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Nano-revolution in heavy metal removal: engineered nanomaterials for cleaner water

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Engineered nanomaterials have emerged as a promising technology for water treatment, particularly for removing heavy metals. Their unique physicochemical properties enable them to adsorb large quantities of metals even at low concentrations. This review explores the efficacy of various nanomaterials, including zeolites, polymers, chitosan, metal oxides, and metals, in removing heavy metals from water under different conditions. Functionalization of nanomaterials is a strategy to enhance their separation, stability, and adsorption capacity. Experimental parameters such as pH, adsorbent dosage, temperature, contact time, and ionic strength significantly influence the adsorption process. In comparison, engineered nanomaterials show promise for heavy metal remediation, but several challenges exist, including aggregation, stability, mechanical strength, long-term performance, and scalability. Furthermore, the potential environmental and health impacts of nanomaterials require careful consideration. Future research should focus on addressing these challenges and developing sustainable nanomaterial-based remediation strategies. This will involve interdisciplinary collaboration, adherence to green chemistry principles, and comprehensive risk assessments to ensure the safe and effective deployment of nanomaterials in heavy metal remediation at both lab and large-scale levels.

KEYWORDS

adsorption, engineered nanomaterials, functionalization, heavy metal removal, sustainability, water treatment

1 Introduction

A clean water source is essential for the long-term survival of life. However, water pollution has become a global issue, threatening the entire ecosystem and life on Earth (Chandran et al., 2023; Rangappa et al., 2024; Rybarczyk et al., 2024). A variety of industrial improvements (Figure 1), including energy plants, mining industries, and environmental disasters caused by climate change, have had a significant impact on the spread of harmful toxins in aquatic ecosystems. Pollution and increased demand due to population development have resulted in a widespread scarcity of safe drinking water in many locations around the world (Sukmana et al., 2021). Heavy metal ions in wastewater are a form of pollution that has caused serious health problems (Sharma et al., 2023; Moukadiri et al., 2024). These ions are of special significance because of their persistence in the environment, long-term accumulation, and potential threat to human health via the food chain. Heavy metals are defined as elements with atomic weights ranging from −63 to −201 and densities above 5 gm/cm³ (Arun Karnwal, 2012; H Karami, 2013). They include toxic elements such as chromium (Cr), nickel (Ni), arsenic (As),

FIGURE 1
Sources of heavy metal pollution.

cobalt (Co), zinc (Zn), copper (Cu), and mercury (Hg) (Lu and Astruc, 2018). Untreated or badly treated effluents from many enterprises release harmful heavy metals into the environment, hence exacerbating water pollution. The inappropriate treatment of landfill sites has compounded the situation, as the leachates from these sites contain considerable amounts of heavy metals that can infiltrate groundwater (NC). Arun Karnwal (2012); Arun et al. (2018); Sall et al., 2020; Zamora-Ledezma et al. (2021). Scientists and engineers have become more conscious of the gravity of this pollution, but developing effective and economically viable solutions remains a difficult task.

In recent years, several technologies have been utilized to clean wastewater and purify water. These technologies encompass both proven procedures and novel ways for combating water pollution (Qiu et al., 2022; Goyal et al., 2023). Although these technologies have the potential to eradicate a wide range of pollutants, they typically face restrictions such as high costs, complex procedures, and unsatisfactory performance (Abd Elnabi et al., 2023; Fei and Hu, 2023; Solanki et al., 2024). Even when utilizing well-established approaches, the broad dispersion of heavy metal contaminants in water makes their clearance difficult, owing to problems connected to their ionic forms and ion selectivity. The adsorption approach has gained popularity because it is a safe, environmentally acceptable, and highly effective way to treat heavy metal ion-polluted industrial wastewater (K Liu et al., 2023). Adsorbent materials with large surface areas, considerable porosity, and the ability to be reused have proved efficacy, making the adsorption process economically viable (Bahadi et al., 2024). Jain et al. (2022) investigated the use of economical organic biosorbents (SCB, PHB, and OPB) for eliminating Methylene Blue dye from textile wastewater. Through batch adsorption tests employing a central composite design (CCD) approach, optimal conditions for dye removal are determined. Langmuir and Freundlich adsorption isotherms elucidate the equilibrium reached after 90 min. Response surface methodology (RSM) coupled with CCD optimizes experiments, while kinetic modeling assesses pseudo-first- and pseudo-second-order kinetics. Thermodynamic analysis indicates endothermic, natural adsorption. FTIR characterization confirms Methylene Blue adsorption, suggesting SCB, PHB, and OCB as viable substitutes for commercial biosorbents in wastewater treatment.

Certain limitations hinder the usage of typical adsorbents such as activated carbon and metal oxides. As a result, novel nano adsorbents have been created that use nanoparticles to overcome these limitations (Umeh et al., 2023). Nanomaterials have emerged as possible adsorbents for heavy metal removal due to their unique properties, such as a large specific surface area and the ability to be modified (Yu et al., 2021). Because of their specific surface charge, porosity, and high capacity to bind ions, nanomaterials have a wide range of forms and architectures, which improves their effectiveness in removing heavy metals. Nonetheless, several challenges exist in the practical application of these technologies, particularly in the separation of treated water. To solve this difficulty, nanomaterials are chemically modified to increase their ability to segregate and adsorb diverse compounds (Abdelbasir and Shalan, 2019; Abu Shmeis, 2022). Nanomaterials' recyclability makes them an intriguing and cost-effective option for adsorption-based heavy metal removal from water and wastewater. This review investigates the use of nanomaterials to adsorb and remove heavy metals from water and wastewater. As part of the analysis, a variety of variables influencing this process are examined. These parameters include pH, temperature, contact time, initial heavy metal concentration, and adsorbent quantity.

TABLE 1 Comparative analysis of mechanisms for heavy metal removal from aqueous solutions: Advantages, disadvantages, and applications (Azimi et al., 2017; Almomani et al., 2020; Bhandari et al., 2021; Alzahrani et al., 2022; Aragaw and Ayalew, 2022; Beiranvand et al., 2022; Abdullah et al., 2023).

Mechanism	Description	Advantages	Disadvantages	Examples of materials/Methods
Adsorption	Physical or chemical binding of metal ions to a solid surface	• High efficiency and selectivity	• Potential for saturation and regeneration challenges	• Activated carbon
				• Zeolites
		• Wide range of applicable materials	• May not be specific to target metals	• Biochar
		• Easy implementation		• Metal oxides
Ion Exchange	Exchange of ions between an aqueous solution and a solid material with similar charged ions (Figure 2B)	• High selectivity for specific metals	• Limited capacity for metal uptake	• Zeolites
		• Reversible process for regeneration	• Requires specific ion exchange resins	• Clay minerals
				• Ion exchange resins
Precipitation	Conversion of soluble metal ions into insoluble salts through chemical reactions	• Effective for removing large quantities of metals	• Requires specific pH and chemical conditions	• Co-precipitation with other metals/hydroxides
		• Relatively simple process	• May generate secondary waste	• Sulfide precipitation
Membrane Separation	Selective separation of metal ions from water through membranes based on size, charge, or other properties	• High purity of treated water	• High energy consumption	• Reverse osmosis
		• Can be combined with other processes	• Membrane fouling issues	• Nanofiltration
				• Electrodialysis
Biosorption	Uptake of metal ions by living organisms or their biomass (Figure 2D)	• Environmentally friendly	• Slow process	• Bacteria (e.g., *E. coli*)
		• Potential for *in-situ* remediation	• Limited capacity for metal uptake	• Algae (e.g., Chlorella)
			• Specificity to certain metals	• Fungi (e.g., Aspergillus)
Bioaccumulation	Intracellular accumulation of metal ions by living organisms	• High selectivity for specific metals	• Slow process	• Bacteria (e.g., *Pseudomonas*)
		• *In-situ* remediation possible	• May impact organism viability	• Yeast (e.g., *Saccharomyces*)
Biomineralization	Transformation of toxic metal ions into less bioavailable forms by microorganism (Figure 2E)	• Reduces mobility and toxicity of metals	• Specificity to certain metals	• Bacteria (e.g., Shewanella)
		• *In-situ* remediation possible	• Requires specific environmental conditions	• Enzymes (e.g., urease)
Electrochemical Methods	Removal of metal ions through reduction or oxidation at an electrode surface	• High efficiency and selectivity	• High energy consumption	• Electrodeposition
		• Can be automated	• Requires specialized equipment	• Electrocoagulation

2 Methods for removing heavy metals from water

The risk of heavy metal contamination looms over our world, endangering ecosystems and human health. These persistent contaminants enter water sources through industrial, mining, and agricultural processes, where they accumulate in living creatures and pose serious health concerns (Abd El-Aziz et al., 2023; Ahmadian et al., 2023; Ali et al. Fortunately, scientists are equipped with a variety of remediation options, and knowing the mechanisms underlying heavy metal removal from aqueous solutions is critical for their successful implementation (Abd Elnabi et al., 2023). Table 1 provides a comparative review of heavy metal removal processes from aqueous solutions, revealing a range of advantages, disadvantages, and applications. Various processes, including as adsorption, precipitation, ion exchange, and membrane filtration, provide distinct advantages, including high efficiency, cost-effectiveness, and adaptability (Lu and Astruc, 2018). However, each technique has limitations, including limited capacity, pH dependence, and regeneration issues (Azimi et al., 2017; Bui et al., 2021). Understanding the merits and disadvantages of each approach is critical for determining the best technique for a given environmental remediation scenario. This detailed investigation helps to advance long-term solutions for reducing heavy metal pollution in water systems.

2.1 Adsorption: a sticky situation for metals

One of the most widely employed techniques for heavy metal removal is adsorption (Figure 2A). In this process, metal ions

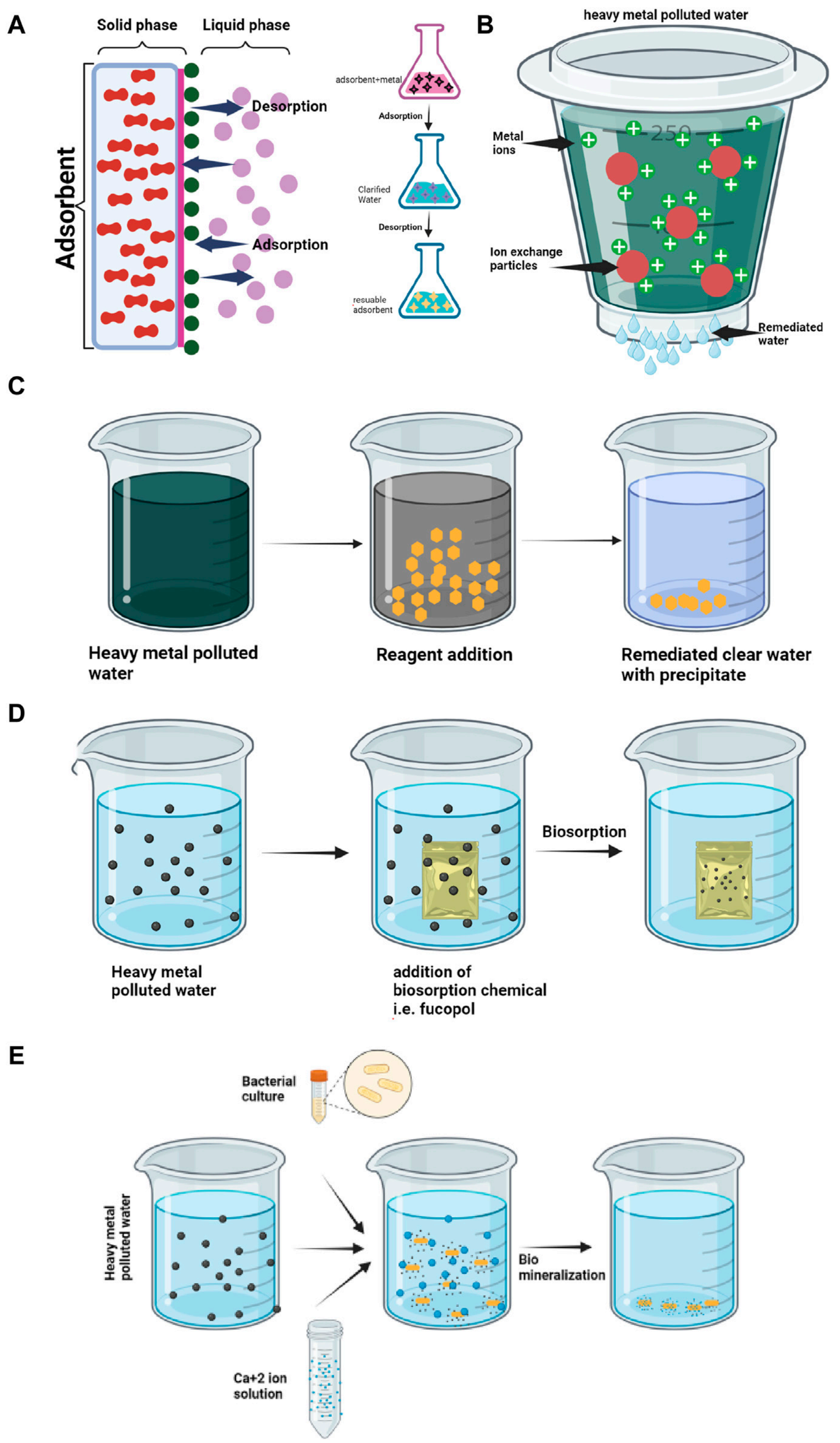

FIGURE 2
Various mechanisms used for remediation of heavy metals from water **(A)** Adsorption; **(B)** Ion Exchange; **(C)** Precipitation; **(D)** Biosorption; **(E)** Biomineralization.

cling to the surfaces of adsorbent materials, effectively trapping them and preventing their spread (Abobakr and Abdo, 2022; Adisasmito et al., 2023). The key players in this adsorption drama are:

- Adsorbents: These materials, with their high surface areas and abundant functional groups, act as magnets for metal ions. Activated carbon, clays, zeolites, and various nanomaterials are popular choices.

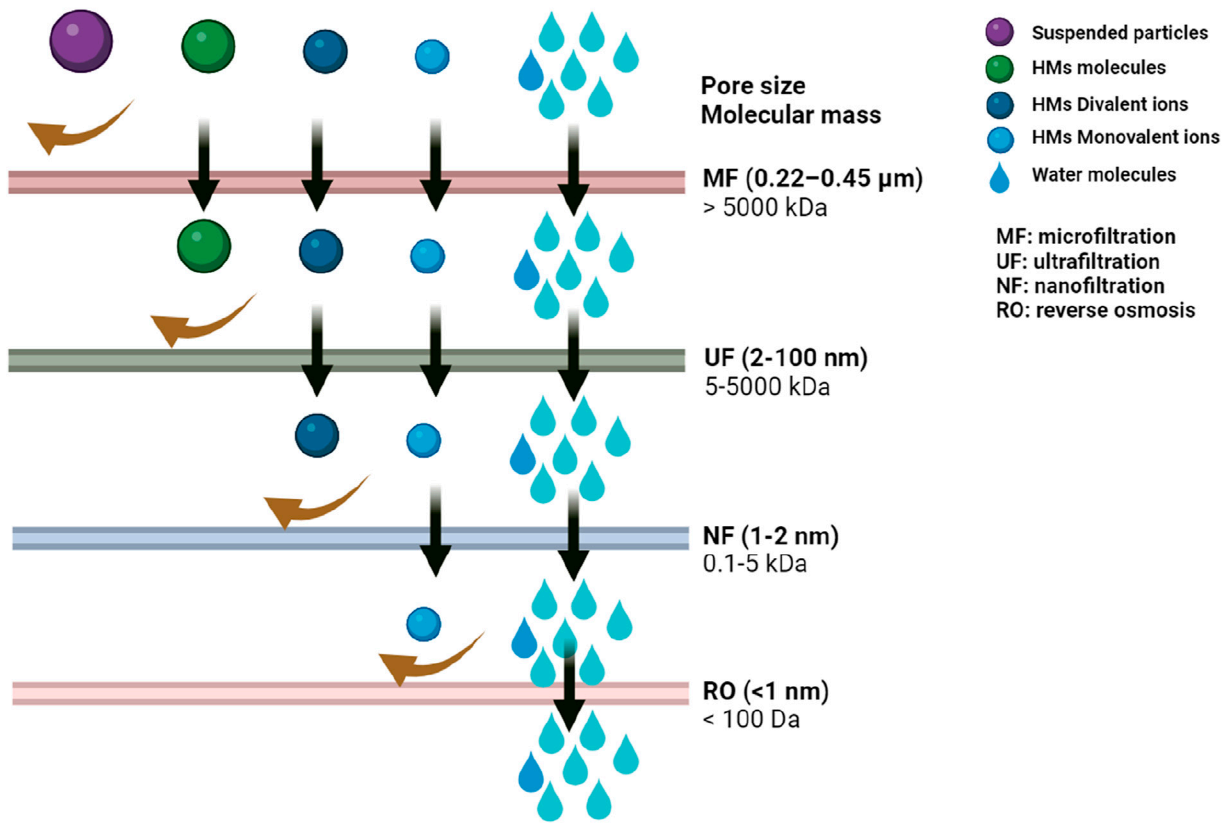

FIGURE 3
Performance evaluation of four membranes in rejecting various heavy metal particles and ions.

- Metal ions: These positively charged metallic culprits are attracted to the negatively charged sites on the adsorbent surface.

Several mechanisms govern the adsorption dance:

- Physical adsorption (physisorption): This weak, van der Waals force-driven interaction creates a temporary bond between the metal ion and the adsorbent surface.
- Chemical adsorption (chemisorption): This stronger, covalent, or ionic bond formation leads to more permanent metal ion attachment.
- Ion exchange: Metal ions replace other cations bound to the adsorbent surface, achieving selectivity for specific metals (Figure 2B).

Factors like pH, temperature, and initial metal concentration influence the adsorption process. Optimizing these parameters is crucial for maximizing metal removal efficiency.

2.2 Precipitation: turning metals into solid sediments

Another popular approach involves precipitation. By altering the solution's pH or adding specific chemicals, metal ions are transformed into insoluble precipitates, settling out of the water as solid particles (Figure 2C) (Yu et al., 2021). This method is particularly effective for metals like lead, copper, and cadmium (Godwin et al., 2023; L Liu et al., 2022).

The mechanisms at play here involve:

- Hydrolysis: Metal ions react with water molecules, forming insoluble hydroxide precipitates.
- Precipitation with anions: Adding anions like phosphates or sulfates forms insoluble salts with the metal ions, promoting their removal.

The choice of precipitating agent and optimal pH conditions are critical for efficient precipitation.

2.3 Membrane filtration: straining out the contaminants

Imagine tiny sieves selectively filtering out metal ions while allowing clean water to pass through. That is the essence of membrane filtration (Cevallos-Mendoza et al., 2022; Chadha et al., 2022). Membranes with varying pore sizes can be employed to physically separate metal ions based on their size (Figure 3).

Here is how it works:

- Reverse osmosis: A pressure difference forces water molecules through a semipermeable membrane, leaving behind larger metal ions.
- Nanofiltration: Membranes with smaller pores allow selective passage of water molecules while rejecting larger metal ions and some organic contaminants.

Membrane selection, pressure control, and pretreatment of the solution are crucial aspects of successful metal removal using this technique.

2.4 Bioaccumulation: nature's detoxification squad

Nature itself holds the key to some promising remediation strategies. Certain microorganisms and plants have the remarkable ability to bioaccumulate heavy metals, taking them up and accumulating them in their tissues (Z Xu et al., 2023). This natural detoxification process offers a sustainable and environmentally friendly approach.

The mechanisms involved are complex and diverse, including:

- Biosorption: Microorganisms bind metal ions to their cell walls or extracellular polymers (Figure 2D).
- Bioaccumulation: Specific proteins within plants or microorganisms actively transport and sequester metal ions.
- Biotransformation: Some microorganisms can convert toxic metal forms into less harmful ones.

While further research is needed to optimize and scale up bioaccumulation techniques, their potential for eco-friendly metal removal is significant.

No single technique holds the silver bullet for heavy metal removal. Often, combining multiple approaches proves most effective (Abbas, 2021). For instance, adsorption followed by membrane filtration can achieve high removal efficiencies. Integrating bioaccumulation with other methods can enhance sustainability and reduce environmental impact. By understanding the diverse mechanisms behind heavy metal removal, scientists can tailor strategies to specific contaminants and environmental conditions. Ongoing research continues to explore novel materials, optimize existing processes, and develop cost-effective solutions. The ultimate goal? A cleaner, healthier planet free from the threat of heavy metal pollution.

3 Nanomaterials for heavy metals removal from aqueous reservoir

Wastewater treatment is undergoing a significant revolution with the application of nanomaterials. Researchers are exploring a diverse range of these materials, including zeolite, various forms of carbon, polymers, chitosan, ferrites, magnetic particles, metal oxides, bimetallic structures, and even pure metals (Aloulou et al., 2022; Amariei et al., 2022; Gao et al., 2022). These nanoparticles boast a remarkable property called adsorption. This essentially means they can act like tiny magnets, attracting and holding onto heavy metals from wastewater, effectively removing them. As a valuable resource for those working in environmental remediation, Table 2 offers a snapshot of the latest nanobiotechnology strategies being used to tackle heavy metal contamination. It details innovative methods and techniques specifically designed to combat this form of environmental pollution.

3.1 Functionalized carbon (C) nanomaterials for removing toxic metals from wastewater

Functionalized carbon nanoparticles are currently employed as effective adsorbents for removing hazardous metals from wastewater due to their distinctive chemical and physical characteristics, showing significant potential for application in water purification initiatives (Surti et al., 2023). These materials have gained considerable attention across scientific and technical disciplines for their exceptional thermal, mechanical, optical, chemical, and physical properties. Various carbon-based nanomaterials, such as carbon nanotubes, nanocomposites, and graphene, have been utilized for eliminating contaminants from water sources (Abbasi and Khan, 2021). Graphene, a two-dimensional substance composed of a single layer of carbon atoms, is extremely thin (Abdel Wahab et al., 2023). Carbon nanotubes, on the other hand, are cylindrical nanostructures made of sp2-bonded carbon atoms. The hydrophilic nature of graphene, attributed to the oxygen functional groups present on the surface of graphene oxide (GO), enables exceptional solubility in water (Abdel Wahab et al., 2023). The use of GO in water purification is highly recommended due to its large surface area and various functional groups. Nanoparticles based on graphene have been proven to be exceptionally effective in eliminating various pollutants from water (Ahlawat et al., 2021; H Ahmad and Liu, 2021). Complexes formed between oxygen functional groups on graphene and cationic metals play a crucial role in the adsorption mechanism utilized by graphene for removing hazardous metals. Similarly, in the case of organic dyes (Cano et al., 2023), contact occurs through the expanded configuration of π-electrons within graphene. The incorporation of MnO_2 nanotubes into reduced graphene oxide (rGO) hydrogel by Zeng et al. resulted in the creation of a three-dimensional nanomaterial with a size of 20 nm. This material effectively removed various heavy metals from the environment, including zinc (83.9 mg/g), copper (121.5 mg/g), silver (138.2 mg/g), cadmium (177.4 mg/g), and lead (Zeng et al., 2019). These impressive adsorption capacities are attributed to the synergistic interaction between manganese dioxide nanotubes (MnO_2) and reduced graphene oxide (rGO) within the material's 3D porous structure. Notably, GO nanosheets also exhibited good adsorption potential for cobalt, demonstrating a removal quantity of 68.2 mg/g. Similarly, Cd (II) ions were removed using graphene oxide nanosheets, which showed a removal capacity of 106.3 mg/g (Zhou et al., 2023).

Environmental engineers find carbon nanotubes (CNTs) highly appealing due to their unique attributes, such as extensive surface area, small dimensions, cylindrical hollow structure, and electrical conductivity (Suresh and Rajendran, 2022). CNTs primarily exist in two forms: multi-walled carbon nanotubes (MWCNTs) and single-walled carbon nanotubes (SWCNTs). Several investigations have delved into the utilization of CNTs for treating wastewater to eliminate toxic heavy metals via adsorption. Researchers have effectively employed CNTs to remove ions of manganese (II), zinc (II), cobalt (II), lead (II), and copper (II) (Sun et al., 2015; Trojanowicz, 2006; J Zhang et al., 2021). An additional investigation

TABLE 2 Summary of nanobiotechnology approaches for mitigating heavy metal pollution (Biswas et al., 2021; Gong et al., 2021; Kolluru et al., 2021; Baby et al., 2022; Dhara, 2024).

Approach	Nanomaterial used	Mechanism of action	Advantages	Disadvantages	Examples
Nanosorption	- Metal oxides (e.g., nZVI, TiO2) - Activated carbon nanoparticles - Biochars	Adsorption of heavy metals onto the high surface area of nanoparticles	- High efficiency and selectivity - Cost-effective -Easy implementation	- Potential for nanoparticle release into the environment - Regeneration of spent nanoparticles	- Removal of Pb, Cd, As, and Hg from water and soil
Bioaccumulation	- Bacteria (e.g., *Escherichia coli*, *Bacillus subtilis*) - Fungi (e.g., *Saccharomyces cerevisiae*, *Aspergillus niger*) - Algae (e.g., *Chlorella vulgaris*, *Scenedesmus* quadricauda)	Accumulation of heavy metals within the biomass of living organisms	- Environmentally friendly - *In situ* remediation possible	- Slow process - Limited capacity for metal uptake - Specificity to certain metals	- Bioaccumulation of Cu, Zn, Ni, Co by bacteria
Nano-phytoremediation	- Nanoparticles used to enhance plant uptake of metals (e.g., nZVI for Cr) - Engineered plants with increased metal tolerance	- Facilitation of phytoextraction (removal of metals) and phytostabilization (immobilization of metals)	- Cost-effective -Sustainable approach -Large-scale application potential	-Potential for phytotoxicity of nanoparticles -Limited understanding of long-term effects	- Phytoremediation of Pb, Cd, Ni using nanoparticles combined with plants
Biomineralization	- Microorganisms (e.g., *Pseudomonas aeruginosa*, *Shewanella oneidensis*) - Enzymes (e.g., urease, phosphatase)	Transformation of toxic heavy metals into less bioavailable forms (e.g., carbonates, phosphates)	- Reduces mobility and toxicity of metals - *In situ* remediation possible	- Specificity to certain metals - Requires specific environmental conditions	- Biomineralization of As, Pb, Cd by bacteria
Biocatalysis	- Enzymes immobilized on nanoparticles - Engineered enzymes with increased specificity and activity	Degradation of organic pollutants that mobilize heavy metals	- Can target specific contaminants - High efficiency and selectivity	- Complex and expensive enzyme development - Potential for enzyme inactivation	- Degradation of PAHs, BTEX, MTBE to reduce mobilization of Pb, Cd

revealed that the effective removal of lead ions from water yielded a remarkable adsorption capacity of 70.2 mg/g (Marwani et al., 2022). The application of MnO_2 as a coating on oxidized multi-walled CNTs resulted in an adsorption capacity of 41.7 mg/g for the removal of cadmium ions from water (Y Liu et al., 2021). Recent advancements have led to the development of nanocomposites comprising carbon-layered silicates, offering enhanced properties compared to traditional carbon nanomaterials. One such composite, known as nano adsorbent montmorillonite/carbon (H Zhang et al., 2023), exhibited a remarkable adsorption capacity of 247.86 mg/g for lead ions, making it a promising and eco-friendly solution for water treatment. Table 3 presents a comparative analysis of various nanomaterials used for the removal of heavy metals from aqueous reservoirs, highlighting their effectiveness, mechanisms of action, and specific heavy metals targeted. This comparison aids in understanding the suitability and performance of different nanomaterials in remediation processes.

3.2 Zeolites nanoparticles

Zeolite materials are composed of crystalline hydrated aluminosilicate structures (Jarosz et al., 2022), exhibiting a highly porous skeletal framework with pores and channels spanning from nano to micrometer dimensions. Zeolites consist of tetrahedral SiO_4 and AlO_4 units (Marotta et al., 2021), these units form a framework of pores and channels capable of accommodating cations, water, and small molecules, resembling a sponge with numerous small or extremely small pores but lacking flexibility. Within the crystal structure, Si and Al atoms occupy central positions, while O atoms are located at the corners, shared between SiO_4 and AlO_4 units, creating regular gaps and channels. The negatively charged Al3 ions attract positively charged cations such as Na+, Mg2+, K+, and Ca2+, allowing them to occupy vacant positions and neutralize the framework's negative charge (Mahdavi Far et al., 2022; Mo et al., 2022). Zeolites demonstrate robust three-dimensional framework structures with limited interactions between ions and molecules confined within pores and voids, facilitating the removal of ions without damaging the zeolite structure. Zeolites are categorized into three groups based on their Si/Al molar ratio:

- zeolites A and X, with low silica content and an Al/Si ratio less than 2;
- zeolites Y and L, with intermediate silica content and an Al/Si ratio between2 and 5; and
- zeolites beta and ZSM-5, with high silica content and an Al/Si ratio greater than 5.

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TABLE 3 A comparative analysis of nanomaterials for heavy metal removal from aqueous reservoirs(Bhagat and Giri, 2021; S Biswas et al., 2021; Dong et al., 2021; Solanki et al., 2024; J Yang et al., 2019).

Nanomaterial	Mechanism of removal	Surface area (m^2/g)	Porosity	Functional groups	Adsorption capacity (mg/g)	Regeneration ease	Magnetic properties	Metal selectivity	Advantages	Disadvantages	Examples	Cost	Maturity
Functionalized Carbon Nanomaterials (CNTs, Graphene, Graphene Oxide)	Adsorption, ion exchange, chelation	High	Moderate	Carboxyl, Hydroxyl, etc.	Varies	Moderate	No	Broad	High surface area, high adsorption capacity, tunable functionality	Potential environmental risks, difficult regeneration	Functionalized CNTs for Pb, Cd, As	High	Medium
Zeolite Nanoparticles	Ion exchange, adsorption	Moderate	High	Silanol, Aluminol, etc.	Varies	Moderate	No	Depends on zeolite type	High selectivity, good regeneration potential	Limited capacity, pH-dependent	Clinoptilolite for Pb, Cd, Cs	Medium	High
Polymer-Based Nanomaterials	Adsorption, encapsulation, chelation	Low to Moderate	Low	Amine, Thiol, etc.	Varies	Low to Moderate	No	Tailorable with functional groups	Biocompatible, good stability	Can be an expensive, complex synthesis	Chitosan beads for Cu, Cr	Medium	Medium
Cellulose-Based Nanomaterials	Adsorption, chelation	High	Moderate	Hydroxyl, Carboxyl, etc.	Varies	Moderate	No	Abundant, renewable	Biocompatible, low cost	Lower capacity than some other materials	Cellulose nanofibers for Hg, Pb	Low	Medium
Dendrimer-Based Nanomaterials	Adsorption, chelation	Moderate	Low	Amine, Carboxyl, etc.	Varies	Low to Moderate	No	A high degree of functionalization	Highly selective, high-capacity	Complex synthesis, high cost	PAMAM dendrimers for Pb, Hg	High	Low
Chitosan-Based Nanomaterials	Adsorption, chelation	Moderate	Moderate	Amine, Hydroxyl, etc.	Varies	Moderate	No	Good biocompatibility, abundant	Biodegradable, high adsorption capacity	Limited pH range, lower capacity than some	Chitosan beads for Cu, Cr	Low	Medium
Magnetic Nanomaterials	Adsorption, separation with magnetic field	Varies	Varies	None	Varies	Moderate	Yes	Easy separation, reusable	Tunable properties, high recovery efficiency	Potential environmental risks, complex synthesis	Iron oxide nanoparticles for As, Pb	Medium	Medium
Nanocomposite Magnetic Nanoparticles	Adsorption, separation with magnetic field	Varies	Varies	Depends on Components	Varies	Moderate	Yes	Enhanced adsorption capacity, tunable properties	High recyclability, good selectivity	Complex synthesis has, higher cost than a single component	Fe_3O_4-graphene oxide for Pb, Hg	High	Low
Metal Oxides and Metal-Based Nanomaterials (TiO_2, ZnO)	Adsorption, photocatalysis	High	Moderate	Hydroxyl, Carboxyl, etc.	Varies	Moderate	No	Varies with metal oxide	High reactivity, potential for degradation	Can be expensive, pH-dependent	TiO_2 for Pb, Cr	Medium	High
Silica-Based Nanomaterials	Adsorption, encapsulation	High	Moderate	Silanol, Hydroxyl, etc.	Varies	Moderate	No	High surface area, good stability	Biocompatible, can be functionalized	Lower capacity than some other materials	Mesoporous silica for Pb, Cd	Medium	Medium

TABLE 4 Zeolite nanoparticles for heavy metal removal from aqueous solutions (Mo et al., 2022; Umejuru et al., 2023; B Zhao et al., 2024).

Parameter	Description	Advantages	Disadvantages	Examples
Mechanism of Removal	- **Ion exchange:** Exchange of ions between zeolite framework and metals in solution	- High efficiency and selectivity for specific metals	- Limited capacity for some metals	- Clinoptilolite for Pb, Cd, Cs. - NaX for Pb, Ni. - Mordenite for Cu, As
	- **Adsorption:** Physical attraction of metal ions to the high surface area of zeolite nanoparticles	- High adsorption capacity	- pH-dependent performance	
	- **Chelation:** Formation of strong bonds between metal ions and functional groups on zeolites	- Good regeneration potential	- Potential for nanoparticle release into the environment	
		- Environmentally friendly		
Surface Area	Typically in the range of 200–800 m^2/g, providing abundant sites for metal interaction	- Increased adsorption capacity	- Can be energy	- Nanoporous zeolites synthesized with hydrothermal methods
		- Enhanced removal efficiency	- intensive to achieve high surface area	
Pore Size	Can be microporous (<2 nm), mesoporous (2–50 nm), or macroporous (>50 nm), allowing targeting of specific metal sizes	- Tailored selectivity for different metal ions	- Complex synthesis methods for desired pore size distribution	- Mesoporous zeolites for larger metal ions like Pb. - Microporous zeolites for smaller ions like Cd
		- Increased accessibility for larger metal ions		
Surface Modification	Introduction of functional groups (e.g., -OH, -NH2, -SH) to enhance metal binding	- Improved selectivity and adsorption capacity for specific metals	- Can increase the cost and complexity of synthesis	- Amine-functionalized zeolites for Cu removal. - Thiol-functionalized zeolites for Hg removal
		- Can target different mechanisms (e.g., chelation)		
Composites	Combining zeolites with other materials (e.g., magnetic nanoparticles, biopolymers) for enhanced functionality	- Improved separation and reusability with magnetic properties	- Can be more complex to synthesize and characterize	- Zeolite-magnetic nanoparticle composites for easy separation. - Zeolite-biopolymer composites for improved durability
		- Increased stability and biocompatibility with biopolymers		
Cost	Generally lower than some other nanomaterials (e.g., dendrimers), but dependent on specific synthesis methods and modifications	- Affordable option for large-scale applications	- Highly purified and modified zeolites can be more expensive	- Naturally occurring zeolites like clinoptilolite are cost-effective
Maturity	Well-established technology with numerous research studies and pilot-scale demonstrations	- Reliable and readily available technology	- Not all advanced modifications are commercially available yet.	- Several commercial products based on natural and modified zeolites exist

These differences result in distinct characteristics in the structure of zeolite frameworks, enabling various industrial applications (Umejuru et al., 2023). For instance, zeolites with low silica content and a Si/Al ratio of 1, possess a larger number of cation exchange sites, leading to higher cation contents and exchange capacities. Zeolites with moderate silica content are essential for enhancing heat and acid resistance, crucial for catalytic purposes. Conversely, high silica zeolites exhibit excellent adsorption capabilities, particularly for organic molecules with lower polarity, and limited affinity for water and other polar substances. They feature a more uniform surface and a preference for organic molecules, along with greater resistance to water due to their porous crystal structure (Mo et al., 2022).

Table 4 presents data on the efficacy of zeolite nanoparticles in removing heavy metals from aqueous solutions, detailing their adsorption capacity and efficiency for various heavy metal contaminants. This table provides valuable insights into the potential of zeolite nanoparticles as efficient adsorbents in water treatment processes.

Zeolites serve as effective catalysts in chemical processes due to their porous properties, facilitating unimpeded liquid flow through their pores and supporting chemical reactions on their surfaces. Additionally, they can be modified to enhance their adsorption capacity. Zeolite nanoparticles are utilized for eliminating hazardous metals from wastewater owing to their reactive surfaces and expansive area (Deravanesiyan et al., 2015). Both natural zeolites like clinoptilolite and synthetic variants such as zeolite 4A and zeolite X are commonly employed for heavy metal treatment (Gao et al., 2022). These zeolites assist in transmitting alkali and alkaline earth metals to balance the overall negative charge within the framework. Sprynskyy et al. (2006) conducted a sorption experiment using natural zeolites, specifically clinoptilolite, for heavy metal elimination. The process involved three phases: rapid adsorption on the surface, an inversion stage, and diffusion flow from within the microcrystals. Particle size significantly influenced metal ion absorption, with smaller particles enhancing removal. However, clinoptilolite's adsorption efficacy varied slightly when treating solutions with one metal *versus* multiple metals due to distinct sorption sites.

Various studies have distinguished natural and synthetic zeolites, highlighting synthetic versions' superior effectiveness in metal ion removal (Vishnu et al., 2021; Jarosz et al., 2022). Yurekli (2016) demonstrated that incorporating zeolite nanoparticles (NaX) into polysulfone membranes effectively removes lead and nickel from water-based solutions, enhancing metal impurity elimination and reducing membrane pressure. Jain et al. (2021) developed an ultrathin forward osmosis (FO) membrane using cellulose acetate (CA) and titanium dioxide (TiO2) nanoparticles through phase inversion. The membrane exhibited high water permeability and stability, characterized by scanning electron microscopy, elemental mapping, and x-ray diffraction. Evaluating FO performance showed consistent water flux and low reverse salt flux, with an average water flux of 33.63 L/m2/h and reverse salt flux of 10.34 g/m_2/h attributed to strong hydrogen bonding between cellulose ester and titania particles. The membrane demonstrated high efficiency for water desalination, promising for practical applications. In another study, Khorram Abadi et al. (2023) employed electrospun nanofibers made of polyvinyl alcohol and nano zeolite (PVA/NaX) to eliminate Ni2+ and Cd2+ ions, finding Cd2+ ions had higher adsorption capacity. Another study evaluated three sorbents (ANIZ, NaX zeolite granules, Al_2O_3 nanoparticles) for Cr3+ and Co2+ ion removal, emphasizing pH's crucial role, with pH 5 and 6 most effective for Cr3+ and Co2+ removal, respectively. ANIZ exhibited superior removal efficiency for both ions compared to Al_2O_3 nanoparticles and NaX.

Furthermore, Al-Jubouri & Holmes (2020) demonstrated the production of carbon composites using 4A and 4A zeolite to extract cobalt ions from water solutions, significantly increasing ion exchange capacity and enhancing cobalt removal efficiency by adjusting pH and temperature.

3.3 Polymer-based nanomaterials

Scientists have shown significant interest in nanofibrous membranes based on polymers such as cellulose and chitosan, widely regarded as environmentally friendly remediation methods (Yu et al., 2021). The presence of a well-designed porous fiber network, along with a large specific surface area and high gas permeability, enhances their ability to absorb pollutants effectively (Muthukumaran et al., 2022). Their biodegradable nature, customizable surface functional groups, and robust structural integrity make them ideal alternatives for adsorption. Polymer-filled nanomembranes exhibit notable selectivity and adsorption prowess due to unique functional moieties such as NH_2, COOH, and SO_3H (Elakkiya et al., 2021). These nano adsorbents can be categorized based on the substrate utilized, showcasing their versatility in heavy metal removal applications. With their distinct properties and adaptable functionalities, polymer-based nanomaterials have emerged as promising solutions for addressing heavy metal contamination in water.

A significant advantage of these materials lies in their high specific surface area, facilitating increased interaction sites for heavy metal ion adsorption. This feature enhances adsorption efficiency by promoting stronger interactions between the polymer matrix and metal ions. Moreover, the surface chemistry of polymer-based nanomaterials can be tailored to selectively bind to specific heavy metal pollutants, ensuring efficient removal from water sources (Razman Shah et al., 2023; Y Wang and Sun, 2021). Additionally, these materials boast impressive mechanical properties, including high strength and flexibility, ensuring durability and stability during the adsorption process, even under challenging environmental conditions, maintaining consistent performance over time. Table 5 presents an overview of polymer-based nanomaterials used in heavy metal removal processes, showcasing their promising adsorption capacities and tailored characteristics for effective capture of heavy metal ions from aqueous solutions.

Synthesis methods for polymer-based nanomaterials, such as electrospinning, polymerization, and self-assembly, offer versatility in fabricating diverse structures tailored to specific applications. Moreover, their cost-effectiveness and eco-friendliness make them attractive options for large-scale water treatment endeavors. Polymer-based nanomaterials show great potential for heavy metal removal from water due to their high adsorption capacity, customizable surface chemistry, and robust mechanical properties. Continued research and development efforts are necessary to optimize their performance and overcome challenges for their practical implementation in water treatment processes.

3.3.1 Cellulose-based nanomaterials

Researchers investigated the efficacy of biopolymer-based adsorbents, particularly cellulose, for the removal of harmful heavy metals from water (Yusuf, 2021). Abou-Zeid et al. (2018) synthesized three bioadsorbents: tetramethyl piperidine oxide-oxidized 2,3,6-tricarboxylic cellulose nanofibers (T-CNFs), TPC-cellulose nanofibers (TPC-CNFs) with and without polyamide-amine-epichlorohydrin crosslinker (PAE). They assessed the effectiveness of these adsorbents in purifying water contaminated with Cu, Pb, and Ca ions. For lead and copper ions, the adsorption capacities of crosslinked TPC-CNFs were determined to be 82.19 mg/g and 97.34 mg/g, respectively. Mautner et al. (2016) showed that CNF/P, formed by adding phosphate groups to cellulose nanofibers using phosphoric acid, efficiently removed copper ions from water. Cellulose nanofibers were developed by Choi and Lee (2022) using electrospun cellulose acetate deacetylation and subsequent esterification to incorporate thiol groups. According to the Langmuir isotherm (Abuhatab et al., 2023), this modified nanomaterial has adsorption capabilities of 22.0 mg/g, 45.9 mg/g, and 49 mg/g for lead (II), cadmium (II), and copper (II) ions, respectively. The functionalized nanomaterial facilitated the removal of metal ions through complexation interactions between surface thiol groups and divalent metals, showcasing its effectiveness in water remediation. Similarly, cellulose nanofibrous mats modified with citric acid were fabricated using the same method, and batch adsorption studies confirmed their efficacy in eliminating chromium ions, particularly Cr (VI), from aqueous solutions (Chen et al., 2022).

3.3.2 Dendrimer-based nanomaterials

A highly efficient method for eliminating toxic metals involves utilizing organic polymers equipped with functional groups capable of strongly binding these harmful substances (Guo et al., 2022). This system comprises a polymeric support with functional appendages, with various ratios of acrylamide and acrylic acid being employed to fabricate a superabsorbent polymer hydrogel (Ahmadian et al.,

TABLE 5 Polymer-based nanomaterials for heavy metal removal (Asif et al., 2021; Zambare and Nemade, 2021; Chauhan et al., 2022; Kayanja et al., 2023).

Property	Description	Advantages	Disadvantages	Examples
Functional Groups	- Amine (-NH2) - Thiol (-SH) - Carboxyl (-COOH) - Phosphonate (-PO_3H_2)	- Tailorable for specific metal affinities - High selectivity & and capacity	- Synthesis complexity - Potential toxicity concerns	Chitosan beads (-NH_2) for Cu, Cr
Surface Area	- High surface area to volume ratio	- Increased adsorption sites	- Can be limited by particle size & and morphology	Polyaniline nanofibers for Pb, Cd
Porosity	- Microporous, mesoporous, macroporous structures	- Enhanced accessibility for metal ions	- Fabrication complexity, potential pore collapse	Chitosan hydrogels (macroporous) for Hg
Biodegradability	- Degradable by natural processes	- Reduced environmental impact	- Lower mechanical stability & and reusability	Cellulose nanocrystals for As
Charge	- Cationic, anionic, neutral	- Tailored electrostatic interactions with metals	- Limited effectiveness for oppositely charged metals	Chitosan (cationic) for Cu
Composites	- Incorporation of magnetic nanoparticles, metals, zeolites, etc.	- Synergistic properties for removal & and regeneration	- Increased complexity & cost	Metal-organic frameworks (MOFs) for Pb, Cd
Stimuli-Responsiveness	- Respond to pH, temperature, light, etc.	- Controlled release & regeneration	- Complex design & and synthesis	pH-responsive hydrogels for Hg

2023). Designed to remove Cd (II), Ni (II), Cu (II), and Co (II) from water, this hydrogel exhibits remarkable adsorption capacity. However, the effectiveness of the material in adsorbing cadmium and nickel ions is comparatively lower than its ability to adsorb copper and cobalt ions (Naseem et al., 2019). This discrepancy may arise from the smaller size of the cations, allowing them to easily penetrate the polymeric support and undergo rapid chelation by the functional arms.

The adsorption capacities of Zn (II), Pb (II), and Cd (II) ions were found to be 7.2, 8.8, and 6.1 mmol/g, respectively, in nanofibers made of a polyacrylonitrile base polymer, diethylenetriamine, ethylene glycol, and ethylenediamine, according to another study (Morillo Martín et al., 2018). These nanofibers' remarkable adsorption capacity is due to their large surface area, which allows functional groups to interact with toxic metals more effectively. Additionally, 1,3,5-tris (6-isocyanatohexyl)-1,3,5-triazinane-2,4,6-trione and diethylenetriamine were combined to form two novel polymers (Cegłowski et al., 2018). The ethylene amine groups found in these nanomaterials can undergo complexation processes and bind metallic ions. The effectiveness of the nano adsorbent in absorbing divalent copper, chromium, cobalt, and cadmium ions was greatly enhanced by including pentaethylenehexamine to form longer amine chains, as compared to diethylenetriamine.

Scientists made nanofiber membranes out of polyacrylonitrile and metal-organic frameworks (MOF-808) using a co-electrospinning technique (Efome et al., 2019). The PAN/MOF-808 nano adsorbent that was produced was outstanding in removing heavy metals from water, in the following order: Hg (II) < Pb (II) < Cd (II) < Zn (II). This implies that the size and configuration of the metals influence their interaction with active sites and complex formation. Another study (Ren et al., 2013) showcased the efficient extraction of hexavalent chromium impurities from wastewater using nanofibers composed of poly-(ethylene-co-vinyl alcohol), achieving an impressive adsorption capacity of 90.75 mg/g within a timeframe of less than 100 min. Furthermore, employing amidoxime-modified polyacrylonitrile nanofibers proved highly effective in eliminating divalent lead and copper ions from water.

Poly (styrene-alt-maleic anhydride) resin underwent chemical modification using either 1,2-diaminoethane or 1,3-diaminopropane, alongside 3-aminobenzoic acid, for the removal of Pb (II), Zn (II), Cu (II), and Fe (II) from water (Hasanzadeh et al., 2013; Hasanzadeh et al., 2017). Additionally, Sohail et al. (I Sohail et al., 2020; Sohail et al., 2021) adopted a divergent approach to synthesize poly-amidoamine (PAMAM) dendrimers, yielding zero-generation dendrimers measuring between 200 and 400 nm. These dendrimers, featuring a higher concentration of functional groups on their external surface, effectively eliminated nickel ions from water.

3.4 Chitosan based nanomaterials

Chitosan nanoparticles, derived from shellfish and crustaceans like squid beaks, shrimp, prawns, and crabs, have several uses (Ahmed et al., 2023). This hydrophilic polymer has beneficial properties such as non-toxicity, biodegradability, biocompatibility, renewability, and biorenewability. Chitosan is often obtained by breaking down chitin under acidic conditions such as strong NaOH or enzymatic hydrolysis with chitin deacetylase. Its unique characteristics can be further modified chemically and mechanically to generate new functionalities, expanding its potential applications. The increasing presence of -NH_2 and -OH groups in chitosan, coupled with its excellent solubility in water and organic solvents, has attracted attention for its potential use as a chelating agent for pollutants like heavy metals and dyes in water purification processes (Bilal et al., 2022; Agha et al., 2024).

Chemical changes and chelation can add functional groups to chitosan's structure, increasing its sorption and selectivity properties. For instance, Dubey et al. (2016) produced carbon nanoparticles (CANPs) to remove Hg2+ ions from water, demonstrating an impressive adsorption capacity of 217.4 mg/g at 30°C. According to Saad et al. (2018), a nanocomposite made of ZnO and chitosan successfully removed lead, copper, and cadmium ions from water, exhibiting a strong predilection for

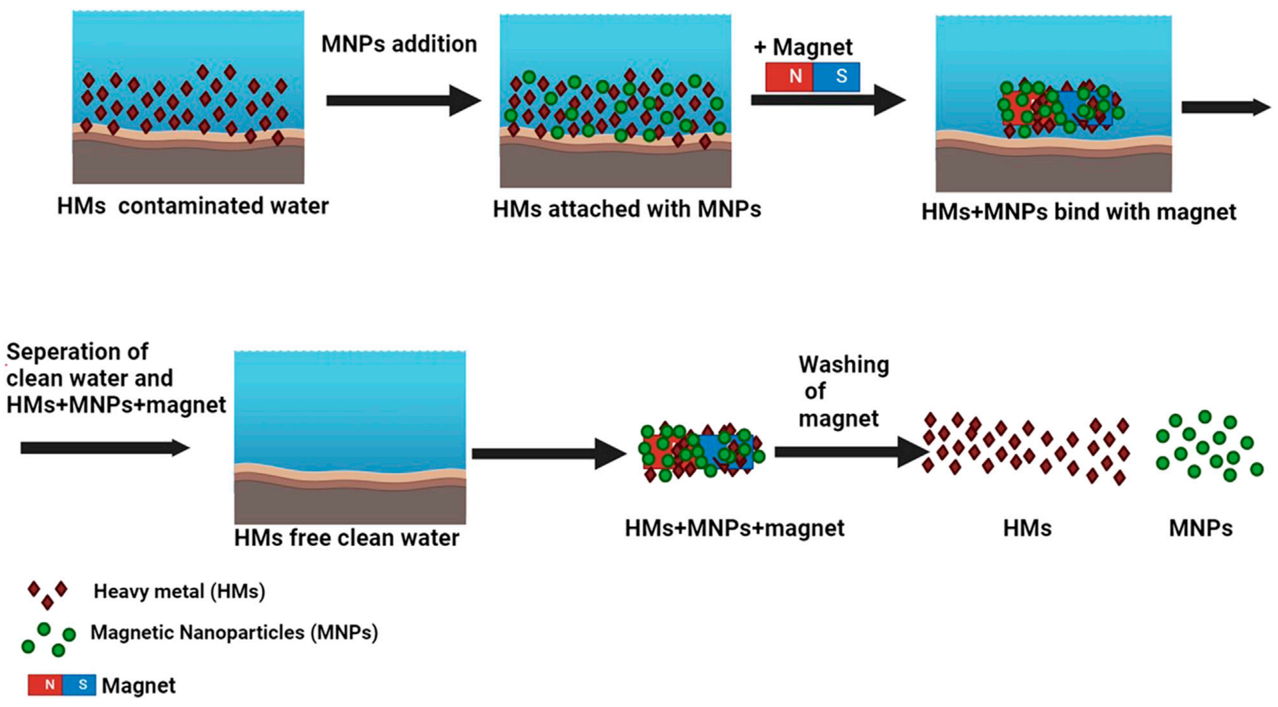

FIGURE 4
Illustration depicting the procedural steps involved in water purification utilizing MNPs.

Pb2+ ions, while adsorbing Cd2+ and Cu2+ ions at lesser rates. Similarly, a mixture of TiO_2 and chitosan nanoparticles efficiently absorbed copper and divalent lead ions (Razzaz et al., 2016).

Esmaeili and Khoshnevisan (2016) developed an alginate-functionalized chitosan nanoparticle composite, achieving a 94.9% removal of Ni2+ ions from water. Moreover, Yuan et al. (2018) engineered porous three-dimensional carbon materials using chitosan, exhibiting strong adsorption capabilities for Pb2+ and Cd2+ ions in aqueous environments. The adsorption mechanism involves coordination and electrostatic interactions with functional groups present in the carbon compounds derived from chitosan. Chitosan-based nanoparticles hold promise for various environmental applications, particularly in heavy metal removal from water, owing to their unique properties and versatile functionalities. Further research and innovation are crucial to enhance their effectiveness and advance their practical implementation in water treatment processes.

3.5 Magnetic nanomaterials

Magnetic nanoparticles, distinguished for their exceptional capacity to enhance toxic metal extraction and facilitate magnetic separation (Zaman et al., 2022), are extensively utilized in environmental remediation due to their excellent recyclability post-separation. As their dimensions decrease, significant alterations occur in their properties. Non-magnetic nanoparticles, possessing smaller surface areas and undergoing challenging separation processes, exhibit lower efficiency in water treatment compared to their magnetic counterparts (Ukhurebor et al., 2023). In contrast, magnetic nanoparticles, with substantial surface areas, lack toxicity, and easily disperse, prove to be reliable, efficient, and cost-effective water purifiers, particularly effective in removing heavy metals (Ukhurebor et al., 2023). Figure 4 illustrates the sequential steps involved in water purification with MNPs, highlighting the efficiency of MNPs in removing heavy metal impurities from water at each stage.

Iron oxide nanoparticles, widely acknowledged for their reusability, easy separability, and high adsorption capacity (Tao et al., 2023), play an indispensable role in various applications. Fe_3O_4 nanoparticles, with an adsorption capability of 36 mg/g, effectively remove divalent lead ions from water-based solutions (Nassar, 2010). Additionally, Fe3O4 nanoparticles have successfully extracted Cu (II), Pb (II), Mn (II), and Zn (II) ions from water in separate research projects. Changes in conditions influence the electrostatic interactions between these nanoparticles and the specific metals, consequently impacting their adsorption capacity (Yamini et al., 2023; K Zhang et al., 2023).

Table 6 provides a comprehensive analysis of magnetic nanomaterials utilized for the removal of heavy metals, offering detailed insights into their efficacy and mechanisms of action. This exploration sheds light on the diverse range of magnetic nanoparticles employed in heavy metal remediation strategies, highlighting their potential for environmental applications. Through a systematic examination, Table 6 elucidates the promising advancements and challenges in harnessing magnetic nanomaterials for efficient heavy metal removal.

Nanorods, nanowires, and nanotubes, owing to their larger surface area, demonstrate remarkable efficiency in removing heavy metals from wastewater and water. For instance, Fe_3O_4 nanorods exhibited adsorption capacities ranging from 76 to 127 mg/g for

TABLE 6 Magnetic nanomaterials for heavy metal removal: A detailed exploration (Suhasini & Thiagarajan, 2021; Targuma et al., 2021; Thakur & Kumar, 2023; Yamini and Devi Rajeswari, 2023; Yaseen et al., 2021; K Zhang et al., 2023; Zhu et al., 2016).

Nanomaterial	Mechanism of removal	Metal selectivity	Advantages	Disadvantages	Examples	Current status
Iron Oxide Nanoparticles (Fe3O4, γ-Fe_2O_3)	Adsorption, co-precipitation, magnetic separation	Broad (Pb, Cd, As, Hg, etc.)	High surface area, tunable properties, easy separation with magnet, reusable	Potential environmental risks, agglomeration, pH dependence	Magnetite nanoparticles, maghemite nanoparticles	Mature, widely researched, and commercially available
Cobalt Ferrite Nanoparticles ($CoFe_2O_4$)	Adsorption, surface complexation, magnetic separation	Pb, Cd, Ni, Co	High magnetic susceptibility, high adsorption capacity, good stability	Higher cost than iron oxides, potential toxicity	Cobalt ferrite nanoparticles	Emerging, promising due to high performance but requires further research on environmental safety
Nickel Ferrite Nanoparticles ($NiFe_2O_4$)	Adsorption, ion exchange, magnetic separation	As, Cu, Zn	High thermal stability, good chemical resistance, magnetically separable	Lower adsorption capacity than some other ferrites, potential toxicity	Nickel ferrite nanoparticles	The early stage of development requires further optimization and research on the toxicity
Carbon-Based Magnetic Nanomaterials (Fe3O4-Graphene Oxide, Fe3O4-CNTs)	Adsorption, chelation, magnetic separation	Broad (Pb, Hg, As, Cr, etc.)	Enhanced adsorption capacity, high surface area, good conductivity, magnetically separable	Complex synthesis has, higher cost than single-component materials	Fe3O4-GO composites, Fe3O4-CNT composites	Growing interest, is promising due to enhanced performance but requires further research on large-scale synthesis and cost reduction
Polymer-Magnetic Nanomaterials (Fe3O4-Chitosan, Fe3O4-PAMAM)	Adsorption, encapsulation, chelation, magnetic separation	Tailorable with functional groups (specific metal selectivity)	Biocompatible, easy functionalization, magnetically separable	Complex synthesis, potential environmental risks depending on the polymer component	Fe3O4-chitosan beads, Fe3O4-PAMAM dendrimers	The early stage of development, is promising for specific applications but requires further optimization and research on the environmental impact

Cu+2, Cd+2, Ni+2, Zn+2, Pb+2, and Fe+2 ions in water (H Karami, 2013; N Karami et al., 2024). However, the oxidation and aggregation tendencies of bare magnetic nanoparticles limit their practical value in water. Functionalizing the surface of magnetic nanoparticles enhances stability, increases adsorption capacity, and improves selectivity.

Various surface modifiers, such as carbonaceous, biomolecule, inorganic, organic, and polymer substances, have been utilized to modify magnetic nanoparticles' surfaces. Functionalization prevents aggregation and enhances interactions between metals and surfaces, including electrostatic, chemical bonding, and complex formation. Tailoring magnetic nanoparticles' surfaces to selectively bind hazardous metals through chelation significantly influences their selectivity and effectiveness in adsorbing pollutants. Additionally, capping with hydrophilic coatings like polyethylene glycol inhibits aggregation and increases surface area, further enhancing their adsorption capabilities.

3.5.1 Nanocomposite magnetic nanoparticles

Nanocomposite magnetic nanoparticles are recognized as a promising solution for heavy metal contamination due to their unique characteristics and versatile applications (Bui et al., 2021). Comprising a magnetic core enclosed in a composite material, these nanoparticles offer several advantages for efficiently extracting heavy metals from polluted water sources. One significant advantage is their heightened magnetic sensitivity, allowing for easy extraction using external magnetic forces (Hasanzadeh et al., 2017). This simplifies the cleanup process by facilitating the retrieval of nanoparticles along with attached heavy metal pollutants, enabling further treatment or disposal.

Moreover, the composite structure enables the integration of different adsorbent materials onto the magnetic core, allowing for precise customization of performance in removing specific heavy metals. Materials like activated carbon, graphene oxide, or chitosan can be incorporated to enhance adsorption efficiency (Abo Markeb et al., 2023).

Additionally, nanocomposite magnetic nanoparticles exhibit exceptional stability and reusability, making them cost-effective alternatives for prolonged cleanup efforts. The presence of a magnetic core ensures the nanoparticles remain suspended in water during remediation, preventing aggregation and ensuring consistent performance across multiple cycles. Recent research has demonstrated their effectiveness in removing various heavy metals, such as lead, cadmium, mercury, arsenic, and chromium (Hasanzadeh et al., 2017; Shahamati Fard et al., 2021; Joshi et al., 2022; Jjagwe et al., 2023; Mallick et al., 2023; Rani et al., 2023), indicating their potential for practical use in addressing environmental challenges.

Kim et al. (2013) synthesized flower-shaped Fe_3O_4/MnO_2 nanocomposite. The research focuses on the development and application of various metal ferrite nanocomposites for heavy metal removal from aqueous solutions. Firstly, an adsorbent exhibited superior adsorption capacity for Cd2+, Cu2+, Pb2+, and Zn2+ compared to Fe_3O_4 nanoparticles. Additionally, researchers synthesized metal ferrite magnetic nanoparticles with magnetic separation properties, represented by the general formula M (Fe_xO_y), where M denotes the metal atom forming divalent bonds. Several metal ferrites including copper ferrite ($CuFe_2O_4$), zinc ferrite ($ZnFe_2O_4$) (Tu et al., 2016; Tu et al., 2017), and manganese-zinc ferrite ($Mn_{0\cdot67}Zn_{0\cdot33}Fe_2O_4$) (Tu et al., 2013) have been developed for the removal of heavy metals. Specific studies highlighted the efficacy of $ZnFe_2O_4$ in eliminating lead ions, $CuFe_2O_4$ in removing molybdenum ions, and Mn-Zn ferrites in removing As5+, Cd2+, and Pb2+ ions. Furthermore, cobalt spinel ferrites ($CoFe_2O_4$ and $MnFe_2O_4$) synthesized via the co-precipitation method were utilized to remove divalent zinc ions with notable adsorption capacities (Asadi et al., 2020). Another study (Vamvakidis et al., 2020) demonstrated the effectiveness of a nanocomposite cobalt ferrite ($CoFe_2O_4$) modified with octadecylamine coating in adsorbing Cu2+ ions from aqueous solutions, with efficient separation and recovery processes. Overall, these findings illustrate the potential of metal ferrite nanocomposites as efficient adsorbents for heavy metal removal in water treatment applications.

Various magnetic nanocomposites, including metal oxides, have been developed for extracting heavy metals from water. For example, a Fe_3O_4/MnO_2 nanocomposite with a flower-shaped structure showed improved adsorption compared to iron oxide nanoparticles (Kim et al., 2013). Metal ferrite magnetic nanoparticles, such as $ZnFe_2O_4$ and $CuFe_2O_4$, have demonstrated a strong affinity for specific heavy metals, effectively removing them from aqueous solutions (Wang et al., 2021; Alshehri et al., 2024). Nanocomposite magnetic nanoparticles offer a promising method for addressing heavy metal contamination by providing effective removal, convenient retrieval, and exceptional stability. Further research and development in this area hold the potential to enhance the performance and scalability of these nanoparticles for broader environmental remediation initiatives.

3.5.2 Inorganic functionalized magnetic nanoparticles

Inorganic magnetic nanoparticles are increasingly being recognized as a viable method for tackling heavy metal pollution in several environmental contexts. The nanoparticles, made of magnetic substances like iron oxides or metal ferrites, have distinct characteristics that make them efficient adsorbents for removing heavy metals in water remediation procedures. An important benefit of inorganic magnetic nanoparticles is their ability to respond to magnetic forces, enabling them to be easily separated from water using external magnetic fields (Gangaraju et al., 2022). This enhances the retrieval of nanoparticles together with absorbed heavy metal contaminants, streamlining the process of cleaning up and allowing for further treatment or disposal.

Furthermore, inorganic magnetic nanoparticles demonstrate elevated surface area-to-volume ratios, which offer abundant active sites for the adsorption of heavy metals. The increased surface area facilitates effective interaction between the nanoparticles and heavy metal ions in water, resulting in fast adsorption rates and high removal efficiencies. Studies have demonstrated that certain kinds of inorganic magnetic nanoparticles, such as iron oxide nanoparticles (Fe_3O_4) and metal ferrites (e.g., $ZnFe_2O_4$, $CuFe_2O_4$), have a high attraction to certain heavy metals (El Messaoudi et al., 2024; Y Zhang et al., 2021). Fe3O4 nanoparticles have been employed to effectively eliminate lead (Pb), cadmium (Cd), and arsenic (As) ions from water solutions due to their exceptional adsorption abilities. Conversely, metal ferrite nanoparticles have exhibited distinct adsorption characteristics for various heavy metals, depending on their chemical compositions (Chandrani et al., 2024). For example, $ZnFe_2O_4$ nanoparticles have demonstrated a significant attraction to lead ions, whereas $CuFe_2O_4$ nanoparticles possess a notable ability to adsorb copper ions (Tu et al., 2017).

Modifying inorganic magnetic nanoparticles offers a versatile approach to increase their affinity for specific heavy metals. Applying organic ligands or polymers to these nanoparticles can improve their specificity and durability, thereby boosting their effectiveness in heavy metal removal. The magnetic nanoparticles can be altered using various inorganic elements such as silica, metals, nonmetals, and metal oxides. The coatings stabilize nanoparticles in water-based solutions and increase their chemical bond to particular ligands. The magnetic nanoparticles were modified by adding amorphous oxide shells made of Mn-Co. As a result, surfaces with substantial negative charges were formed at different pH values. These nanoparticles were modified to enhance their ability to bind to Cu (II), Cd (II), and Pb (II) ions (Ma et al., 2013). The reference provided the adsorption capacities for these ions as 481.2, 386.2, and 345.5 (Ma et al., 2013). According to the electrical properties of the atoms participating in the complexation reaction, the technique efficiently removed lead ions but zinc ions to a lesser extent. To influence the creation of stable complexes by highly ionic-potential metals, the adsorption sequence tracked the hydrated ionic radius of the metals.

Calcium carbonate, an inexpensive, non-toxic, and easily soluble chemical, belongs to the carbonate group of inorganic chemicals utilized to modify magnetic nanoparticles for recovering heavy metals from water. Despite its numerous advantages, constraints such sludge formation, restricted efficacy, and separation challenges hinder its widespread application in water and wastewater treatment (Fadia et al., 2021). These challenges can be reduced through the use of magnetic nanoparticles, which increase their adsorption capacity and facilitate their separation from the experimental media. Nanocomposites composed of magnetic mesoporous calcium carbonate were synthesized by Wang et al., 2020 via annealing after solvothermal treatment. The nanocomposites, measuring 50 nm in size and having an irregular spherical shape, efficiently eliminated Pb (II) and Cd (II) from water, with maximum adsorption capacities of 821 mg/g and 1179 mg/g, respectively. Inorganic magnetic nanoparticles have the potential to remove heavy metals due to their extensive surface area, specific affinity for heavy metals, and the capability to be controlled using magnets (A Islam et al., 2021; Islam et al., 2017). Further research and development are required to enhance the design and application of these nanoparticles for efficient environmental remediation.

3.5.3 Carbon materials magnetic nanoparticles

There have been significant breakthroughs made in the removal of heavy metals from aqueous solutions by the utilization of nano adsorbents, like graphene oxide and activated carbon. In order to improve the adsorption capacity of surface nano adsorbents, Danesh et al., 2016 carried out a study in which they investigated the efficacy of graphene oxide, iron oxide, and EDTA for the adsorption of lead ions. This improvement is attributed to the coordinating properties of ethylenediaminetetraacetic acid (EDTA) and the hydroxyl and carboxyl groups that are thought to be present in graphene oxide. Increased electrostatic interactions between the surface functional groups and hazardous metals are made possible as a result of these properties. By producing extremely effective Fe3O4 nano adsorbents that were treated with EDTA, Ghasemi et al., 2017 were able to attain adsorptive capacities that ranged between 71 and 169 mg/g for ions such as Hg2+, Ag+, Cd2+, Pb2+, Mn2+, and Zn2+. A nanocomposite with a peak adsorption capability of 28.8 mg/g for the removal of lead2+ was created by Li et al., 2020 by the synthesis of Fe_3O_4@C-SH nanoparticles. This was accomplished by functionalizing the nanoparticles with thiol (SH) groups.

Functional groups derived from organic sources have been explored to enhance the ability of magnetic nanoparticles to adsorb heavy metals. Ge and co-authors (Ge et al., 2012) synthesized Fe_3O_4 magnetic nanoparticles and functionalized them with 3-amino propyl triethoxysilane (APTES), acrylic acid (AA), and crotonic acid (CA) for the removal of metal ions. The use of the modified adsorbent demonstrated a preferential elimination sequence of metal ions, with decreasing reactivity observed in the order of Pb > Cu > Zn > Cd. Another study utilized EDTA-modified silica-coated magnetic nanoparticles to remove divalent mercury, with the addition of dithiocarbamate groups leading to increased hazardous metal removal and enhanced adsorption capability. The modification of silica-coated magnetic nanoparticles was done using glutathione to create the GSH/SiO_2/Fe_3O_4 nano adsorbent, specifically designed for removing lead ions from water (J Wang et al., 2024; P Xu et al., 2017). Lead ion adsorption was enhanced at higher temperatures and the magnetic properties of the adsorbent aided in its removal from the reaction mixture. The study used iron oxide nanoparticles treated with metformin and amine to remove copper ions from water. The addition of silica and 0.1 wt% metformin led to a significant reduction of 92% in copper ions (Ghaemi et al., 2015; Ghaemi, 2016). Meanwhile, Shen et al. (Shen et al., 2012; Shen et al., 2013) investigated the adsorption process of Cr6+ using tetraethylene pentaamine-modified magnetic nanoparticles. Their findings revealed that a decrease in electrostatic interaction and charge transfer on the resulting adsorbents facilitated the adsorption of Cr6+. Zhang et al., 2019 effectively extracted Cr6+ from water using nitrogen-doped Fe_3O_4 magnetic porous carbon modified with humic acid, achieving a mass of 130.5 mg/g due to the presence of surface functional groups. A nanocomposite comprising Fe_3O_4/SiO_2/chitosan and triethylenetetramine was capable of extracting Cr6+ from water, adsorbing 254.6 mg/g Cr6+ within 15 min (X Wang et al., 2020). Additionally, Shen et al., 2013 synthesized core-shell Fe_3O_4 nanoparticles with NH_2 magnetic nanoparticles, demonstrating the adsorption of Cr6+ and Cu2+ ions in both simultaneous and individual metal-ion systems (MISs). Changes in pH significantly impacted how well copper (Cu2+) and chromium (Cr6+) ions stuck (adsorbed) to the material. At low pH (2–4), electrostatic forces were the main driver of adsorption. However, as the solution became more acidic, the -NH2 groups changed their charge (protonated), reducing their ability to bind metal ions. Interestingly, Cu2+ adsorption still improved despite this change. Above pH 4, Cu2+ likely formed precipitates due to the attraction between negatively charged chromate ($HCrO_4$) and positively charged -NH3+ groups. Furthermore, competition between chromate and hydroxide (OH-) ions for binding sites weakened the adsorption as the pH rose. While other components present in low amounts or at higher pH levels didn't affect the process, this method proved effective for removing metal ions at low pH and high metal concentrations.

3.6 Metal-based nanomaterials for efficient heavy metal remediation

Metal oxides and metal-based nanomaterials play a significant role in heavy metal remediation due to their unique properties and high surface area-to-volume ratios, which make them efficient adsorbents for removing heavy metals from contaminated environments (Gupta et al., 2021; Ani and Egbosiuba, 2023; Bichave et al., 2023). These nanomaterials can be tailored to target specific heavy metals, offering a versatile and effective approach to remediation. Iron oxide (Fe_3O_4), titanium dioxide (TiO_2), and manganese dioxide (MnO_2) nanoparticles have been extensively studied for their ability to adsorb heavy metals through mechanisms like ion exchange, surface complexation, and precipitation (Bichave et al., 2023). For example, Fe_3O_4 nanoparticles have shown promising results in removing heavy metals like lead, cadmium, and arsenic from water systems.

These materials can be functionalized or modified with specific ligands or coatings to enhance their adsorption capacity and selectivity for target heavy metals. For instance, silver nanoparticles have demonstrated excellent antibacterial properties and can be utilized in conjunction with other nanomaterials for the removal of heavy metals and microbial contaminants from water sources (Alamier et al., 2023; Dutta et al., 2023). Table 7 presents an overview of nanoparticles and metal oxides utilized in the removal of heavy metals from water. It details their properties, efficiency, and mechanisms of action, providing valuable insights for environmental remediation strategies. This comprehensive compilation aids in understanding the diverse applications of nanomaterials in tackling heavy metal pollution in aqueous environments.

Regeneration: Additionally, the utilization of hybrid nanomaterials, which amalgamate metal oxides with organic compounds or polymers, engenders synergistic effects enhancing adsorption efficiency and stability (Babar et al., 2022). These hybrid materials offer tailored properties that mitigate challenges related to heavy metal contamination, such as pH sensitivity, competition from other ions, and environmental stability. Recent investigations (Raza et al., 2023; Vinoth and Wang, 2023) suggest that metallic and metal oxide nanoparticles hold promise in removing heavy metals from water. However, due to their inherent instability and difficulties in separation, pure metal nanoparticles are not ideal for use as adsorbents. Encapsulating or modifying the surface of nanostructured adsorbents improves their stability and facilitates their separation (Kanel et al., 2006). Zero-valent nanoiron Fe0 is biologically inert, exhibits stability in water treatment applications, boasts a substantial surface area, and demonstrates excellent adsorption capacity (Kanel et al., 2006). Consequently, some researchers have utilized Fe0 as a means to eliminate harmful metals from water (Kanel et al., 2006; Xiao et al., 2017; Xia et al., 2023). The oxygen present in metallic oxides reacts with aqueous pollutants, leading to their removal. Numerous studies worldwide

TABLE 7 Nanoparticles and metal oxides for the removal of heavy metals from water (Balakumar and Manivannan, 2021; Iqbal et al., 2022; Alhalili, 2023; Chakraborty et al., 2023; El-Sawy et al., 2023).

Metal Oxide/ Metal-Based nanomaterial	Mechanism of removal	Metal selectivity	Advantages	Disadvantages	Examples	Cost	Maturity
Iron Oxide (Fe2O3, Fe3O4)	Adsorption, photocatalysis	Varies based on type (e.g., Cr for Fe_3O_4)	High surface area, good recyclability, low cost	Can be pH-dependent, potential environmental risks	Magnetite (Fe_3O_4) for As, Pb, Cd	Low	High
Titanium Dioxide (TiO2)	Photocatalysis, adsorption	Broad, enhanced under UV light	High activity, good stability, self-cleaning	Requires UV light, potential toxicity concerns	Anatase TiO_2 for Pb, Hg, Cr	Medium	High
Zinc Oxide (ZnO)	Adsorption, photocatalysis	Broad, enhanced under UV light	High surface area, photoluminescence properties	Can be pH-dependent, potential toxicity concerns	ZnO nanoparticles for Pb, Cu, Cd	Medium	High
Aluminum Oxide (Al2O3)	Adsorption, ion exchange	High for As, P	High surface area, good stability, abundant	Lower capacity than some other oxides	Activated alumina for As, F	Medium	High
Manganese Oxide (MnO2)	Adsorption, oxidation	Broad, high affinity for As	High surface area, high redox potential	Can be unstable at low pH, potential environmental risks	Birnessite (MnO_2) for As, Pb, Hg	Medium	High
Cerium Oxide (CeO2)	Adsorption, oxidation	Broad, high affinity for arsenic	High surface area, good redox stability	Expensive, limited commercial availability	CeO_2 nanoparticles for As, Pb	High	Low
Silver Nanoparticles (Ag)	Antimicrobial activity, adsorption	Broad, especially antibacterial	High biocidal activity, good dispersibility	Expensive, potential environmental risks	Silver nanoparticles for bacterial disinfection and metal removal	High	Medium
Metal-Organic Frameworks (MOFs)	Adsorption, ion exchange	Tailorable for specific metals	High surface area, tunable porosity	Complex synthesis, limited stability	UiO-66 MOF for Pb, Cd	High	Low

have investigated various nano metal oxides, including ferric oxides such as hydrous ferric oxide, hematite (α-Fe_2O_3), goethite (α-FeOOH), maghemite (γ-Fe_2O_3), magnetite (Fe_3O_4), zinc oxides, cerium oxides, titanium oxides, aluminum oxides, and magnesium oxides, as well as hydrous manganese oxide and mixed-valence manganese oxide (Recillas et al., 2010; Wang et al., 2010; Wang et al., 2011; El Mouden et al., 2023). Hierarchically structured metal oxides are renowned for their high reactivity towards heavy metal ions, favorable surface-to-volume ratio, mechanical strength, and ease of regeneration. Fe^0 exhibits a higher absorption capacity than metallic nanoparticles. When combined with water, Fe^0 nanoscale zero-valent iron effectively eliminates 99% of pentavalent arsenic.

The plant *Syzygium jambos* exhibits a high adsorption capacity for Cr+6, reaching 983.3 mg/g. In a relevant study (Xiao et al., 2017), zero-valent iron (Fe^0) was synthesized from ferric chloride ($FeCl_3$) using this plant material. To ensure the stability of nano-iron particles, some studies incorporate stabilizing agents in conjunction with Fe^0. The chitosan carboxymethyl β-cyclodextrin containing Fe^0 acts as a biodegradable stabilizer that reduces Cu2+ and Cr+6 to Cu^0 and Cr3+, while also oxidizing Fe^0 to Fe3+(Sikder et al., 2014). In addition, bimetallic nanoparticles can eliminate heavy metals. The efficiency of removing divalent copper ions by kaolinite-embedded Fe/Ni nanoparticles is 99.8% (C Li et al., 2022; Zhan et al., 2021). Metal oxides possess the ability to effectively remove heavy metals from water. The metal oxide nanoparticles were categorized into magnetic and non-magnetic types. Copper, Manganese, Iron, Cerium, Aluminum, and Zinc oxides are frequently used to purify water contaminated with heavy metals. Sounthararajah et al., 2015 demonstrated that the process of single-system adsorption effectively eliminated a greater number of metals as a result of the competition for adsorption sites among many adsorbates. A sodium titanate-based nanofibrous adsorbent effectively eliminated Pb+2, Cu+2, Cd+2, Ni+2, and Zn+2 (Zhou et al., 2021). The CuO nanoparticles, produced via magnetron sputtering, exhibited a high absorption capacity of 37.02 mg/g for Pb2+ and 15.62 mg/g for Cr6+ in aqueous solutions (Sounthararajah et al., 2015).

3.7 Silica based nanomaterials

Silica-based nanomaterials are essential for cleansing water contaminated with heavy metals due to their carefully designed pore size, regulated surface properties, and large surface area. Modifying these nano adsorbents with thiol and amino groups improves their ability to selectively adsorb metals and increases their adsorption capacity (Sankareswaran et al., 2022; Trofymchuk et al., 2023). Due to their eco-friendly and non-toxic characteristics, they have become more widely used in water treatment applications. Studies have compared the effectiveness of functionalized and non-functionalized silica nano adsorbents in binding divalent ions such as lead, nickel, and cadmium (Y Li et al., 2019; Peralta et al., 2021). The materials evaluated included NH_2-functionalized silica gel, non-functionalized silica nanoparticles, and hollow silica spheres (Najafi et al., 2012). The modified versions showed adsorption capabilities of 96.80 mg/g for lead, 31.40 mg/g for nickel, and 40.74 mg/g for cadmium. Chemical changes using phenyl groups and 3-

aminopropyl were utilized on silica nanospheres to improve the adsorption and elimination of divalent copper ions.

Interestingly, adding amino groups increased copper ion adsorption. In a separate investigation, nitrilotriacetic acid altered silica gel to treat wastewater with two-valence lead, cadmium, and copper ions. The improved nano adsorbent adsorbs 76.23, 53.15, and 63.6 mg/g of Pb, Cd, and Cu in 2–20 min. The authors used silicon waste with kerf loss to create nanoporous silicon (NPSi) functionalized with 3-amino-propyl-ethoxysilane (APTES) via chemical etching and nanosilver. The functionalized nano adsorbent was investigated for hexavalent chromium Cr (VI) adsorption from water (Z Yang et al., 2020). The greatest adsorption capacity was 103.75 mg/g in 1 hour. Protonated amino groups reduced Cr (VI) to Cr (III) for adsorption. This improved nano adsorbent works after 5 adsorption cycles.

4 Environmental factors affecting the performance of nanomaterials

Nanomaterials have gained significant attention in environmental remediation due to their unique properties and potential applications in removing heavy metals from aqueous environments. However, the performance of these nanomaterials can be influenced by various environmental factors (Kolluru et al., 2021; Kumar & Kumar, 2023; Madkour et al., 2021; Solanki et al., 2024; J Yang et al., 2019). Understanding these factors is crucial for optimizing the efficiency and effectiveness of nanomaterial-based remediation strategies.

4.1 pH impact

The solution pH plays a crucial role in the interactions between nanomaterials and heavy metal ions. pH levels influence the surface charge of nanomaterials, consequently affecting their adsorption capacity. At lower pH values, increased proton reactions occur with nanomaterials like Nanoscale Zero-Valent Iron (NZVI), leading to a higher rate of conversion from H^+ to H_2, resulting in more reactive H^+ and faster reduction rates (Suazo-Hernández et al., 2023; Y Zhang et al., 2022). Under neutral pH conditions, surface coordination, electrostatic sorption, and precipitation become more robust, leading to enhanced removal rates. Several studies have investigated the influence of pH on the adsorption capacity of nanoscale zero-valent iron (NZVI). Zhang et al. (2023) and Zhao et al. (2021) observed a significant decrease in NZVI's adsorption ability under extreme alkaline or acidic conditions. This phenomenon can be attributed to the impact of pH on NZVI corrosion and its consequent reactive lifespan. Liu et al. (2014) explored the effect of pH on the removal efficiency of Hg(II) and Cr(VI) using pumice-supported NZVI in aqueous solutions. Their findings revealed that higher pH levels led to increased removal rates for Hg(II) but decreased removal rates for Cr(VI). Similarly, Wu et al. (2019) reported enhanced removal rates of Cr(VI) with FeS nanoparticles stabilized by sodium alginate at increasing pH levels (from 4.0 to 6.0). However, they also observed a decline in removal efficiency at a pH of 10.0. Xu and Zhao (2007) investigated the impact of pH on the immobilization of Cr(VI) in contaminated soil using carboxymethyl cellulose-stabilized NZVI. Lowering soil pH from 9.0 to 5.0 decreased Cr(VI) leaching from around 30%–20%. pH levels in aqueous solutions significantly influence the performance of nanomaterials, affecting their surface charge, reactivity, and adsorption capacity for heavy metals (Alli et al., 2023; Asmat-Campos et al., 2023; Assad et al., 2022; R Biswas et al., 2023).

4.2 Impact of contact duration

The length of time nanosorbents interact with metal ions plays a crucial role in the cost-efficient treatment of water or wastewater polluted with harmful heavy metals. Extended contact durations between pollutants and adsorbents enhance adsorption efficiency by prolonging the interaction between active chelation sites and the metals (Aghababai Beni and Jabbari, 2022; Ahmad et al., 2023; Areche et al., 2023). Usually, in the early stages of adsorption, the removal efficiency shows quick advancement, then progresses gradually. A study on the adsorption of divalent mercury ions onto carbon-based nanoparticles (CANPs) showed a significant increase in adsorption as the contact duration increased from 0 to 90 min (Dubey et al., 2016). The adsorption rate initially increased rapidly, then slowed down gradually, and finally stabilized at 90 min.

Another study examined how divalent cadmium and lead ions bind to the surfaces of composite materials made from magnetic nanoparticles (Hasanzadeh et al., 2017). Adsorption efficiency reached 91% within the initial 20 min of contact, achieving the maximum adsorption capacity of 48.54 mg/g for Cd(II) ions and 100% efficiency with a capacity of 53.35 mg/g for Pb(II) ions (Hasanzadeh et al., 2017).

4.3 Adsorbent dosage impact

The amount of pollutants eliminated is directly proportional to the dosage of adsorbent used in the adsorption process. The increase in dosage results in a greater number of active sites that can bind to heavy metals, hence improving the ability to absorb these metals (T Ahmed et al., 2023; Baby et al., 2022; Chandran et al., 2023; Li et al., 2021). Nevertheless, even though there is a beneficial impact, the effectiveness of active sites declines when the surface area becomes smaller, worsened by the clumping together of nanoparticles, finally limiting the ability to adsorb. Several research studies have examined how varying amounts of adsorbents affect the removal of heavy metals from water solutions (Kaur and Roy, 2021; Guo et al., 2022; Kumar & Kumar, 2023). An instance of using TiO_2-coated chitosan was to eliminate divalent copper and lead ions from water (Razzaz et al., 2016; Kashi et al., 2024). The concentration utilized for this procedure was 2000 mg/L. It was noted that exceeding the ideal dosage of nanosorbent resulted in the buildup of nanoparticles and reduction of surface area, which in turn diminished the ability to adsorb harmful metals.

Similarly, Huang et al. (Huang et al., 2017; Huang et al., 2019) showed that increasing the amount of adsorbent from 0.5 to 2 g/L enhanced the efficacy of Fe_3O_4@C nano adsorbent in eliminating lead ions from water, resulting in an increase in removal efficiency from 41% to 92%. Nevertheless, a higher dosage of the adsorbent led to a decrease in the efficiency of removal, decreasing from 41% to 22%. This fall can be due to the clustering of the active sites responsible for binding lead ions. In a separate investigation, Nithya et al. (K Nithya et al., 2018; R Nithya et al., 2021) conducted an experiment using superparamagnetic iron oxide nanoparticles at varying doses between 0.1 and 1.8 g. The objective was to eliminate Ni2+ from aqueous solutions within a 90-min timeframe. (Rad et al., 2014). The researchers discovered that the highest level of removal effectiveness, reaching 99%, was attained when using an adsorbent dosage of 0.2 g (K Nithya et al., 2018). The quantity of nanomaterials employed is a critical determinant affecting the efficacy of heavy metal ion removal. Multiple studies have identified the optimal quantities of adsorbents needed to achieve specific degrees of pollutant removal, aiding in the efficient and cost-effective utilization of nanomaterials. Arshadi et al., 2014 found that increasing the quantity of immobilized NZVI on sineguelas waste biomaterial from 0.05 to 0.15 g resulted in a rise in the clearance rate of Pb(II) from 15.6% to 89%. However, escalating the dosage further did not notably enhance the elimination effectiveness.

Fu et al., 2015 investigated how sepiolite-supported NZVI performed in removing Cr(VI) and Pb(II) from groundwater. Increasing the adsorbent quantity from 0.05 to 3.2 g/L improved the removal rates of Cr(VI) and Pb(II). The most effective dosage was determined to be 1.6 g/L, although clearance rates only showed a small improvement above this concentration. Zand et al., 2020 did a study using different quantities of TiO_2 nanoparticles for phytoremediation of soil contaminated with Cd. Higher dosages of TiO_2 NPs were found to enhance the absorption of Cd by Trifolium repens. Excessive doses led to a reduction in plant biomass as a result of toxicity.

4.4 The effect of temperature

The kinetics of adsorption processes incorporating nanoparticles are greatly affected by temperature. The temperature variations can influence the speed at which heavy metal ions are adsorbed, diffused, and desorbed on the surface of nanomaterials (J Liu et al., 2020). Elevated temperatures can promote the movement of metal ions and intensify their interaction with nanomaterials, leading to an augmentation in adsorption capacity (Shi et al., 2023). Nevertheless, high or low temperatures might induce alterations or clustering of nanomaterials, which can have a detrimental impact on their functionality (Behnam and Firouzi, 2023; Khorram Abadi et al., 2023). The temperature-dependent energy of reaction activity is a critical factor in the adsorption process. Temperature variations significantly affect the equilibrium adsorption capacity of nanomaterials. Elevated temperatures lead to a reduction in the interparticle spacing and expedite the redox reaction process (Yu et al., 2023). Dubey et al., 2016 investigated to evaluate the efficacy of chitosan-alginate nanoparticles in the removal of Hg(II) across a temperature range of 10°C–40°C. The results revealed an enhancement in removal efficiency with increasing temperatures, peaking at 30°C and subsequently declining gradually. Similar trends were consistently observed across various studies (Roostaee et al., 2022; Khorram Abadi et al., 2023; Morales et al., 2023). Nassar (Nassar, 2010) noted an increase in the adsorption of Pb(II) using Fe_3O_4 nanoparticles at elevated temperatures, particularly within the range of 298–328 K, indicative of an endothermic adsorption process. Furthermore, Liu et al. (1996) investigated the immobilization of Re(VII) in soil and groundwater employing starch-stabilized NZVI. They observed a positive correlation between temperature and immobilization efficiency, with higher temperatures ranging from 15°C to 45°C resulting in increased efficiency, consistent with the principles outlined in the Arrhenius equation.

4.5 Effect of ionic strength

A solution's ionic strength, or ion concentration, is an important determinant of nanomaterials' efficacy in heavy metal removal. According to Yang et al. (F Yang and Yang, 2022; G Yang et al., 2022), nanomaterials may have their adsorption effectiveness reduced in solutions with high ionic strength because metal ions compete more strongly with other ions in the solution. An increase in ionic strength may also affect nanomaterial performance by changing their stability and aggregation behaviour (L Kong et al., 2023; Q Kong et al., 2021). Adsorption processes rely on ionic strength, which quantifies the effect of extra ions on molecule adsorption onto the adsorbent surface (Y Liu et al., 2022; Musso et al., 2019), as it estimates the concentration of ions dissolved in a solution. To explore how experimental ionic strength affects chelation efficacy, ions like Cl– and Na + are commonly added to the solution. The concentrations and affinities of these extra ions can greatly impact the adsorption effectiveness.

The role of ionic strength in particle aggregation cannot be overstated when considering electrostatic interactions. Particles aggregate when ionic strength increases, which lowers electrostatic repulsion and, consequently, the number of available binding sites and the number of ions that can be adsorbed (Y Liu et al., 2022). Sodium chloride, at a concentration of 0.025 mM, enhanced the surface functional group dispersion of Fe_3O_4/SiO_2/GSH nanoparticles, which in turn promoted the adsorption of Pb2+ ions (P Xu et al., 2017). Increasing the sodium chloride concentration to 0.2 mM reduced lead ion adsorption, perhaps because it decreased the number of available chelation sites (P Xu et al., 2017). Hasanzadeh et al., 2017 showed that the nanocomposite surface's affinity for Cd2+ and Pb2+ ions over Na + ions remained constant, as heavy metal ion adsorption was unaffected even in the presence of 3 mol/L NaCl. These data highlight the sensitivity of the adsorption process to sodium chloride content, as well as other parameters that influence the adsorbent's affinity for the target adsorbate.

5 Navigating the nano-revolution: environmental impacts and challenges of nanomaterial-based heavy metal remediation

Although nanoparticles present promising opportunities for wastewater treatment due to their versatile features and ability to selectively remove various contaminants through mechanisms such as adsorption and photocatalysis, there are still some obstacles that need to be overcome (Elsaid et al., 2023). The exponential advancement of nanomaterials surpasses our comprehension of their potential environmental and health hazards (Table 8). Significant areas of knowledge that need to be addressed include the mechanisms by which nanomaterials are released, transported, and exhibit behavior in water systems. Furthermore, it is necessary to conduct thorough toxicological studies to investigate any negative health consequences at appropriate dosages. Membrane filtration, a

TABLE 8 Potential Environmental and Health Impacts of Nanomaterials (Ahmed et al., 2024; Babu et al., 2021; Elsaid et al., 2023; Roostaee et al., 2022; Yaqoob et al., 2020).

Category	Potential impact	Explanation	Example	Research needs
Environmental Impact	**Disruption of Ecosystems**	Due to their small size, nanoparticles can easily enter and accumulate in organisms, potentially disrupting their physiology and impacting ecosystems	Silver nanoparticles used in clothing may harm aquatic life if released during washing	- Better understand the long-term effects of nanomaterials on different organisms. - Develop methods to monitor nanomaterials in the environment
	Soil Contamination	Nanoparticles can bind to soil particles and potentially alter nutrient cycling and soil fertility	Landfills containing nanomaterials could contaminate surrounding soil	- Research the impact of nanomaterials on soil microbial communities. - Develop strategies to remediate soil contaminated with nanomaterials
	Water Contamination	Nanoparticles can enter water bodies through wastewater discharge or industrial processes, potentially harming aquatic life and impacting water quality	Fullerenes used in solar cells could leach into water if not properly disposed of	- Investigate the fate and transport of nanomaterials in water systems. - Develop methods to remove nanomaterials from wastewater
Health Impact	**Inhalation**	Inhaling airborne nanoparticles can lead to respiratory problems and inflammation	Workers in nanomaterial production facilities are at risk of inhaling nanoparticles	- Improve workplace safety regulations for handling nanomaterials. - Develop personal protective equipment for workers
	Skin Contact	Nanoparticles can penetrate the skin and cause irritation or allergic reactions	Consumers using cosmetics containing nanomaterials could experience skin problems	- Conduct thorough safety testing of nanomaterial-based consumer products. - Develop labeling guidelines for products containing nanomaterials
	Ingestion	Ingestion of nanomaterials through contaminated food or water can lead to gastrointestinal problems and potentially other health effects	Nanoparticles used in food packaging could migrate into food	- Investigate the potential for nanomaterials to migrate from food packaging to food. - Develop regulations for the safe use of nanomaterials in food packaging
	Unknown Long-Term Effects	The long-term health effects of exposure to nanomaterials are still largely unknown	The potential for nanomaterials to cause cancer or other diseases needs further investigation	- Conduct long-term studies to assess the health risks of nanomaterials. - Develop methods for monitoring human exposure to nanomaterials

current treatment technique, is hindered by issues such as pore obstruction and reduced effectiveness over time caused by fouling (Morales et al., 2023; Roostaee et al., 2022; Yaqoob et al., 2020). Likewise, the ability to be used again is a significant obstacle for nanosorbents. Optimally, these materials should effectively eliminate contaminants while facilitating straightforward post-treatment retrieval. The US Environmental Protection Agency (USEPA) has recognized crucial inquiries regarding the elimination of nanoparticles throughout the process of wastewater treatment. These factors encompass comprehending the processes involved in eliminating nanoparticles, their interactions with other pollutants, and the efficacy of conventional techniques such as coagulation and carbon adsorption. Moreover, it is necessary to develop tests in order to detect probable degradation products that are produced during the treatment process using these approaches. Continued research is essential to create economical and reliable methods for assessing the intricate characteristics of nanoparticles in wastewater treatment (Babu et al., 2021; Elsaid et al., 2023; Ahmed et al., 2024).

5.1 Advantages of nanomaterials

- High Efficiency and Selectivity: Due to their large surface area and unique functionalities, nanomaterials can effectively capture and remove even very low concentrations of specific heavy metals from aqueous solutions and soil.
- Versatility and Tunability: Different types of nanomaterials can be tailored to target various metals through surface modifications and functionalization, offering a highly adaptable approach.
- Potential *In-situ* Remediation: Certain nanomaterials can be directly injected into contaminated sites, enabling targeted and efficient decontamination without extensive excavation.

5.2 Challenges and environmental concerns

- Limited Understanding of Long-Term Impacts: The long-term fate and behavior of nanomaterials in the environment are still not fully understood, raising concerns about potential unintended consequences.

- Unforeseen Toxicity and Ecotoxicity: Some nanomaterials can exhibit toxicity towards organisms, potentially harming beneficial bacteria and disrupting ecosystems.
- Release and Persistence in the Environment: Accidental release or leaching of nanomaterials from treatment sites can lead to their accumulation in various environmental compartments, posing risks to water resources and food chains.
- Difficulties in Recovery and Reuse: Efficient and cost-effective methods for recovering and reusing spent nanomaterials after remediation are still under development, raising concerns about waste management.
- Regulatory Uncertainty: As nanotechnology is a rapidly evolving field, regulatory frameworks often struggle to keep pace, creating challenges for responsible development and application.

5.3 Mitigating the risks

Several strategies can be adopted to minimize the environmental impact of nanomaterial-based remediation:

- Environmental Design and Risk Assessment: Developing nanomaterials with inherent biodegradability or biocompatibility and conducting thorough risk assessments before large-scale application.
- Surface Modification and Coating: Coating nanomaterials with biocompatible and environmentally friendly materials can reduce their toxicity and enhance their stability.
- Development of Recovery Technologies: Investing in efficient and cost-effective methods for collecting and reusing spent nanomaterials is crucial for sustainable application.
- Improved Regulation and Collaboration: Strengthening regulatory frameworks and promoting collaboration between scientists, engineers, and policymakers is essential for responsible development and deployment.

5.4 The future of nanoremediation

Despite the challenges, nanotechnology holds immense potential for revolutionizing heavy metal remediation. Through ongoing research, development, and responsible implementation, the risks can be mitigated while harnessing the benefits of these transformative technologies. Public awareness, engagement, and transparent communication are all vital aspects of building trust and ensuring the responsible development and application of nanomaterial-based solutions for a cleaner and healthier environment.

6 Conclusion

In conclusion, the advancements in nanotechnology and nanoscience have heralded a new era in environmental engineering, offering many eco-friendly, cost-effective, and efficient materials for addressing pressing challenges such as heavy metal pollution in water. The unique physicochemical properties of nanomaterials make them highly promising for water treatment, particularly in removing heavy metals, owing to their high adsorption capacity and selectivity, even at low concentrations. Throughout this review, we have explored the efficacy of various nanomaterials, ranging from zeolites, polymers, chitosan, and metal oxides to metals, in extracting heavy metals from water under diverse environmental conditions. Moreover, the functionalization of nanomaterials has emerged as a strategic approach to enhance separation efficiency, stability, and adsorption capacity, achieved through the incorporation of molecules such as biomolecules, polymers, and inorganic materials.

However, despite the remarkable potential of engineered nanomaterials, several challenges and limitations persist, including issues related to aggregation, stability, mechanical strength, long-term performance, and scalability. Furthermore, nanomaterials' potential environmental and health impacts necessitate thorough investigation and consideration. In order to overcome these issues and create sustainable nanomaterial-based remediation techniques, focused efforts must be made in the future. This will require interdisciplinary collaboration, adherence to green chemistry principles, and comprehensive risk assessments to ensure nanomaterials' safe and effective deployment in heavy metal remediation at both laboratory and large-scale levels.

Further research endeavours are essential to optimize synthesis processes, enhance reusability and separation techniques, and minimize environmental impacts. By doing so, we can contribute to developing robust solutions for mitigating heavy metal pollution in water and safeguarding human health and the environment for future generations. In essence, while the journey towards harnessing the full potential of nanomaterials for heavy metal remediation may be challenging, it is a journey worth undertaking to improve society and preserve our planet's precious water resources.

Author contributions

AK: Conceptualization, Methodology, Supervision, Validation, Writing–original draft, Writing–review and editing. TM: Data curation, Formal Analysis, Investigation, Resources, Writing–original draft.

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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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