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Innovative Approaches in Nanomaterials for Efficient Heavy Metal Removal from Wastewater: A Scientific Review

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ABSTRACT

Heavy metal contamination of water resources poses a severe threat to human health and ecosystems due to the toxic nature and bioaccumulative potential of these pollutants. While adsorption has emerged as a promising technique for heavy metal removal, recent nanotechnology advancements have led to the development of highly efficient nanoadsorbents. This review provides a comprehensive overview of the latest progress in utilizing nanomaterials for heavy metal adsorption from wastewater. We delve into various types of nanoadsorbents, including metal oxides (e.g., TiO_2, Fe_3O_4), carbon-based materials (e.g., graphene, carbon nanotubes), and polymeric nanocomposites, highlighting their effectiveness in removing heavy metals such as lead, cadmium, chromium, and mercury. This review critically analyzes key factors influencing adsorption efficiency, including surface properties, pore structure, and the role of functional groups. Furthermore, we emphasize the crucial need for designing innovative reactor systems that enable the recovery and reuse of nanoadsorbents and adsorbed heavy metals, promoting sustainability and scalability for real-world applications. By integrating nanotechnology with adsorption processes, this review showcases the potential for developing highly efficient and sustainable solutions to mitigate the pressing issue of heavy metal pollution in water systems. This work aligns with the United Nations Sustainable Development Goals, aiming to promote safe water, sustainable industrial practices, efficient resource utilization, and environmental preservation.

Keywords: Nanomaterials; Heavy metals; Wastewater treatment; Adsorption; Nanoadsorbents; Wastewater remediation

1. INTRODUCTION

The rapid pace of industrialization and urbanization in recent decades has led to an alarming increase in the discharge of heavy metals into the aquatic environment. These heavy metals, including lead, cadmium, chromium, and mercury, pose significant threats to human health and ecological systems (Feisal *et al*. 2024; Vardhan *et al*. 2019). Unlike organic pollutants, heavy metals are non-biodegradable and persist in the environment, where they tend to bioaccumulate in living organisms. This bioaccumulation can lead to severe health issues, such as neurological disorders, organ damage, and various types of cancer (Vardhan *et al*. 2019; Jaishankar *et al*. 2014). Conventional wastewater treatment methods, such as chemical precipitation, ion exchange, and membrane filtration, often face limitations regarding efficiency, cost-effectiveness, and the generation of secondary wastes (Burakov *et al*. 2018; Baby *et al*. 2022; Wang and Chen 2009). The challenges associated with traditional methods necessitate exploring alternative and more efficient technologies for heavy metal removal. Emerging techniques aim to address these limitations and provide sustainable solutions to mitigate the impact of heavy metals on the environment. Among the various methods explored for heavy metal removal, adsorption has emerged as one of the most promising due to its high efficiency, simplicity, and cost-effectiveness (*Kausar et al*. 2022). Adsorption processes involve the adherence of heavy metal ions onto the surface of adsorbent materials, thereby removing them from the aqueous phase. Various adsorbent materials have been extensively studied for this purpose, including activated carbon, zeolites, and clay minerals. These materials are valued for their large surface areas and active sites, which facilitate the adsorption of heavy metal ions from contaminated water sources (Foo and Hameed 2010; Vijayaraghavan and Yun 2008; (Babel and Kurniawan, 2003). The versatility and adaptability of adsorption techniques make them suitable for a wide range of applications in wastewater treatment (Baby *et al.* 2022). Researchers continue to investigate and develop new adsorbent materials with enhanced properties to improve the efficiency of heavy metal removal.

Integrating nanotechnology into wastewater treatment has led to the development of innovative nanoadsorbents that offer superior performance in heavy metal removal (Kausar *et al.* 2022; Ali *et al.* 2023). Nanomaterials, characterized by their high surface area, unique physicochemical properties, and tunable functionalities, exhibit remarkable adsorption capacities, fast kinetics, and selectivity towards heavy metal ions(Alidokht *et al.* 2021; Siddeeg *et al.* 2021; Kunduru *et al.* 2017; Burakov *et al.* 2018; Qu *et al.* 2013). These properties make nanomaterials particularly effective in addressing the limitations of traditional adsorbents and enhancing the overall efficiency of the adsorption process. Various nanomaterials, including metal oxide nanoparticles, carbon-based nanomaterials, and polymer-based nanocomposites, have been explored for their potential in heavy metal adsorption. Integrating these nanomaterials into existing wastewater treatment systems holds promise for significantly improving the removal of heavy metals and reducing environmental pollution. This review aims to provide a comprehensive analysis of recent advancements in applying nanomaterials for heavy metal removal from wastewater. The review covers the various types of nanomaterials, their adsorption mechanisms, and the factors influencing their adsorption efficiency. To improve adsorption, recent developments have included the introduction of new adsorbents, hydrogels, membrane separation methods, photocatalysis, and electrodialysis. By examining the latest research and developments in this field, the review seeks to highlight the potential of nanotechnology in enhancing wastewater treatment processes and addressing the challenges posed by heavy metal contamination. Additionally, it discusses the practical applications of nanoadsorbents, potential environmental impacts, and future research directions to guide the development of sustainable and effective wastewater treatment technologies (Ali *et al.* 2023; Wang and Chen 2009).

2. PROPERTIES AND ADVANTAGES OF NANOMATERIALS

Nanomaterials possess several unique properties that enhance their effectiveness in removing heavy metals from wastewater. Their high surface area-to-volume ratio provides a greater number of active sites for adsorption, significantly boosting their capacity to adsorb heavy metals. Additionally, the surfaces of nanomaterials can be functionalized with various chemical groups, allowing for targeted removal of specific contaminants from complex wastewater matrices. Their nanoscale dimensions also enable rapid kinetics, quick adsorption of heavy metal ions, and reduce treatment times. Magnetic nanomaterials further facilitate easy separation from treated water using external magnetic fields, simplifying recovery and reuse. These properties result in higher reactivity, enhanced sorption capacities, and overall improved removal efficiencies compared to conventional adsorbents. Moreover, the ability to customize surface functionalization, the ease of separation and recovery, and the potential for cost savings and environmental sustainability make nanomaterials a superior choice over traditional methods for heavy metal removal. Table 1 highlights the key properties and advantages of nanomaterials for heavy metal removal, providing a concise overview of their benefits compared to traditional methods.

3. TYPES OF NANOMATERIALS FOR HEAVY METAL REMOVAL

3.1 Metal Oxide Nanomaterials

Metal oxide nanomaterials are highly effective for heavy metal removal due to their large surface area, high adsorption capacity, and tunable surface properties (Ali *et al.* 2023). Key examples include Iron oxide (Fe_3O_4) nanoparticles are widely used for their magnetic properties, which facilitate easy separation from water using an external magnetic field. They exhibit high adsorption capacities for metals such as arsenic, lead, and chromium due to their abundant surface hydroxyl groups (Vardhan *et al.* 2019; Siddeeg *et al.* 2021). Titanium dioxide (TiO_2) nanoparticles are known for their photocatalytic properties, which enhance their ability to remove heavy metals and degrade organic pollutants under UV light. TiO_2 has been effectively used to adsorb lead, cadmium, and zinc ions from water Vardhan *et al.* 2019), and Aluminum oxide (Al_2O_3) nanoparticles have a high surface area and can adsorb various heavy metals, including chromium and mercury. Their surface can be easily modified to improve selectivity and adsorption capacity (Siddeeg *et al.* 2021).

3.2 Carbon-based Nanomaterials

Carbon-based nanomaterials have gained significant attention due to their high surface area, unique pore structure, and functional groups that can effectively bind heavy metal ions. Types include, Graphene and its derivatives like Graphene oxide (GO), and reduced graphene oxide are renowned for their exceptional surface areas and the presence of oxygen-containing functional groups, which provide high adsorption capacities for heavy metals like lead, cadmium, and arsenic (Akchiche *et al.* 2021). Carbon Nanotubes are single-walled and multi-walled carbon nanotubes have high surface areas and strong adsorption affinities for various heavy metals. Their unique cylindrical structure allows for efficient adsorption and removal of contaminants (Burakov *et al.* 2018) and Activated carbon nanoparticles have high porosity and surface area, making them highly effective for adsorbing heavy metals such as mercury, lead, and chromium. Their surface chemistry can be tailored to enhance adsorption performance (Yang *et al.* 2019).

Table 1. Summary of properties and advantages of nanomaterials for heavy metal removal from wastewater

Category	Aspect	Details	References
Unique Properties	High Surface Area-to-Volume Ratio	Provides more active sites for adsorption, enhancing the capacity to adsorb heavy metals.	Kunduru *et al*. (2017)
	Functionalization Capability	Surfaces can be functionalized with chemical groups to target specific heavy metals.	Adeleye *et al*. (2016)
	Rapid Adsorption Kinetics	Quick capture of heavy metal ions from the aqueous phase, reducing treatment time.	Siddeeg *et al*. (2021)
	Magnetic Properties	Magnetic nanoparticles can be easily separated using an external magnetic field, facilitating recovery and reuse.	Akchiche *et al*. (2021)
	Enhanced Reactivity and Sorption Capacity	Small size and high reactivity lead to effective interaction with heavy metal ions, often resulting in higher sorption capacities.	Wang and Chen (2009)
Advantages over traditional methods	High Surface Area and Enhanced Removal Efficiency	A large number of active sites improves removal efficiency compared to conventional adsorbents like activated carbon and zeolites.	Burakov *et al*. (2018)
	Customizable Surface Functionalization	Tailorable functionalization improves adsorption capacity and selectivity for specific heavy metals.	Voisin *et al*. (2017)
	Rapid Adsorption Kinetics	Faster adsorption kinetics reduce treatment time compared to methods like chemical precipitation and ion exchange.	Duan *et al*. (2020)
	Easy Separation and Recovery	Magnetic nanoparticles allow for easy separation and reuse, reducing operational costs and environmental impact.	Vallinayagam *et al*. (2021)
	Cost-Effectiveness	High efficiency, rapid kinetics, and reusability lead to overall cost savings and reduced secondary waste management.	Yang *et al*. (2019)
	Environmental Sustainability	Can be designed to be environmentally friendly, aligning with sustainable and green technologies.	Rana *et al*. (2024)

3.3 Metal-based Nanomaterials

Metal-based nanomaterials include zero-valent metals, metal oxides, and metal sulfides, each offering distinct advantages. Nanoparticles of zero-valent metals like iron (nZVI) are effective in reducing and adsorbing heavy metals such as chromium (VI) and arsenic (III) from water. Their reactivity and surface properties facilitate rapid and efficient removal (Duan *et al*. 2020). Nanoparticles of metal sulfides, such as zinc sulfide (ZnS) and cadmium sulfide (CdS), exhibit a strong affinity for heavy metal ions due to their high surface areas and reactive sites. They are particularly effective in removing lead and cadmium from aqueous solutions (Wang and Chen 2009).

3.4 Polymer-based Nanomaterials

Polymer-based nanomaterials combine the properties of polymers and nanomaterials, enhancing their adsorption capacities and functionalities. The Functionalized polymer nanoparticles are designed with specific functional groups that interact strongly with heavy metal ions, improving adsorption efficiency. Examples include polymer nanoparticles functionalized with thiol, amine, or carboxyl groups (Voisin *et al*. 2017). The Polymer-based nanocomposites incorporate nanoparticles into a polymer matrix, combining the advantages of both components. They can be engineered to exhibit magnetic properties, enhancing separation and recovery after adsorption (Burakov *et al.* 2018; Karnwal and Malik 2024).

3.5 Bio-based Nanomaterials

Bio-based nanomaterials offer environmentally friendly and sustainable alternatives for heavy metal removal like the Nanocellulose derived from natural cellulose, nanocellulose exhibits a high surface area and can be chemically modified to enhance adsorption capacities. It is effective in removing heavy metals such as copper, lead, and mercury from water (Rana *et al.* 2024). Also, the Chitosan nanoparticles a biopolymer obtained from chitin, can be converted into nanoparticles with excellent adsorption properties for heavy metals. It is biodegradable, low-cost, and can be functionalized to target specific metal ions (Vallinayagam *et al*. 2021).

4. ADSORPTION MECHANISMS AND INFLUENCING FACTORS

4.1 Adsorption Mechanisms of Nanomaterials

The adsorption of heavy metals by nanomaterials occurs through various mechanisms, each influenced by the properties of the nanomaterial, the characteristics of the heavy metal ions, and the solution chemistry. The Ion exchange mechanism involves the exchange of heavy metal ions with ions present on the surface of the nanomaterials. For instance, nanomaterials with surface functional groups such as hydroxyl or carboxyl can exchange their hydrogen or sodium ions with heavy metal ions in the solution *(Kobielska et al.* 2018). The Surface complexation in which heavy metal ions form stable complexes with the functional groups on the nanomaterial's surface. This process often involves the coordination of metal ions with oxygen, nitrogen, or sulfur-containing groups, leading to strong adsorption (Burakov *et al*. 2018). Further, the Electrostatic attraction of nanomaterials with charged surfaces can attract and adsorb heavy metal ions of opposite charge. The efficiency of this mechanism is highly dependent on the pH and ionic strength of the solution *(Kunduru et al.* 2017). Also the precipitation in some cases, heavy metal ions can precipitate on the surface of nanomaterials as insoluble compounds. This is particularly common for metals like lead and chromium, which can form hydroxides or oxides upon interaction with nanomaterials (Topare and Wadgaonkar 2023).

4.2 Factors Influencing Adsorption Efficiency

The efficiency of nanomaterials in removing heavy metals from wastewater is influenced by several factors the Solution pH, the adsorbent dosage, initial metal concentration, contact time, and temperature. The pH of the solution affects the surface charge of nanomaterials and the speciation of heavy metal ions. Optimal pH ranges are necessary to maximize adsorption efficiency (Siddeeg *et al.* 2021). The adsorbent dosage for the amount of nanomaterial used influences the availability of active sites for adsorption. Increasing the dosage generally enhances the adsorption capacity up to a certain limit (Vardhan *et al*. 2019). The higher initial concentrations of heavy metal ions can increase the driving force for adsorption but may also lead to saturation of active sites, thus affecting the overall efficiency (Akchiche *et al.* 2021). Further, the duration of contact between the nanomaterial and the heavy metal solution impacts the adsorption kinetics. Sufficient contact time is necessary to reach equilibrium adsorption (Kunduru *et al*. 2017). The temperature can also influence the adsorption process, with higher temperatures potentially increasing the adsorption rate and capacity due to enhanced diffusion of metal ions (Burakov *et al*. 2018).

4.3 Surface Properties

The surface properties of nanomaterials play a crucial role in determining their adsorption capacity and selectivity towards heavy metal ions. A higher surface area provides more active sites for adsorption, enhancing the adsorption capacity (Vallinayagam *et al*. 2021). The size and distribution of pores in nanomaterials affect the accessibility of heavy metal ions to the active sites. Properly tailored pore structures can facilitate efficient mass transport and adsorption (Kobielska *et al*. 2018). The presence of functional groups such as hydroxyl, carboxyl, and amino groups on the surface of nanomaterials enhances their interactions with heavy metal ions, leading to improved adsorption capacity and selectivity (Dash *et al*. 2024).

5. REACTOR DESIGN AND RECOVERY OF ADSORBED HEAVY METALS

5.1 Importance of Reactor Design

Effective reactor design is crucial for the practical implementation of nanomaterials in large-scale industrial applications. Key considerations include: Mixing efficiency ensuring uniform mixing of nanomaterials with the wastewater to maximize contact and adsorption efficiency (Yang *et al.* 2019). Flow dynamics designing reactors that optimize flow dynamics to enhance mass transfer and minimize resistance to adsorption (Rana *et al*. 2024). Also, the scalability of developing scalable reactor designs that can handle varying volumes of wastewater while maintaining high adsorption efficiency (Duan *et al*. 2020).

5.2 Recovery of Adsorbed Heavy Metals

The recovery of adsorbed heavy metals is important for both economic and environmental reasons. The efficient recovery methods, such as magnetic separation or chemical desorption, allow for the reuse of nanomaterials, reducing operational costs (Vallinayagam *et al*. 2021). Also the ability to recover and recycle valuable heavy metals, such as gold, silver, and platinum, from wastewater can provide additional economic benefits (Akchiche *et al*. 2021).

6. SYNTHESIS AND FUNCTIONALIZATION TECHNIQUES

6.1 Synthesis Techniques

Various synthesis techniques have been employed to produce nanoadsorbents with tailored properties for heavy metal removal like the sol-gel method. This technique involves the hydrolysis and condensation of metal alkoxides to form a gel-like network, which is then dried and calcined to produce nanomaterials with high surface area and controlled porosity (Dash *et al*. 2024). The hydrothermal synthesis, in this method, involves the crystallization of nanomaterials from aqueous solutions at high temperatures and pressures, allowing for the production of well-defined nanostructures (Rana *et al*. 2024). Also, the Co-precipitation technique, in this metal salts are precipitated simultaneously from the solution by the addition of a precipitating agent, resulting in the formation of nanoparticles with high purity and homogeneity (Kobielska *et al.* 2018).

7. FUNCTIONALIZATION TECHNIQUES

Functionalization of nanomaterials enhances their adsorption properties by introducing specific functional groups or modifying surface characteristics. Such as surface modification in which the nanomaterials can be functionalized with various chemical groups, such as thiol, amine, or carboxyl groups, to improve their affinity for heavy metal ions (Burakov *et al*. 2018). The polymer coating with polymers can enhance their stability, dispersibility, and adsorption capacity. Polymers such as polyethyleneimine (PEI) and polyaniline (PANI) are commonly used for this purpose (Yang *et al*. 2019). Also, the magnetic particles within nanomaterials facilitate easy separation and recovery from wastewater using an external magnetic field (Duan *et al*. 2020).

8. ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

8.1 Environmental Impact

The environmental impact of using nanomaterials for heavy metal removal must be carefully considered to ensure sustainability. Assessing the potential toxicity of nanomaterials to aquatic organisms and human health is crucial. Non-toxic and biodegradable nanomaterials are preferred to minimize adverse environmental effects (Rana *et al*. 2024). Also, the proper disposal and recycling methods should be implemented to prevent the release of spent nanomaterials into the environment. Recycling strategies can reduce waste generation and improve sustainability (Vallinayagam *et al*. 2021).

8.2 Economic Feasibility

The economic feasibility of using nanomaterials for heavy metal removal depends on several factors such as the cost of synthesis. Developing cost-effective synthesis methods for nanomaterials is essential to make the technology economically viable for large-scale applications (Akchiche *et al*. 2021). Operational costs by minimizing these costs, including energy consumption and chemical usage, can enhance the economic feasibility of nanomaterial-based treatment processes (Dash *et al*. 2024). Also, the recovery of valuable metals from wastewater can offset the costs of treatment and provide additional economic benefits (Siddeeg *et al.* 2021).

9. CASE STUDIES AND APPLICATIONS

Recent advancements in nanomaterials for heavy metal removal from various wastewater types underscore their significant potential for enhancing treatment efficiency. In the textile industry, which often discharges heavy metals such as chromium, copper, and zinc, graphene oxide nanomaterials have been demonstrated to effectively remove up to 98% of chromium ions, showcasing their suitability for large-scale applications (Dash *et al*. 2024). For the electroplating industry, known for high concentrations of nickel, cadmium, and lead in wastewater, iron oxide nanoparticles have proven effective, removing up to 95% of nickel and cadmium ions, thus highlighting their industrial applicability (Wang and Chen 2009). Urban runoff, which can contain heavy metals like lead, copper, and zinc, has been treated with carbon nanotubes that showed high adsorption capacities, removing over 90% of lead and copper ions, making them appropriate for municipal wastewater treatment (Duan *et al*. 2020). In sewage treatment plants, which face challenges with trace amounts of heavy metals, chitosan nanoparticles have been used to adsorb up to 85% of mercury and arsenic ions, significantly improving treatment efficiency (Vallinayagam *et al*. 2021). Agricultural runoff, often contaminated with pesticides and heavy metals, has been addressed using titanium dioxide nanomaterials, which can both degrade pesticides and adsorb heavy metals, offering a dual-function solution (Rana *et al*. 2024). Finally, for acid mine drainage containing high concentrations of arsenic, lead, and mercury, magnetic nanomaterials have been investigated, showing high adsorption capacities for arsenic and lead and allowing for easy separation and recovery due to their magnetic properties (Yang *et al.* 2019). This collective research illustrates the diverse applications and effectiveness of nanomaterials in improving wastewater treatment across various industries and environmental conditions. Table 2 summarizes recent advancements in the use of nanomaterials for heavy metal removal from various types of wastewaters, highlighting their effectiveness and application areas.

Table 2. Overview of nanomaterials used for heavy metal removal

Study	Nanomaterial	Heavy Metals/Contaminants	Results
Dash *et al*. (2024)	Graphene oxide	Chromium, Copper, Zinc	Up to 98% removal of chromium ions
Wang and Chen (2009)	Iron oxide nanoparticles	Nickel, Cadmium, Lead	Up to 95% removal of nickel and cadmium ions
Duan *et al*. (2020)	Carbon nanotubes	Lead, Copper, Zinc	Over 90% removal of lead and copper ions
Vallinayagam *et al.* (2021)	Chitosan nanoparticles	Mercury, Arsenic	Up to 85% removal of mercury and arsenic ions
Rana *et al*. (2014)	Titanium dioxide	Pesticides, Heavy Metals	Degradation of pesticides and adsorption of heavy metals
Yang *et al*. (2019)	Magnetic nanoparticles	Arsenic, Lead, Mercury	High adsorption capacities and easy separation

While nanomaterials have demonstrated significant potential in laboratory settings, scaling them up for industrial use poses substantial challenges. The high cost of large-scale production can limit their practical application in wastewater treatment. Future research should prioritize developing cost-effective synthesis methods and scalable production techniques. Green synthesis methods, such as those using plant extracts or other natural sources, could reduce both costs and environmental impact (Ying *et al.* 2022). Additionally, enhancing scalability through techniques like continuous flow synthesis could bridge the gap between lab research and industrial deployment. Evaluating the environmental impact and safety of nanomaterials is also essential. It is important to understand how these materials behave, move, and their toxicity in the environment to ensure their safe use in wastewater treatment. Some nanomaterials are toxic to aquatic organisms and may pose risks to human health through bioaccumulation (Adeleye *et al.* 2016). Comprehensive risk assessments and the development of guidelines for safe use and disposal are essential. Research should also focus on creating biodegradable or less toxic nanomaterials to minimize environmental risks. Integrating nanomaterials with existing wastewater treatment systems can improve overall treatment efficiency. Exploring hybrid systems that combine traditional methods like coagulation, flocculation, and biological treatment with nanotechnology could enhance heavy metal removal. For example, integrating nanomaterials with membrane filtration systems can boost heavy metal removal efficiency and reduce membrane fouling as shown in Fig. 1 (Sheoran *et al.* 2022). Developing modular, adaptable systems that can be seamlessly incorporated into existing infrastructure will support the adoption of nanotechnology in wastewater treatment facilities. Regulatory frameworks and policies must be established to ensure the safe use and disposal of nanomaterials. Collaboration among researchers, industry stakeholders, and policymakers is vital to address the regulatory challenges associated with nanomaterial applications in wastewater treatment. Implementing standardized testing protocols and environmental impact assessments will ensure the safe and effective use of these materials. Additionally, policies that encourage the development and adoption of sustainable nanotechnologies can drive innovation and commercialization.

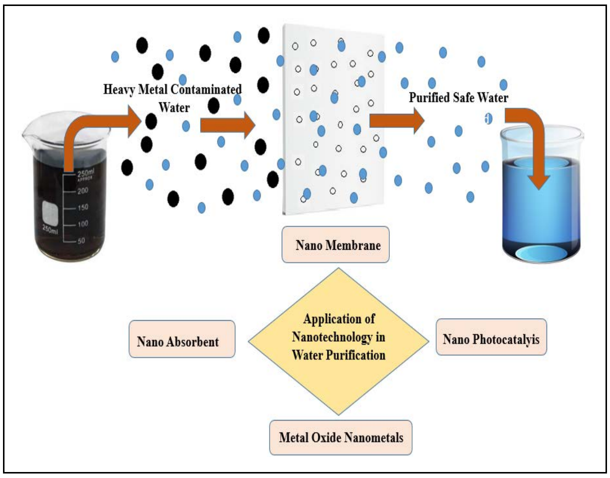

Fig. 1: Nanotechnology based methods for water purification

Nanomaterials have emerged as highly effective tools for the advanced removal of heavy metals from wastewater, offering innovative solutions to environmental contamination challenges. Among these, titanium dioxide (TiO_2) nanoparticles stand out for their exceptional performance in lead removal, attributed to their large surface area and potent photocatalytic properties. This allows TiO_2 nanoparticles to degrade lead ions effectively under UV light, transforming them into less harmful substances. Similarly, sulfur-modified graphene oxide and magnetic nanoparticles have shown considerable efficacy in mitigating mercury toxicity through dual mechanisms of adsorption and reduction, which convert mercury into less toxic forms. Iron oxide nanoparticles are particularly notable for their superior performance in cadmium removal due to their high adsorption capacities and the formation of stable cadmium complexes, which are needed for treating wastewater contaminated by electroplating processes.

Further research is expanding in the application of nanomaterials to target a broader spectrum of toxic and carcinogenic metals, such as chromium, arsenic, and selenium. Advances in green synthesis methods, which leverage natural resources for nanoparticle production, are enhancing the sustainability and cost-effectiveness of nanomaterial production. Additionally, the development of hybrid nanomaterials that combine carbon-based structures with metal oxides is proving to be advantageous, as these hybrids offer synergistic effects that improve both performance and economic viability. Functionalization techniques, which involve modifying nanomaterials with specific organic molecules or metal ions, further enhance their selectivity and efficiency in targeting particular contaminants. Numerous case studies corroborate the effectiveness of these nanomaterials in various wastewater treatment scenarios. For example, TiO_2 nanoparticles have been successfully used to address lead contamination in industrial effluents (Rana *et al*. 2024), while iron oxide nanomaterials have proven effective in removing cadmium from electroplating wastewater (Wang and Chen 2009). These studies, along with others (Siddeeg *et al.* 2021; Kobielska *et al.* 2018; Kunduru *et al.* 2017), underscore the versatility and robustness of nanomaterials in tackling diverse heavy metal contamination issues. Such findings highlight the significant potential of nanomaterials to revolutionize wastewater treatment and address complex environmental and health challenges associated with heavy metal pollution.

The use of nanomaterials for wastewater treatment presents several challenges and limitations. One major concern is their potential toxicity and environmental impact, as nanomaterials can interact with biological systems at the molecular level, potentially causing unintended health and ecological effects. To mitigate these risks, long-term studies on their environmental fate and behavior are necessary, and the development of safer, biodegradable, or naturally-derived nanomaterials is crucial (Ethaib *et al.* 2022). Additionally, cost and scalability issues pose significant barriers to the widespread adoption of these technologies; high synthesis costs and difficulties in scaling up production need to be addressed through cost-effective methods, such as green synthesis and bulk production techniques, supported by collaborations among academia, industry, and government (Gupta *et al*. 2009). The long-term stability and performance of nanomaterials in real-world applications are also critical, as factors like chemical degradation and fouling can affect their efficiency over time. Research should focus on enhancing stability through surface modifications and the development of composite materials. Future research opportunities include the development of cost-effective and scalable synthesis methods, such as microwave-assisted and biogenic synthesis, and the exploration of new nanomaterials and functionalization techniques to improve adsorption capacities and selectivity. Greener synthesis methods using plant extracts or waste materials can reduce environmental impact, while hybrid nanomaterials combining different types can offer synergistic benefits. Integration of nanomaterials with existing wastewater treatment systems, such as membrane filtration, can enhance overall efficiency and reduce operational costs. Finally, advanced characterization techniques like high-resolution electron microscopy and X-ray photoelectron spectroscopy are essential for optimizing nanomaterial design and performance. Table 3 provides an integrated view of the current challenges and potential future directions in the use of nanomaterials for wastewater treatment.

10. CONCLUSION

The application of nanomaterials for heavy metal removal from wastewater represents a significant breakthrough in environmental engineering. Their advanced properties, such as high surface area, enhanced reactivity, and the ability to be engineered at the nanoscale levels, allow for efficient and effective removal of toxic heavy metals, which traditional methods often struggle to address. The high adsorption capacities and rapid kinetics of nanomaterials promise to improve the performance and efficiency of wastewater treatment processes, offering a potential paradigm shift towards more effective and sustainable solutions. However, the successful large-scale implementation of nanomaterial-based technologies presents several challenges. These include the need for cost-effective production methods, the development of scalable processes, and a thorough understanding of the environmental impact of nanomaterials throughout their lifecycle. To realize the full potential of nanomaterials in industrial wastewater treatment, future research must focus on overcoming these limitations. This involves not only advancing the synthesis and optimization of nanomaterials but also designing innovative reactor systems and recovery strategies that enhance their performance while minimizing environmental risks. As industrial activities continue to grow and contribute to increasing levels of heavy metal contamination in water resources, the need for advanced and efficient treatment technologies becomes ever more critical. Nanomaterial-based technologies offer a promising avenue for addressing these challenges, potentially leading to more effective, sustainable, and economically viable solutions. Heavy metal-containing wastewater gets treated by technologies such as adsorption, chemical precipitation, ion flotation, ion exchange, electrodialysis, membrane filtration, biosorption, coagulation/flocculation, and photocatalysis. Nanomaterial-based technologies provide solutions that enhance water quality and reduce pollution, which is in line with the Sustainable Development Goals (SDGs) of the UN, especially SDG 6, which highlights the significance of clean water and sanitation. These developments also help achieve SDG 13 (Climate action) by developing innovations that can reduce environmental contamination and SDG 12 (Responsible consumption and production) by encouraging sustainable industrial practices. By investing in research and development to refine these technologies and tackle associated challenges, we move closer to achieving safer and cleaner water resources for communities worldwide, ultimately contributing to the protection of public health and the environment.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

David Daneesh Massey: Conceptualization, methodology, original manuscript draft and editing.
P. Susan Verghese: Conceptualization, manuscript review, and writing the conclusion.
Mahima Habil: Manuscript review and editing.
Ram Kumar Saraswat: Manuscript review and editing.

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