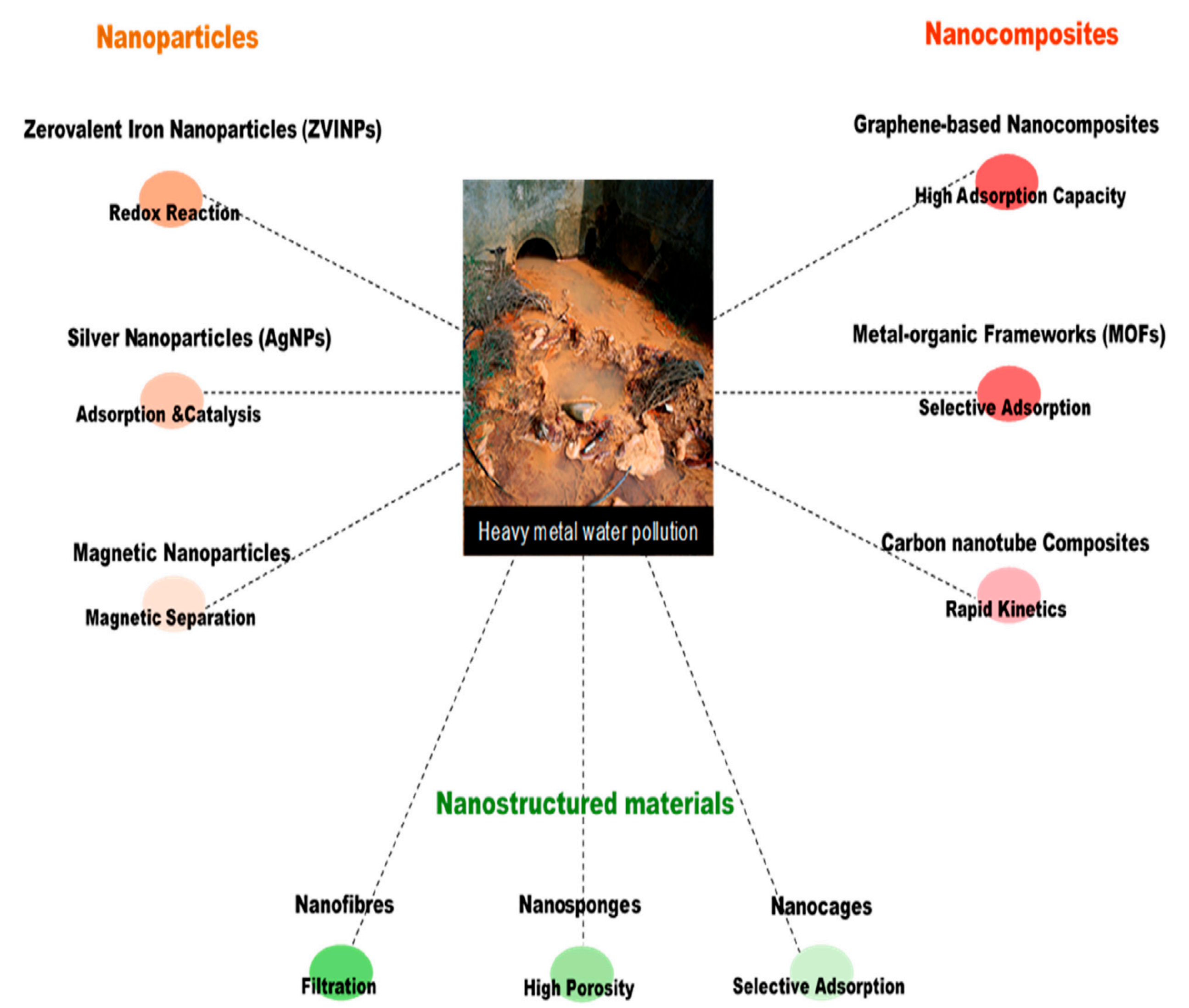

FIGURE 1
Overview of nanomaterials and their mechanisms for heavy metal remediation in water sources.

2.1.1.1 Zerovalent iron nanoparticles (ZVINPs)

Zerovalent iron nanoparticles (ZVINPs) have garnered significant attention for their ability to efficiently reduce a wide range of heavy metal ions through redox reactions. Recent studies have demonstrated that ZVINPs efficiently adsorb metal ions onto their surface, followed by electron transfer, resulting in the formation of insoluble metal oxides or hydroxides (Rodríguez-Rasero et al., 2024; Moond et al., 2024). The adsorption process is significantly favored by an increase in temperature (Tang et al., 2023; Bazarin et al., 2024). ZVINPs can be regenerated through simple treatments such as pH adjustment or chemical reduction, which enhances their reusability and cost-effectiveness (Thomas et al., 2017). Due to their relatively low toxicity compared to other nanomaterials, ZVINPs present a safer option for environmental applications. However, ongoing research is addressing their environmental and health impacts while optimizing their performance and scalability for large-scale remediation projects (Naveed et al., 2023; Xu et al., 2020).

2.1.1.2 Silver nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) possess inherent antimicrobial properties and have emerged as effective adsorbents for heavy metal ions (Egbewole et al., 2022). Recent research has shown that AgNPs efficiently remove toxic metals such as mercury, cadmium, and copper from contaminated water sources (Sudarman et al., 2023). AgNPs also catalyze the reduction of heavy metal ions into less toxic forms, further enhancing remediation efficiency. However, concerns regarding the potential environmental impact of AgNPs, particularly their ecotoxicity and long-term stability, have been raised (Noga et al., 2023). Further investigations are required to ensure the safe and sustainable use of AgNPs in environmental applications.

2.1.2 Magnetic nanoparticles

Magnetic nanoparticles, such as magnetite (Fe3O4) and maghemite (γ-Fe2O3), offer distinct advantages due to their magnetic properties, which enable easy separation and recovery from water using external magnetic fields (de Oliveira et al., 2020; Zeng et al., 2020; Borji et al., 2020). Functionalized magnetic nanoparticles have been explored for the selective removal of heavy metal ions through surface modification with chelating agents or ligands. These modifications improve the specificity and binding affinity toward target heavy metals (Shao et al., 2020; Pardo et al., 2021), making magnetic nanoparticles suitable for large-scale water treatment applications. Their magnetic properties facilitate rapid and efficient contaminant removal, and their regeneration and reuse reduce operational costs. Moreover, integrating magnetic nanoparticles with other nanomaterials enhances adsorption capacity and recyclability, further improving their performance in heavy metal remediation.

2.2 Nanocomposites

Nanocomposites, composed of two or more distinct components at the nanoscale, offer synergistic properties for enhanced heavy metal removal. Compared to single-component systems, two distinct components at the nanoscale level offer synergistic properties that significantly enhance heavy metal removal (Singh and Bhateria, 2021). By incorporating the unique properties of each constituent nanomaterials, superior stability, adsorption capacities (Baig et al., 2021), and improved selectivity towards specific contaminants can be reached. This combination of properties allows for more efficient and effective remediation processes compared to single-component systems. Moreover, the possibility of tunability in the design of nanocomposites can be optimally repurposed for various environmental conditions. (Darwish et al., 2022; Hassan et al., 2021). This tunability is a versatile tool in the fight against heavy metal pollution. As research in this field progresses, the development of novel nanocomposite materials will provide highly extensive sustainable, and high-performance water treatment technologies. In this study, we will delve a little into the recent study of nanocomposites and their applications to remediate heavy metals from the environment. Some such nanocomposites include graphene nanocomposites, metal-organic frameworks (MOFs), and carbon nanotube composites.

2.2.1 Graphene-based nanocomposites

Due to their low cost, well-defined pore-forming mechanisms, and excellent magnetic properties that facilitate magnetic separation, graphene-based nanocomposites have emerged as a viable option for heavy metal remediation (Donga et al., 2021; Goyat et al., 2022). These materials have attracted significant interest because of their high surface area, exceptional mechanical strength, and chemical stability. Recent advancements in graphene-based materials have also demonstrated their potential as antifouling agents (Su and Hu, 2021), thanks to their excellent antibacterial properties, leading to the development of novel adsorbents for heavy metal removal. Graphene oxide (GO) and reduced graphene oxide (rGO) composites functionalized with various functional groups exhibit excellent adsorption capacities for heavy metal ions (Jahan et al., 2022), including cadmium, lead, and nickel. The unique structure of graphene-based nanocomposites enables rapid and selective removal of contaminants from aqueous solutions (Malhotra and Jain, 2021; Pena-Pereira et al., 2021), offering potential solutions to mitigate heavy metal pollution.

2.2.2 Metal-organic frameworks (MOFs)

Metal-organic frameworks (MOFs) are porous materials composed of metal ions or clusters coordinated with organic ligands, offering high surface areas and tunable pore structures. Recent research has demonstrated the applicability of MOFs as efficient adsorbents for heavy metal removal due to their photocatalytic reduction properties (Li et al., 2021). The modular nature of MOFs allows for precise control over their pore size and surface chemistry, enabling selective adsorption of specific heavy metal ions. MOFs can be functionalized with various active sites to enhance their adsorption capacities and catalytic activities (Hou et al., 2022). This adaptability makes them promising candidates for tailored environmental remediation strategies, addressing diverse and complex contamination scenarios. Furthermore, the incorporation of functional groups or post-synthetic modifications enhances the adsorption capacity and stability of MOFs, making them promising candidates for water purification.

2.2.3 Carbon nanotube composites

Carbon nanotubes (CNTs) possess extraordinary mechanical strength, electrical conductivity, and large surface area (Nurazzi et al., 2021; Zhang H. et al., 2020), making them ideal candidates for heavy metal remediation applications. Recent studies have investigated the use of CNT-based composites for the removal of heavy metal ions from aqueous solutions (Akhter et al., 2023; Aslam et al., 2022). Functionalization of CNTs with various organic or inorganic materials enhances their adsorption capacity and selectivity towards specific heavy metal contaminants. Through coprecipitation with certain metal oxides such as iron and

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zirconium, they are modified for excellent removal of chromium, mercury, lead, arsenic, etc. From water (by CBN et al., 2020). Additionally, the unique one-dimensional structure of CNTs facilitates the diffusion of metal ions into the internal pore spaces (Dey et al., 2024; Luo et al., 2022), leading to rapid adsorption kinetics and high removal efficiency.

2.3 Nanostructured materials

Nanostructured materials, including nanofibers, nanosponges, and nanocages, offer unique architectures for efficient heavy metal removal. These structures facilitate greater interaction with molecules of the pollutants. Their porous and adaptable designs allow for the incorporation of functional groups that improve selectivity and adsorption capacity. Additionally, the adaptability of these nanostructures enables their application in various environmental conditions, making them highly effective for diverse heavy metal remediation efforts. Some of these nanostructured materials are classified as nanofibers, nano-sponges, and nanocages.

2.3.1 Nanofibers

Nanofibers, characterized by their high aspect ratio and interconnected porous structure, provide large surface areas for the adsorption and filtration of heavy metal ions. Recent advancements in electrospinning techniques have enabled the fabrication of nanofiber-based membranes with precise control of the membrane characteristics tailored for water purification (Liao et al., 2018). Functionalization of nanofibers with specific ligands or nanoparticles enhances their adsorption capacity and selectivity (El-Aswar et al., 2022), making them effective adsorbents for heavy metal removal from aqueous solutions. These functionalized nanofibers exhibit improved mechanical strength and stability, ensuring long-term durability in filtration systems. The ability to integrate multiple functional groups within nanofibers further broadens their application (Zamel and Khan, 2021), providing the avenue for the concurrent removal of various contaminants. This makes nanofiber-based membranes a promising solution for advanced water treatment technologies.

2.3.2 Nanosponges

Nanosponges are porous materials composed of interconnected networks of nanoparticles or nanofibers, offering high surface area and porosity for adsorption applications. Recent research has demonstrated the feasibility of nanosponge-based materials for heavy metal remediation (Iravani and Varma, 2022). The sponge-like structure of nanosponges enables rapid diffusion of heavy metal ions into the interior pores, where they are effectively sequestered through chemical interactions or physical adsorption. Furthermore, the flexibility in the design and synthesis of nanosponges allows for the customization of their properties to meet specific application requirements (Goyal et al., 2023).

2.3.3 Nanocages

Nanocages are hollow nanostructures with well-defined cavities and porous walls, offering unique confinement effects and high surface areas for the adsorption of heavy metal ions. Recent studies have explored the use of nanocages derived from various materials, including metal oxides, carbon-based materials, and polymers, for heavy metal removal. The tunable pore size and surface chemistry of nanocages enable selective adsorption of specific heavy metal contaminants, making them promising candidates for water purification applications (Ahmed et al., 2023).

3 Mechanisms of heavy metal removal

Heavy metal removal from water sources involves various mechanisms, each with its advantages and limitations. These mechanisms include adsorption, precipitation, ion exchange, membrane filtration, and electrochemical methods (Figure 2), each suited to specific types of contaminants and environmental conditions (Li et al., 2022; Peng and Guo, 2020; Singh et al., 2021). The mechanisms of heavy metal removal continue to evolve with advancements in materials science, process engineering, and environmental biotechnology. Innovations such as nanomaterials, bio-based adsorbents, and hybrid systems are pushing the boundaries of efficiency and selectivity (Rajendran et al., 2022). By harnessing the synergistic effects of advanced materials, innovative process technologies, and sustainable practices, researchers and engineers can develop efficient, cost-effective, and environmentally friendly solutions for mitigating heavy metal pollution and safeguarding water quality for future generations. These integrated approaches are crucial for safeguarding water quality for future generations and ensuring compliance with stringent environmental regulations. Table 4 provides a comprehensive comparison of the key nanomaterials used for heavy metal remediation, focusing on their adsorption capacity, selectivity, regeneration efficiency, and unique characteristics.

3.1 Adsorption

Adsorption involves the attachment of heavy metal ions onto the surface of solid adsorbents, forming a monolayer or multilayer adsorption layer (Khulbe and Matsuura, 2018). The process relies on the affinity between the surface functional groups of the adsorbent and the heavy metal ions in the solution. Recent studies have focused on enhancing the adsorption capacity and selectivity of adsorbents through the use of novel materials and surface modifications. Nanomaterials, such as graphene oxide, carbon nanotubes, and metal-organic frameworks (MOFs), exhibit high surface area and tunable surface chemistry, making them effective adsorbents for heavy metal removal (Ahsan et al., 2020; Das et al., 2021). Surface functionalization with specific functional groups, such as carboxyl, amino, or thiol groups, enhances the adsorption affinity towards target heavy metal ions (Ahmad et al., 2020; Zeng et al., 2022). Additionally, hybrid materials combining different types of nanomaterials or incorporating metal nanoparticles demonstrate synergistic effects, leading to improved adsorption capacities and kinetics. Advancements in adsorption mechanisms also include the development of continuous-flow adsorption systems such as fixed-bed columns and membrane adsorbers, for practical applications (Aydına et al., 2021; Taka et al., 2021). These

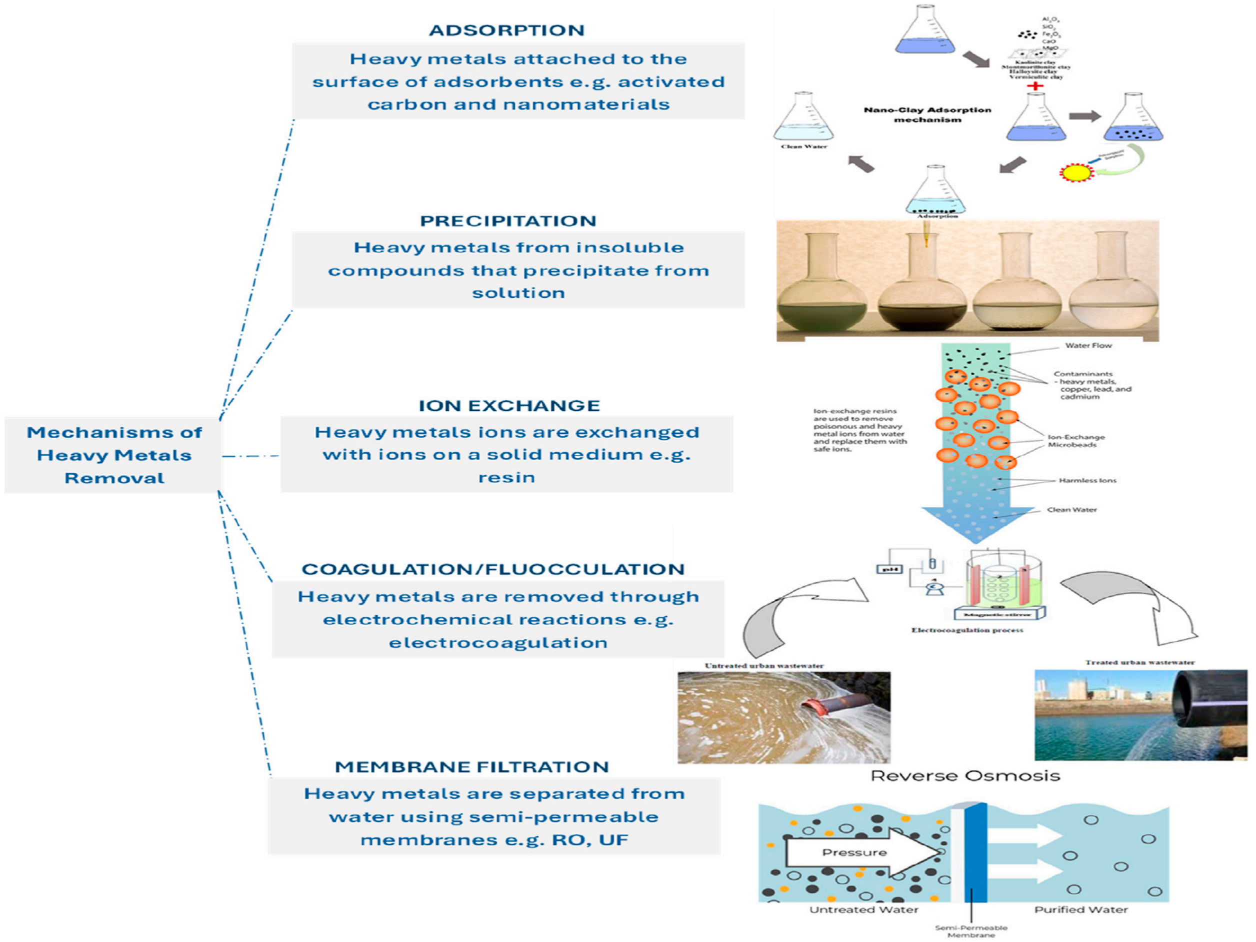

FIGURE 2
Classifications of the mechanisms of heavy metals removal.

systems enable efficient removal of heavy metals from large volumes of water and offer advantages in terms of scalability and cost-effectiveness.

3.2 Ion exchange

Ion exchange involves the replacement of ions in solution with ions attached to a solid phase, typically an ion exchange resin or zeolite (Rathi et al., 2021; Ray, 2023). The process relies on the affinity between the ions in the solution and the functional groups on the surface of the ion exchange material. Recent trends in ion exchange mechanisms focus on improving the selectivity and regeneration capabilities of ion exchange materials. Functionalization of ion exchange resins with specific ligands or chelating agents enables selective removal of target heavy metal ions based on their charge and coordination chemistry (Quintas et al., 2021). Additionally, the regeneration of spent ion exchange materials through elution or desorption processes enables their reuse and reduces operational costs. Integration of ion exchange processes with other treatment methods, such as membrane filtration and adsorption (Peng and Guo, 2020; Vieira et al., 2020), enhances treatment efficiency, and offers synergistic effects. Moreover, advancements in process engineering, including continuous-flow ion exchange reactors and in-line monitoring techniques, enable precise control over ion exchange reactions and facilitate scale-up for industrial applications.

3.3 Precipitation

Precipitation involves the chemical reaction between heavy metal ions and precipitating agents to form insoluble precipitates, which can then be separated from the solution (Pillai and Thombre, 2024; Zhang et al., 2023). The process relies on the solubility product of the metal precipitate and the pH and temperature conditions of the solution. Recent trends in precipitation mechanisms focus on enhancing the efficiency and selectivity of precipitation reactions while minimizing the generation of secondary wastes. Advanced precipitation methods, such as co-precipitation and hydrothermal synthesis (Gholamrezaei et al., 2019), enable the synthesis of highly crystalline and uniform precipitates with controlled morphologies and compositions. The use of novel precipitating agents, including natural polymers, biodegradable chelating agents, and green chemistry reagents, reduces the environmental impact of precipitation processes and enhances the sustainability of heavy metal removal systems. Moreover, recent advancements in process engineering, such as continuous-flow precipitation reactors and in-line monitoring techniques, enable precise control over precipitation reactions and facilitate scale-up for industrial applications.

3.4 Redox reactions

Redox reactions involve the transfer of electrons between chemical species, leading to the transformation of heavy metal ions into less toxic or insoluble forms (Xu et al., 2022). The process relies on the redox potential of the metal ions and the reducing or oxidizing agents present in the solution (Gulcin and Alwasel, 2022). Recent trends in redox reactions for heavy metal removal focus on developing sustainable and energy-efficient processes with minimal environmental impact. Electrochemical methods, such as electrocoagulation, electrooxidation, and electrochemical reduction, offer selective and precise control over redox reactions, enabling the removal of specific heavy metal contaminants from complex water matrices (Feng et al., 2023; Martínez-Huitle et al., 2018; Yasri and Gunasekaran, 2017). Advanced electrode materials, including carbon-based electrodes, metal oxide nanoparticles, and conductive polymers, exhibit enhanced electrochemical activity and stability, leading to improved treatment efficiency and durability of electrochemical reactors. Integration of renewable energy sources, such as solar and wind power, into electrochemical systems reduces the carbon footprint and energy consumption of heavy metal removal processes (Ganiyu and Martinez-Huitle, 2020; Klemeš et al., 2019; Zahmatkesh et al., 2022).

4 Potential synergistic effect of nanomaterials combined with other remediation techniques

Emerging research on the environmental applications of nanomaterials has highlighted their potential to inspire the field of contaminant removal through synergy with existing remediation techniques. Traditionally, remediation methods such as adsorption, filtration, and electrochemical processes operate independently, each with its own limitations regarding efficiency, selectivity, and operational cost. However, the unique properties of nanomaterials, including tunable surface chemistry, high reactivity, and nanoscale porosity, provide a new dimension for enhancing these conventional techniques. In this section we will highlight the concepts—nanomaterial-catalyzed cascade remediation, a hybrid strategy that leverages the cooperative interaction between nanomaterials and existing techniques, forming a chain of processes that cumulatively magnify the overall contaminant removal efficiency.

4.1 Nanomaterial-driven cascade adsorption-electrochemical treatment

Unlike traditional adsorption techniques, which are limited by saturation and slow kinetic rates, nanomaterial-driven cascade systems propose a new mechanism where adsorption is not an endpoint but a trigger for secondary electrochemical reactions (Y. Zhang et al., 2023). For instance, zero-valent iron nanoparticles (ZVINPs) serve as a starting point by reducing heavy metal ions, such as Pb^{2+} and As^{3+}, and simultaneously generating electrons that catalyze subsequent redox reactions in an electrochemical process (Silva-Calpa et al., 2020; Tarekegn et al., 2021; Yang et al., 2021). This cascading system ensures that once the adsorptive sites of the nanomaterials are saturated, electrochemical reduction and oxidation cycles are initiated, allowing continuous heavy metal transformation and immobilization, thus enhancing overall efficiency.

4.2 Photocatalytic-electromagnetic hybrid remediation using functional nanoparticles

The concept of coupling photocatalytic nanomaterials, such as TiO_2 nanoparticles, with electromagnetic fields opens up new avenues for intensifying contaminant degradation. In this hybrid approach, UV-activated TiO_2 nanoparticles generate reactive oxygen species (ROS) capable of breaking down organic pollutants (Park et al., 2021; Sun et al., 2020). However, instead of limiting the process to the photocatalytic activity alone, the addition of a low-frequency electromagnetic field enhances nanoparticle dispersion and accelerates the electron transfer processes involved in pollutant degradation (Cai et al., 2019; Rawat et al., 2021). This strategy increases the reaction rate and extends the lifetime of ROS, effectively expanding the scope of contaminants that can be addressed, including both heavy metals and organic pollutants.

4.3 Nanomaterial-enhanced phytomining: Harnessing biological synergy

Another concept emerging in environmental remediation is nanomaterial-enhanced phytomining, where engineered nanomaterials are combined with hyperaccumulating plants to extract valuable metals from contaminated environments (Li et al., 2020; Tognacchini et al., 2019). Traditional phytoremediation is often hindered by the slow uptake of metals and limited bioavailability (Khalid et al., 2021). By introducing metal-seeking nanoparticles, such as functionalized carbon nanotubes or metal-organic frameworks (MOFs), to the root zone of these plants, the uptake of metals such as nickel, cadmium, and zinc is greatly amplified (Doria-Manzur et al., 2022; Rossi et al., 2019). These nanoparticles enhance the bioavailability of metals by chelating them into soluble forms that are more easily transported through the plant's vascular system, ultimately resulting in higher metal yields. This synergistic approach not only cleanses contaminated soils but also offers a novel method for recovering valuable metals, providing a sustainable alternative to traditional mining processes.

4.4 Dynamic self-regenerating systems with nanocomposites and microbial consortia

A pioneering concept is the design of dynamic self-regenerating systems, in which nanomaterials and microbial consortia work together to sustain long-term contaminant degradation without requiring external inputs (Fu et al., 2021; Xia et al., 2023). For example, magnetic nanoparticles (MNPs) can be combined with microbial biofilms capable of biodegrading organic pollutants (Liu et al., 2022; Zhu et al., 2020). The MNPs serve two primary functions: first, they adsorb heavy metals, preventing them from inhibiting microbial activity; second, they act as catalysts that regenerate the microbial degradation capacity by facilitating electron transfer between the bacteria and the contaminants. This interaction sets up a dynamic feedback loop where contaminants are continuously broken down and the system regenerates itself, maintaining efficiency over extended operational periods.

4.5 Nanoparticle-enhanced thermal remediation for heavy metal recovery

Thermal remediation methods, such as soil heating, have traditionally been used for organic pollutant removal but are less effective for heavy metal immobilization. A novel approach involves using thermally activated nanoparticles, such as aluminum oxide (Al_2O_3) or zirconium oxide (ZrO_2), which, when heated, change their surface chemistry to selectively bind and sequester heavy metals like lead and mercury (Allwin Mabes Raj et al., 2022; Fan et al., 2020; Guo et al., 2021; Huang et al., 2021). This nanoparticle-enhanced thermal remediation technique leverages the temperature-induced phase transformation in the nanoparticles, enhancing their adsorptive capacities and providing an innovative method for metal recovery during remediation processes (Al-Najar et al., 2021; Williams and Peterson, 2021).

4.6 Nanomaterial-enabled electrohydrodynamic remediation

Another concept is the nanomaterial-enabled electrohydrodynamic remediation, which combines electric fields with fluid dynamics to direct the flow of contaminants toward reactive nanomaterials embedded in porous media (Ji et al., 2023; Sprocati and Rolle, 2019). In this system, nanomaterials like functionalized graphene oxide are integrated within a hydrodynamic framework that is manipulated through external electric fields. This enables selective capture of contaminants by steering them towards nanomaterials with high affinity for specific heavy metals, ensuring high capture rates and fast remediation times (Ahmad et al., 2020; Nisola et al., 2020). Additionally, the fluid flow generated by electrohydrodynamics can be fine-tuned to optimize the contact time between the contaminants and the nanomaterials, leading to a highly efficient and targeted removal process.

5 Selectivity of nanomaterials

The selectivity of nanomaterials for heavy metal removal is crucial for ensuring efficient and targeted remediation of contaminated water sources (Tahoon et al., 2020). Surface functionalization, ligand design, and molecular imprinting represent versatile approaches for enhancing the selectivity of nanomaterials in heavy metal remediation (Rafeeq et al., 2022). By tailoring the surface chemistry, incorporating specific ligands, and imprinting molecular recognition sites, researchers can design highly selective adsorbents for targeted removal of heavy metal contaminants from water sources (Fei and Hu, 2022). Continued advancements in materials synthesis, molecular design, and characterization techniques will further accelerate the development of selective nanomaterials for sustainable water treatment applications (Saravanan et al., 2022).

5.1 Surface functionalization

Surface functionalization plays a pivotal role in tailoring the selectivity of nanomaterials by modifying their surface chemistry to preferentially adsorb specific heavy metal ions (Sarma et al., 2019). Recent research has demonstrated the efficacy of surface functionalization strategies for enhancing the selectivity of nanomaterials in heavy metal removal applications (Jawed et al., 2020). Functional groups such as carboxyl (-COOH), amino (-NH2), thiol (-SH), and hydroxyl (-OH) are commonly introduced onto the surface of nanomaterials to impart specific binding affinity towards target heavy metal ions (Rai et al., 2022). For example, graphene oxide (GO) and carbon nanotubes (CNTs) functionalized with carboxyl groups exhibit enhanced selectivity for heavy metal ions such as lead (Pb), cadmium (Cd), and mercury (Hg) due to the formation of strong metal-carboxylate complexes (Mohan et al., 2023). Similarly, metal-organic frameworks (MOFs) can be functionalized with tailored ligands to selectively adsorb specific heavy metal ions based on their size, charge, and coordination chemistry (Wen et al., 2018).

Furthermore, the development of multifunctional nanomaterials through the simultaneous incorporation of multiple functional groups enables synergistic effects and enhanced selectivity toward target heavy metal contaminants. For instance, hybrid nanocomposites composed of graphene oxide and magnetic nanoparticles functionalized with both carboxyl and amino groups demonstrate superior selectivity and adsorption capacity for heavy metal ions compared to individual components (Natarajan et al., 2023). Advancements in surface functionalization techniques, including covalent bonding, electrostatic interactions, and chemical modification, enable precise control over the surface chemistry of nanomaterials, thereby facilitating the design of highly selective adsorbents for heavy metal removal (Liu et al., 2019).

5.2 Ligand design

Ligand design represents a versatile approach for enhancing the selectivity of nanomaterials by incorporating specific chelating agents or receptors that exhibit high affinity towards target heavy metal ions (Dzhardimalieva and Uflyand, 2018). Recent studies have focused on the rational design and synthesis of ligands with tailored properties to selectively form complexes with specific heavy metal contaminants. Ligands such as crown ethers, cyclodextrins, and calixarenes offer unique binding cavities and coordination sites for selective recognition and capture of heavy metal ions (Liang et al., 2022). Functionalization of nanomaterials with ligands featuring complementary functional groups enables the formation of stable metal-ligand complexes, thereby enhancing the selectivity and affinity of nanomaterials for target heavy metal ions (de Oliveira et al., 2021).

Moreover, the integration of molecular modeling techniques, such as density functional theory (DFT) calculations and molecular dynamics simulations, aids in the rational design and optimization of ligands for selective heavy metal removal (Ebenezer and Solomon, 2024). By elucidating the underlying interactions between ligands and heavy metal ions at the molecular level, researchers can tailor the structure and properties of ligands to maximize selectivity and binding affinity (Li et al., 2023a). Furthermore, the development of stimuli-responsive ligands that undergo conformational changes or structural transformations in response to specific environmental cues offers dynamic control over the selectivity of nanomaterials (Grzelczak et al., 2019). Stimuli-responsive ligands can selectively bind heavy metal ions under certain conditions, such as pH, temperature, or redox potential, enabling on-demand capture and release of target contaminants (Mamidi et al., 2021; Sharma et al., 2024).

5.3 Molecular imprinting

Molecular imprinting is an emerging technique for imprinting specific binding sites or cavities within the structure of nanomaterials to selectively recognize and capture target heavy metal ions (Tchekwagep et al., 2022). Recent advancements in molecular imprinting technology have led to the development of highly selective nanomaterials for heavy metal removal (Ali et al., 2024). Molecularly imprinted polymers (MIPs) represent a promising class of materials that mimic the molecular recognition properties of natural receptors or antibodies (Parisi et al., 2022). By imprinting the desired heavy metal ions within a polymer matrix through template-assisted polymerization or sol-gel methods, MIPs can selectively bind and remove target contaminants from aqueous solutions (ul Gani Mir et al., 2022). The precise control over the size, shape, and functionality of imprinted cavities enables high selectivity and affinity towards specific heavy metal ions (El Ouardi et al., 2021).

Moreover, the integration of molecular imprinting technology with nanomaterials, such as graphene-based nanocomposites, metal oxide nanoparticles, and carbon nanotubes, enhances the stability, reusability, and performance of imprinted materials for heavy metal removal applications (Yahaya et al., 2021). Functionalization of nanomaterials with template molecules and cross-linking agents facilitates the formation of well-defined imprinted cavities with tailored recognition properties (Parisi et al., 2020). Furthermore, the development of smart and stimuli-responsive molecularly imprinted nanomaterials offers dynamic control over the selectivity and release of captured heavy metal ions (Li et al., 2023b). Stimuli-responsive MIPs can undergo reversible changes in their structure or properties in response to external stimuli, enabling the on-demand release of adsorbed contaminants under specific conditions (Mintz Hemed et al., 2023).

6 Regeneration strategies

Regeneration of adsorbents and other materials used in heavy metal removal processes is essential for enhancing the sustainability and cost-effectiveness of water treatment systems. Regeneration strategies play a crucial role in enhancing the sustainability and cost-effectiveness of heavy metal removal processes. Recent advancements in desorption techniques, electrochemical regeneration, and photocatalytic regeneration offer promising solutions for the efficient recovery and reuse of adsorbents and electrodes in water treatment systems.

6.1 Desorption techniques

Desorption techniques involve the removal of adsorbed heavy metal ions from the surface of adsorbent materials, allowing for the regeneration and reuse of the adsorbents. Various desorption methods have been developed to efficiently recover heavy metal ions while minimizing the generation of secondary wastes (Lata et al., 2015). Recent trends in desorption techniques focus on enhancing the efficiency and selectivity of desorption processes while reducing energy consumption and environmental impact (Kopac, 2021). Thermal desorption, which involves heating the adsorbent material to release adsorbed contaminants, remains a commonly used method due to its simplicity and effectiveness. However, advancements in alternative desorption methods, such as chemical desorption, solvent extraction, and microwave-assisted desorption, offer advantages in terms of selectivity, speed, and energy efficiency (Jalili et al., 2020).

Chemical desorption techniques involve the use of desorbing agents, such as acids, bases, or complexing agents, to break the bonds between the adsorbent and the heavy metal ions (Chatterjee and Abraham, 2019). Recent studies have investigated the use of environmentally friendly desorbing agents, such as citric acid, EDTA, and hydrochloric acid, to minimize the generation of hazardous wastes and reduce environmental impact (Golmaei et al., 2018; Yaashikaa et al., 2021). Furthermore, the development of innovative desorption techniques, such as ultrasonic-assisted desorption and supercritical fluid extraction, enables rapid and efficient recovery of heavy metal ions from adsorbent materials (Wang J. et al., 2024). These techniques offer advantages in terms of selectivity, speed, and energy efficiency, making them promising candidates for the regeneration of adsorbents in heavy metal removal systems (Shrestha et al., 2021).

6.2 Electrochemical regeneration

Electrochemical regeneration involves the application of an electric current to regenerate adsorbent materials or electrodes used in heavy metal removal processes (Ganzoury et al., 2020). The process relies on electrochemical reactions to desorb and recover heavy metal ions from the surface of the electrodes or adsorbents. Recent advancements in electrochemical regeneration techniques focus on optimizing electrode materials, operating conditions, and regeneration protocols to enhance efficiency and reduce energy consumption (Romano et al., 2020). Electrochemical regeneration methods, such as electrochemical desorption and electrodialysis, offer advantages in terms of selectivity, scalability, and environmental sustainability (Sedighi et al., 2023).

Advanced electrode materials, including carbon-based electrodes, metal oxide nanoparticles, and conductive polymers, exhibit enhanced electrochemical activity and stability, leading to improved regeneration efficiency and durability of electrochemical regeneration systems (Pan et al., 2019). Moreover, the integration of renewable energy sources, such as solar and wind power, into electrochemical regeneration systems reduces the carbon footprint and energy consumption of heavy metal removal processes (Zahmatkesh et al., 2022). Additionally, the development of smart and adaptive electrochemical regeneration systems enables real-time monitoring and control of regeneration processes, leading to enhanced efficiency and reliability (Lv et al., 2023). These systems offer advantages in terms of process optimization, resource utilization, and environmental sustainability, making them promising candidates for the regeneration of adsorbents and electrodes in heavy metal removal systems (Shrestha et al., 2021; Younas et al., 2021).

6.3 Photocatalytic regeneration

Photocatalytic regeneration involves the use of photocatalysts to facilitate the degradation or transformation of adsorbed contaminants under irradiation with light, typically ultraviolet (UV) or visible light (Liao et al., 2022). The process relies on the generation of reactive oxygen species (ROS) or photoinduced electrons and holes to oxidize or reduce the adsorbed contaminants (Afreen et al., 2020). Recent trends in photocatalytic regeneration focus on developing efficient photocatalysts with enhanced activity and stability for the degradation of heavy metal ions (Pang et al., 2024). Advanced photocatalytic materials, such as metal oxides, semiconductor nanoparticles, and carbon-based nanomaterials, exhibit high photocatalytic activity and selectivity towards specific heavy metal contaminants (Farhan et al., 2023).

Moreover, the integration of advanced reactor designs, such as photocatalytic membranes, immobilized photocatalysts, and flow-through photocatalytic reactors, enables efficient utilization of light energy and enhancement of mass transfer kinetics (Molinari et al., 2021; Wang Z. et al., 2021). These reactor designs offer advantages in terms of scalability, continuous operation, and process integration, making them suitable for practical applications in heavy metal removal systems (Qasem et al., 2021). Hence, the development of hybrid photocatalytic systems, such as photocatalytic-adsorption and photocatalytic-electrochemical systems, enables synergistic effects and enhanced regeneration efficiency. These hybrid systems offer advantages in terms of selectivity, efficiency, and versatility, making them promising candidates for the regeneration of adsorbents and electrodes in heavy metal removal systems.

7 Scalability and practical considerations

Scalability and practical considerations are critical factors in the development and implementation of heavy metal removal nanotechnologies (Ateia et al., 2024). Recent advancements in synthesis methods, stability, longevity, cost-effectiveness, and integration with existing water treatment infrastructure offer promising solutions for addressing heavy metal contamination in water sources and ensuring access to clean and safe drinking water for all (Hussain et al., 2024; Jadhao et al., 2024; Maji and Dutta, 2024).

7.1 Synthesis methods

Synthesis methods are crucial in determining the scalability, reproducibility, and properties of nanomaterials used in heavy metal removal technologies (Wawata and Fabiyi, 2024). Recent advancements in synthesis techniques focus on enhancing the scalability and cost-effectiveness of nanomaterial production while maintaining control over the properties and performance of the materials (Gohar et al., 2024; Saleh, 2024). Traditional synthesis methods, such as chemical precipitation, sol-gel, and hydrothermal synthesis, offer advantages in terms of simplicity, versatility, and scalability (Zohrabi, 2024). However, these methods may suffer from limitations in terms of particle size control, uniformity, and reproducibility (Li et al., 2023a; Lin et al., 2023). Recent trends in synthesis methods include the development of scalable and environmentally friendly approaches, such as green synthesis, microwave-assisted synthesis, and continuous-flow synthesis, which offer advantages in terms of energy efficiency, reaction control, and waste reduction (Adeola et al., 2023; Ahmed S. F. et al., 2022; Kaur et al., 2023). Moreover, advancements in bottom-up and top-down fabrication techniques enable precise control over the size, shape, and surface properties of nanomaterials, leading to improved performance and selectivity in heavy metal removal applications. Integration of advanced characterization techniques, such as electron microscopy, X-ray diffraction, and spectroscopy, facilitates real-time monitoring and optimization of synthesis processes, enabling rapid scale-up and commercialization of nanomaterial-based technologies (Abid et al., 2022; Baig et al., 2021; Chen et al., 2022; El-Khawaga et al., 2023).

7.2 Stability and longevity

Stability and longevity are critical factors in the performance and sustainability of nanomaterials used for heavy metal removal, particularly in long-term and continuous water treatment applications (Gul Zaman et al., 2021; Yu et al., 2022). While significant advancements have been made in improving the stability and durability of nanomaterials, challenges remain. Nanomaterials are prone to aggregation due to weaker intermolecular interactions, which can reduce their surface area and subsequently diminish their removal efficiency (Ahmed S. F. et al., 2022). In addition, nanomaterials, particularly nanomembranes, often suffer from mechanical instability, which results in performance degradation over time, limiting their effectiveness in long-term applications. One major issue is the environmental fate of nanomaterials, especially when they interact with microorganisms or are released into aquatic environments. Nanoparticles, such as carbon nanotubes and graphene-based materials, are prone to settling in sediments where they can harm benthic organisms. For instance, graphene oxide can produce reactive oxygen species that damage cell membranes in marine life (Saleem and Zaidi, 2020). These interactions with environmental microorganisms could lead to unintended ecological consequences, complicating the large-scale deployment of nanomaterials in water treatment systems.

The aggregation of nanomaterials in wastewater treatment plants is another significant concern. Studies have shown that a substantial proportion of nanoparticles are removed during the activated sludge process via bioadsorption onto the sludge surface. For example, nanoparticles like WO_3 and TiO_2 were found to accumulate in sludge (Simelane and Dlamini, 2019). The aggregation of nanoparticles in sludge complicates the management of waste sludge, as it can lead to potential environmental risks if not properly managed. To address these challenges, surface modification techniques have been developed to enhance the stability and dispersibility of nanomaterials. Functionalization with stabilizing agents, encapsulation within protective coatings, and immobilization on support matrices can extend the operational lifespan of nanomaterials by preventing aggregation and degradation in harsh water treatment environments (Alipour Atmianlu et al., 2021). For instance, by reducing aggregation and enhancing dispersibility, these modifications can significantly extend the operational lifespan of nanomaterials. However, long-term environmental assessments are still necessary, as exposure to various environmental factors can alter the size, composition, and stability of these materials, potentially changing their behaviour and environmental impact (Simeonidis et al., 2019). Nanoparticles such as Ag and ZnO have been reported to negatively affect phytoplankton and diatoms, demonstrating the need for more research on the environmental impact of spent nanomaterials.

In addition to these stability issues, proper disposal and recyclability of spent nanomaterials are crucial for ensuring sustainable applications. Recycling methods, such as using spent nanoparticles in brick manufacturing or disposing them in controlled landfills, have been suggested, but long-term evaluation is required, as many approaches have only been tested at the laboratory scale (Prathna et al., 2018). Clear guidelines on nanomaterial disposal are also necessary to avoid unintended environmental contamination when scaling up their use in industrial applications. Despite these challenges, advancements in nanocomposite and hybrid materials show promise for enhancing stability and longevity. For example, combining different nanomaterials can create synergistic effects, improving their structural integrity and resistance to environmental degradation (Hassan et al., 2021). Integrating nanomaterials with biodegradable or natural matrices also enhances their environmental compatibility while maintaining high removal efficiency.

7.3 Cost-effectiveness

Cost-effectiveness is a critical consideration in developing and implementing heavy metal removal technologies, particularly for large-scale and decentralized water treatment systems (Ayach et al., 2024; Neisan et al., 2023). Several economic factors can mitigate against investing in nanomaterial-based remediation technologies. The running cost of the technologies can be huge. This may be due to the raw materials used, the synthesis method adopted, specialized equipment and facilities, energy consumption cost, labour, and environmental and health risk assessment costs (Asghar et al., 2024).

However, recent advancements in materials synthesis, process engineering, and system design focus on reducing costs while maintaining performance and reliability (Chai et al., 2021; Gupta et al., 2021). The cost of nanomaterials, energy consumption, and operational maintenance are primary factors influencing the overall cost-effectiveness of heavy metal removal technologies. Recent trends in materials synthesis emphasize scalable and low-cost approaches, such as template-assisted synthesis, self-assembly, and waste-derived materials, to reduce production costs and enhance affordability (Abdullahi et al., 2024; Luo et al., 2021).

Furthermore, advancements in process engineering, such as optimization of reactor design, flow rate control, and automation, enable efficient utilization of resources and energy, leading to reduced operational costs and improved cost-effectiveness (Constance Obiuto et al., 2024). Integration of renewable energy sources, such as solar and wind power, into water treatment systems further enhances sustainability and reduces operating expenses (Shokri and Sanavi Fard, 2022). Moreover, life cycle cost analysis and techno-economic assessments provide valuable insights into the cost-effectiveness and feasibility of heavy metal removal technologies, guiding decision-making and investment strategies for water treatment infrastructure (Ćetković et al., 2022; Ilyas et al., 2021; Kehrein et al., 2021).

Specifically, to address scalability, cost-effectiveness, and environmental sustainability challenges associated with the use of nanoparticles for heavy metal remediation, there is a need to improve surface functionalization. When nanoparticle surfaces are optimally functionalized, the tendency for aggregation is reduced. This will ultimately improve its stability. Also, using green chemistry and biological methods of synthesis would tremendously reduce the cost associated with the use of nano-based heavy metal remediation. Furthermore, optimizing the magnetic properties of nanoparticles to improve their separation from the environment will increase recovery and reusability (Asghar et al., 2024).

7.4 Integration with existing water treatment infrastructure

Integrating nanomaterials with existing water treatment technologies, such as membrane filtration, electrochemical treatment, and biological remediation, presents an opportunity to enhance the efficiency of heavy metal removal (Elgarahy et al., 2021; Khan et al., 2021). Recent efforts focus on hybrid systems that leverage the unique properties of nanomaterials alongside traditional remediation techniques, offering synergistic effects that can improve selectivity, efficiency, and fouling resistance (Adeola and Forbes, 2021; Pérez et al., 2023; Thakur and Kumar, 2022). For instance, membrane-based nanocomposites embedded with functionalized nanoparticles have demonstrated superior performance in selectively removing heavy metals from water while also improving membrane durability and reducing fouling.

The successful incorporation of nanomaterials into current water treatment systems is exemplified by ceramic disk filters coated with nano-ZnO. These filters, which utilize the photocatalytic antibacterial properties of ZnO to reduce *Escherichia coli* in drinking water, offer a cost-effective solution, particularly beneficial for remote and rural communities (Huang et al., 2018). This hybrid approach, combining traditional filtration methods with nanomaterials, provides a low-cost upgrade to existing systems, enhancing water safety without requiring substantial modifications. However, integrating nanomaterials into large-scale WWTPs presents unique challenges, as demonstrated by studies on the behaviour of AgNPs in wastewater treatment processes. Research indicates that during wastewater treatment, AgNPs undergo sulfidation, particularly in anaerobic zones, converting them to Ag_2S. This transformation reduces their effectiveness in contaminant removal (Kent et al., 2014). This transformation complicates the integration of nanomaterials in large-scale systems, due to the altered adsorption properties of the nanoparticles.

Further challenges include the handling of nanomaterials in the sludge generated by wastewater treatment processes. A recent study (Cervantes-Avilés and Keller, 2021) demonstrated that while WWTPs can remove between 84% and 99% of metal-based nanoparticles from influent wastewater, substantial concentrations of nanoparticles, especially Mg, Ni, and Cd, still accumulate in the waste sludge. The accumulation of nanoparticles in waste sludge requires careful consideration during disposal, as the potential release of nanomaterials into the environment could pose additional risks. This was affirmed by another study that researched integrating WO_3 and TiO_2 mixtures into a wastewater treatment plant (Simelane and Dlamini, 2019). The nanoparticles were mainly adsorbed onto the sludge and removed from the wastewater, with the activated sludge process proving effective in their elimination. However, the long-term fate of these nanoparticles, including the stability of their polymorphs like monoclinic WO_3 and anatase TiO_2, remains a concern for sludge management strategies. Moreover, a study on silver nanoparticles in municipal WWTPs demonstrated that both mechanical and biological treatments are effective in reducing nanoscale silver particles from wastewater, with a 95% reduction achieved by combining these processes (Li et al., 2013). However, despite this high reduction rate, residual concentrations of n-Ag-Ps in the effluent still pose a challenge for WWTPs, particularly when scaling up the technology for larger plants.

System optimization and advancements in process integration have facilitated the incorporation of nanomaterials into conventional water treatment infrastructure. For instance, modular approaches allow for easier retrofitting of remediation units, enabling the deployment of nanomaterials without extensive changes to existing systems (Ruíz-Baltazar, 2024; Vasoya, 2023). However, the transformation, stability, and long-term behaviour of nanomaterials within these systems, particularly under varying environmental conditions, remain areas of concern. Collaborative efforts between nanotechnology experts, environmental engineers, and materials scientists are essential for overcoming these challenges and realizing the full potential of nanomaterials in integrated water treatment solutions.

Overall, integrating nanomaterial with existing water treatment infrastructure is essential for the practical implementation and adoption of heavy metal removal technologies in real-world settings (Singh et al., 2023). Recent advancements in system design, modularization, and process optimization focus on compatibility and interoperability with existing treatment processes and infrastructure (Brad et al., 2021). Heavy metal removal technologies should be designed to complement and integrate seamlessly with conventional water treatment processes, such as coagulation-flocculation, sedimentation, filtration, and disinfection (Khan Khanzada et al., 2023; Vidu et al., 2020). Modular and scalable designs enable flexible deployment and retrofitting of treatment units within existing infrastructure, facilitating gradual upgrades and expansions according to specific water quality and capacity requirements (Brears, 2021; Daigger et al., 2020; Leigh and Lee, 2019). Moreover, advancements in sensor technology, remote monitoring, and automation enable real-time data acquisition, process control, and performance optimization, enhancing the operational efficiency and reliability of integrated water treatment systems (Martínez et al., 2020; Park et al., 2020; Zainurin et al., 2022; Zhang W. et al., 2020). Integration of smart sensors and IoT-enabled devices facilitates remote monitoring and control of treatment processes, enabling predictive maintenance and early detection of system failures.

8 Challenges and future directions

Addressing heavy metal contamination in water sources poses significant challenges, ranging from environmental impact assessment to regulatory compliance and scaling up production. Addressing the challenges of heavy metal contamination in water sources requires multidisciplinary approaches, collaboration, and innovation (Chernov et al., 2024; Ding, 2024; Kupa et al., 2024).

8.1 Environmental impact assessment

Nanoparticles could be optimized to become highly reusable. For instance, platinum magnesium and copper oxide nanoparticles have been reused in literature. However, when nanoparticles are not properly managed, they could accumulate in the environment due to their long-term stability. They can react with organic matter in the environment to cause environmental damage, and health issues such as apoptosis, oxidative stress, etc (Fu et al., 2020; Imran et al., 2021; Wahl et al., 2021; Zhang X. et al., 2020).

One of the primary challenges in heavy metal remediation is conducting comprehensive environmental impact assessments to evaluate the potential risks and benefits associated with remediation technologies (Khatun et al., 2024; Rashid et al., 2023). While nanomaterials offer promising solutions for heavy metal removal, concerns remain regarding their environmental fate, toxicity, and long-term effects on ecosystems. Recent studies have focused on assessing the environmental implications of nanomaterial-based remediation technologies through rigorous toxicity testing, fate and transport modelling, and ecological risk assessments (Isibor, 2024; Isibor et al., 2024; Prasad and Gupta, 2024; Shanker, 2024). These efforts aim to identify potential environmental hotspots, evaluate exposure pathways, and mitigate adverse impacts on aquatic organisms, soil microbiota, and human health. Moreover, advancements in life cycle assessment (LCA) and environmental footprint analysis enable holistic evaluation of the environmental impacts of heavy metal remediation technologies, considering factors such as energy consumption, resource utilization, and waste generation (Ding et al., 2024; Pandit et al., 2024; Rothee et al., 2024). Integration of environmental sustainability criteria into the design and implementation of remediation strategies ensures responsible stewardship of natural resources and minimizes unintended consequences.

8.2 Regulatory compliance

Regulatory compliance is another significant challenge in the development and deployment of heavy metal remediation technologies, as stringent regulations govern the use, disposal, and discharge of contaminants in water sources. Recent trends in regulatory compliance focus on harmonizing standards and guidelines for heavy metal concentrations in drinking water, surface water, and wastewater effluents to ensure the protection of human health and the environment (Kumar and Samadder, 2023; Shaikh and Birajdar, 2024). Regulatory agencies, such as the Environmental Protection Agency (EPA) in the United States and the European Chemicals Agency (ECHA) in Europe, play a crucial role in setting and enforcing regulatory requirements for heavy metal remediation technologies (Nwokediegwu et al., 2024). Moreover, advancements in risk-based approaches and adaptive management strategies enable flexible and pragmatic regulatory frameworks that balance environmental protection with technological innovation (Gikay, 2024; Dada et al., 2024). Collaborative efforts between government agencies, industry stakeholders, and research institutions facilitate knowledge exchange, capacity building, and continuous improvement in regulatory compliance.

8.3 Scaling up production

Scaling up the production of nanomaterial-based remediation technologies from laboratory-scale prototypes to commercially viable systems poses practical challenges, including cost considerations, process optimization, and supply chain management. Recent advancements in scaling up production focus on optimizing synthesis methods, improving materials efficiency, and streamlining manufacturing processes to reduce production costs and enhance scalability (Ganguly et al., 2024; Palit and Ranjit, 2024; Tyagi et al., 2024). Automation, robotics, and process intensification techniques enable high-throughput production of nanomaterials with consistent quality and performance (Aithal and Aithal, 2024; Darwish et al., 2024). Furthermore, partnerships between academia, industry, and government agencies facilitate technology transfer, knowledge dissemination, and capacity building to accelerate the commercialization of nanomaterial-based remediation technologies (Kumar et al., 2023). Investment in research infrastructure, pilot-scale testing facilities, and demonstration projects enables validation of scalability and performance under real-world conditions.

8.4 Multifunctional nanomaterials

Multifunctional nanomaterials offer exciting opportunities for addressing multiple challenges in heavy metal remediation simultaneously, including selectivity, stability, and regeneration (Feisal et al., 2024; Nikić et al., 2024). Recent trends in multifunctional nanomaterials focus on integrating multiple functionalities, such as adsorption, catalysis, and sensing, into a single platform to enhance performance and versatility in heavy metal removal applications (Asghar et al., 2024; Godja and Munteanu, 2024; Shanmugavel et al., 2024). For example, nanocomposites composed of graphene oxide, metal nanoparticles, and molecularly imprinted polymers exhibit synergistic effects and enhanced selectivity for specific heavy metal contaminants. Moreover, advancements in responsive and stimuli-triggered nanomaterials enable dynamic control over adsorption, desorption, and regeneration processes, enhancing efficiency and sustainability (Makaev et al., 2023; Shahrokhinia et al., 2024; Zhou et al., 2021).

However, designing multifunctional nanomaterials also presents several challenges. The complexity of synthesizing materials that combine multiple functionalities while maintaining structural integrity and long-term stability is a significant barrier. For instance, some multifunctional materials, such as those used for both adsorption and catalysis, must balance these functions without compromising their effectiveness in any particular role (Li and Liu, 2023). Additionally, the recovery and recyclability of these materials are critical for large-scale applications. Magnetic nanomaterials, such as ZnO-Fe_3O_4 composites, have shown promise in this regard due to their ability to be easily separated from treated water using external magnets, thus enhancing the regeneration process and overall cost-effectiveness (Goyal et al., 2018). Furthermore, multifunctional nanomaterials must maintain high selectivity in complex water matrices containing competing ions, a factor that often limits their performance (Baby et al., 2022).

Despite these challenges, advancements in stimuli-responsive and smart nanomaterials have opened new avenues for overcoming these limitations. Materials that can dynamically alter their adsorption properties based on environmental conditions, such as pH-responsive poly 4-hydroxyphenyl methacrylate single-walled carbon nanotube (PHPMA-SWCNT) nanocomposites, have demonstrated the ability to selectively target heavy metals like Pb^{2+} and Cd^{2+}, even in the presence of multiple interfering ions (Mamidi et al., 2021). This adaptability enhances the material's performance in real-world applications, where water compositions can vary significantly. A practical example of multifunctionality can be seen in the work by Goyal et al. (2018), where ZnO-Fe_3O_4 (ZF) nanocomposites were successfully used for simultaneous adsorption of heavy metals, degradation of organic dyes, and antibacterial activity. This multifunctional performance is crucial for dealing with complex contamination scenarios, such as those found in industrial effluents, where pollutants often coexist. Moreover, the ZF nanocomposite could be easily recovered using magnetic separation and reused multiple times, offering a sustainable solution for water treatment.

Further practical examples of multifunctional nanomaterials include the multifunctional nanomaterials is the biomaterial-functionalized graphene-magnetite (Bio-GM) nanocomposite, developed by Ramalingam et al., 2018, which addresses the challenges of colloidal stability and recyclability in graphene-based materials. By incorporating *Shewanella oneidensis* cells into the nanocomposite, Bio-GM efficiently adsorbed both dyes and Cr^{6+}, with removal capacities of 189.63 mg/g for dyes and 222.2 mg/g for Cr^{6+}. Additionally, the nanocomposite facilitated the biocatalytic reduction of Cr^{6+} to Cr^{3+}, demonstrating its multifunctionality. Bio-GM could be regenerated and reused without releasing harmful components, making it a sustainable option for water treatment. In another example, El Mouden et al., 2023 synthesized NC@Co_3O_4 nanocomposites by co-precipitating natural clay with cobalt oxide nanoparticles for heavy metal removal. These nanocomposites exhibited high adsorption efficiencies for Pb^{2+} and Cd^{2+}, with rates of 86.89% and 82.06%, respectively.

9 Conclusion

Heavy metal contamination poses a significant threat to environmental and public health, necessitating effective remediation strategies. Nanomaterial-based approaches offer promising solutions for heavy metal removal from water sources, leveraging the unique properties of nanomaterials to enhance selectivity, efficiency, and sustainability. Through advancements in synthesis methods, surface functionalization, and integration with existing water treatment infrastructure, nanomaterials have demonstrated remarkable potential in addressing the challenges of heavy metal pollution. However, several critical aspects must be considered to ensure the successful implementation of nanomaterial-based remediation technologies. Environmental impact assessment and regulatory compliance are paramount to mitigating potential risks and ensuring the responsible use of nanomaterials in water treatment applications. Additionally, scalability, cost-effectiveness, and integration with other remediation techniques are essential considerations for practical implementation and widespread adoption of nanomaterial-based solutions. Furthermore, ongoing research efforts should focus on addressing key challenges such as the stability, longevity, and multifunctionality of nanomaterials to enhance their performance and reliability in real-world settings. Collaboration between key stakeholders in academia, industry, government agencies, and communities is essential to drive innovation, foster technology transfer, and accelerate the translation of research findings into actionable solutions.

Author contributions

DBO: Conceptualization, Methodology, Project administration, Resources, Supervision, Validation, Writing–original draft, Writing–review and editing. OZW: Conceptualization, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. BIE: Data curation, Writing–original draft, Writing–review and editing. OF: Writing–original draft, Writing–review and editing. AOI: Data curation, Software, Visualization, Writing–original draft, Writing–review and editing. SOU: Writing–original draft, Writing–review and editing. OA: Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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