Advanced Materials and Emerging Technologies for Heavy Metal Removal from Wastewater: Mechanisms, Performance Evaluation, Sustainability, and Future Perspectives

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Abstract - The contamination of wastewater by heavy metals has been become a very serious global environmental problem, mainly due to rapid industrialization, fast urban expansion, and more intensive agricultural practice. These persistent and non-biodegradable metals, such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), and nickel (Ni), are easily to bioaccumulate and biomagnify, causing high risk to both ecological systems and human healths. Their complex physicochemical property, speciation behavior and mobility in aquatic system makes the removal process more complicated, especially under different pH and redox condition and also in present of many competing ions. Conventional treatment technologies like chemical precipitation, ion exchange, membrane filtration, and electrochemical method are widely using; however, they are facing many limitations, for example producing too much sludge, having very high operation cost, serious problem of membrane fouling, and low efficiency when heavy metal exist in trace concentration. All of this is showing the needs for developing more advanced solutions.

In the last years, more attentions was focused on nanomaterials, bio-derived adsorbent and hybrid intelligent system because of their higher surface areas, better selectivity and possibility of regeneration. Metal oxide nanoparticle, magnetic nanocomposite, biochar-based material and functionalized biopolymer have been show superior adsorption capacity and removal efficiency for many type of heavy metals. New emerging technologies, such as photocatalysis, electrocoagulation, microbial fuel cell, membrane bioreactor and AI-assisted optimization, are also improving treatment performance and overall sustainability. Mechanistic understandings by adsorption isotherm, kinetic model and thermodynamic evaluation is very important for optimize system design and for scaling-up from lab to real application.

Even though a lot of progress has been done, many challenge are remain, especially about validation in real wastewater, removal of many metals at the same time, long-term stability of material, toxicity assessment of nanomaterials, and pilot-scale application in industry. Future perspective is pointing to the development of smart multifunctional material, better integration into circular economy concept, strategy for resource recovery, adoption of Industry 4.0 technology, and stronger regulatory framework, which together will promoting more sustainable and cost-effective heavy metal remediation system soon.

Keywords: Heavy metal removal; Wastewater treatment; Nanomaterials; Bio adsorbents; Magnetic nanocomposites; Adsorption mechanisms; Photocatalysis; Electrocoagulation; Artificial intelligence optimization; Sustainability.

1. INTRODUCTION

The contamination of wastewater by heavy metals has been recognized as a very significant global environmental issues, which is mainly due to the accelerated industrialization, urban developing, and more higher agricultural practices. These metals is non-biodegradable in nature, they can persist for long time in the environment, and have ability to bioaccumulate inside the food chains, therefore presenting long lasting risks to both ecological system and human healths. The complexity of heavy metal pollutions and its environmental behaviors are requiring a multifaceted remediation strategies that integrate innovative material and treatment technology (Abdullayev et al., 2024). The increasing industrial discharges have more intensified concern about sustainable water management, especially in the metallurgical sector (Chalaris et al., 2023).

Industrial effluent still remain the most dominant sources of heavy metal contamination in aquatic system. The key contributor includes metallurgy, mining and smelting operation, electroplating, batteries manufacturing, metal finishing process, textile processing,ando chemical industry (Chalaris et al., 2023;

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Oladimeji et al., 2024). Agricultural runoff which containing phosphate fertilizer and pesticides also introduce many trace metal into water body (Hamzah et al., 2025). In addition, the improper disposed of industrial sludges and electronic wastes is worsening the contamination level. The diversity of the sources and the variability in wastewaters composition is making the selection of effective treatment strategy more complicated (Hussein Abduraboh Ahmed & Hussein Mohammed Alqardai, 2021).

Heavy metal, such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), and nickel (Ni), is showing significant toxicity even in very minimal concentration. Their persistence and bioaccumulative natures can leading to severe neurological, renal, carcinogenic and other systemic health effect in human, and also disrupting the aquatic ecosystem (Oladimeji et al., 2024). The non-biodegradable character of this metals is necessitate more advanced remediation technology which can achieving high removal efficiency (Onyenanu & Onyenanu, 2025).Growing environmental awareness and public health concerns have led to increasingly stringent regulatory standards for permissible heavy metal concentrations in drinking water and industrial effluents. Industries must comply with discharge limits to prevent ecological degradation and health hazards. However, meeting these standards remains challenging due to fluctuating contaminant concentrations and complex wastewater matrices (Purevjav et al., 2025). The need for effective and scalable treatment technologies is therefore more pressing than ever (Kumar et al., 2026; Nemeș et al., 2026).

Traditional techniques, including chemical precipitation, ion exchange, and membrane filtration, have been extensively employed; however, they frequently encounter constraints such as elevated expenses, the production of sludge, and the potential for secondary pollution (Renu et al., 2017; Saluja et al., n.d.). To address these issues, recent research has focused on sustainable and high-performance alternatives. Bioadsorbents derived from natural materials provide eco-friendly and cost-effective solutions (Gupta et al., 2015; Zhang, 2025). Adsorbents based on agricultural waste further support circular economy principles while enhancing adsorption efficiency (Ganesapillai et al., 2026; Hamzah et al., 2025).

Nanotechnology has also transformed heavy metal remediation by introducing nanomaterials with improved surface area, reactivity, and selectivity (Hussein et al., 2025; Vidu et al., 2020). Innovations such as thin-film nanocomposite membranes and reverse osmosis systems have shown enhanced separation efficiency for heavy metal ions (Kapepula & Luis, 2024; Mohamad et al., 2023). Additionally, biochar-based materials have emerged as sustainable adsorbents with dual environmental benefits (Khamkar & Mehta, 2025). The integration of artificial intelligence to optimize treatment parameters further improves operational efficiency and sustainability (Shofia et al., 2025).

Together, these advancements signify a paradigm shift toward integrated, sustainable, and technology-driven wastewater treatment systems. The ongoing processes of research and development are essential for the establishment of solutions that are environmentally sustainable, economically feasible, and compliant with regulatory standards for the removal of heavy metals from wastewater. (Gahrouei et al., 2024; Nemeș et al., 2026).

Fig -1: Schematic Representation of Heavy Metal Contamination in Wastewater: Sources, Impacts, Treatment Technologies, and Future Perspectives

2. Heavy Metals in Wastewater: Characteristics and Challenges

2.1 Physicochemical Properties of Major Heavy Metals

Industrial wastewater frequently contains significant concentrations of heavy metals, including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), and nickel (Ni). These metals are distinguished by their elevated atomic weights, substantial densities, persistence in the environment, and resistance to biological degradation. Their toxicity depends not only on the total concentration but also on the oxidation state and chemical form. Chromium predominantly exists in two oxidation states: trivalent [Cr(III)] and hexavalent [Cr(VI)]. Among these, hexavalent chromium [Cr(VI)] is characterized by significantly greater toxicity and enhanced mobility in comparison to trivalent chromium [Cr(III)]. Additionally, mercury can occur in elemental, inorganic, or organic forms, and each of these forms shows different environmental behavior.

The solubility, ionic radius, redox potential, and complexation ability of these metals influence their interaction with water matrices and adsorbent materials. Surface charge, coordination chemistry, and affinity toward ligands determine the removal efficiency during the treatment process. The persistence and chemical stability of the metals contribute to long-term contamination in aquatic systems (Oladimeji et al., 2024; Onyenanu & Onyenanu, 2025).

2.2 Speciation and Mobility in Aquatic Systems

Speciation refers to the distribution of a metal among different chemical forms in water, including free ions, inorganic complexes, organic complexes, and particulate-bound species. The speciation of heavy metals is significantly affected by various factors, including pH, redox potential, temperature, dissolved oxygen levels, and the presence of competing ions. For example, acidic conditions generally increase the solubility and mobility of metals like Cd and Pb, while alkaline conditions may promote precipitation as hydroxides.

Redox reactions can significantly alter toxicity and mobility, especially for chromium and arsenic. Transformation between oxidation states affects not only environmental persistence but also treatment efficiency. Mobility is more governed by adsorption–desorption equilibrium with sediments and organic matter. Therefore, an understanding of speciation is essential for selecting appropriate remediation strategies (Hussein et al., 2025; Purevjav et al., 2025).

2.3 Bioaccumulation and Biomagnification

The capacity of heavy metals to bioaccumulate within living organisms and to biomagnify throughout the food chain represents one of the most significant environmental issues. Bioaccumulation occurs when organisms absorb metals faster than they can eliminate them, resulting in gradually increasing concentrations in their tissues. Biomagnification refers to the progressive increase of metal concentration at higher trophic levels.

Metals like mercury and cadmium are especially prone to biomagnification, posing severe risks to aquatic organisms and humans who consume contaminated fish or water. Chronic exposure can lead to neurological disorders, kidney damage, carcinogenic effects, and developmental abnormalities. The ecological persistence of these metals necessitates efficient removal strategies to prevent long-term environmental and health impacts (Oladimeji et al., 2024; Qasem et al., 2021).

2.4 Challenges in Heavy Metal Removal

Despite the availability of multiple treatment technologies, several challenges hinder effective heavy metal removal from wastewater.

- Low Metal Concentrations: Heavy metals often exist in trace concentrations (ppm or ppb level), making detection and efficient removal technically demanding.
- Complex Wastewater Matrices: Industrial effluent frequently contains mixed pollutants, including organic compounds, suspended solids, and multiple metal ions that compete for adsorption sites (Chalaris et al., 2023).
- pH Sensitivity: The efficiency of adsorption, precipitation, and membrane-based processes is highly dependent on pH, which influences metal speciation and surface charge interactions (Kapepula & Luis, 2024).
- Interference from Competing Ions: The presence of calcium, magnesium, sodium, and other background ions can reduce selectivity and adsorption efficiency.
- Sludge Generation and Secondary Pollution: Conventional methods may produce toxic sludges requiring further treatment (Saluja et al., n.d.).
- Economic and Scalability Constraints: High operational costs, membrane fouling, and regeneration limitations restrict the large-scale implementation of advanced technologies (Nemeș et al., 2026).

The development of advanced materials and integrated treatment systems capable of achieving high selectivity, stability, and sustainability under real-world wastewater conditions is essential for addressing these challenges (Gahrouei et al., 2024; Hussein et al., 2025).

Fig -2: Characteristics and Environmental Challenges of Heavy Metals in Wastewater: Speciation, Bioaccumulation, and Removal Constraints

3. Conventional Technologies for Heavy Metal Removal

Traditional treatment methodologies have been employed for an extended period to eliminate heavy metals from industrial effluents. These methods are generally well established and widely implemented at industrial scale; however, they also present several technical and environmental limitations (Nemeş et al., 2026; Oladimeji et al., 2024).

3.1 Chemical Precipitation

Chemical precipitation is a widely used method for removing heavy metals. This technique entails transforming dissolved metal ions into insoluble compounds, such as hydroxides, sulfides, or carbonates, by introducing precipitating agents. The resulting precipitates are then separated by sedimentation or filtration. This method is more effective at relatively high metal concentrations and is widely used in the metallurgical and electroplating industries (Onyenanu & Onyenanu, 2025; Qasem et al., 2021).
Despite its simplicity and cost-effectiveness, chemical precipitation often generates large volumes of toxic sludge that require further treatment and safe disposal. Additionally, the process efficiency is very pH-dependent and can be less effective when metal concentrations are low (Renu et al., 2017; Saluja et al., n.d.).

3.2 Ion Exchange

Ion exchange involves the reversible exchange of metal ions in wastewater with more benign ions attached to a solid resin matrix. Synthetic resins and natural zeolites are commonly used as ion-exchange materials. This method provides high selectivity and is especially suitable for removing trace concentrations of heavy metals (Qasem et al., 2021).
However, the process can be very expensive due to the cost of resins and regeneration chemicals. Fouling, reduced efficiency when competing ions are present, and disposal of regenerant solutions are other challenges (Nemeş et al., 2026; Purevjav et al., 2025).

3.3 Membrane Filtration (RO, NF, UF)

Membrane technologies, including reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF), have become increasingly significant owing to their elevated separation efficiency and capacity to proficiently eliminate dissolved metal ions. Reverse osmosis operates using a semi-permeable membrane that retains heavy metal ions while allowing water molecules to pass through (Kapepula & Luis, 2024).
Advances in thin-film nanocomposite membranes have improved permeability, selectivity, and resistance to fouling (Mohamad et al., 2023). Membrane systems can achieve high removal efficiencies even at low concentrations; however, they require high operational pressure, consume significant energy, and are susceptible to membrane fouling and scaling (Purevjav et al., 2025; Shofia et al., 2025).

3.4 Electrochemical Methods

Electrochemical techniques, including electrocoagulation and electrodeposition, use electrical current to destabilize and remove metal ions from wastewater. These methods can achieve rapid treatment with relatively low chemical usage and are effective for a wide range of metals (Onyenanu & Onyenanu, 2025).
However, high energy requirements, electrode passivation, and operational costs can limit their large-

scale application. Additionally, secondary sludge formation remains a concern (Oladimeji et al., 2024).

3.5 Limitations of Conventional Technologies

Although conventional technologies are widely applied, they exhibit several important limitations, including:

- Generation of hazardous sludge that requires disposal
- High operation and maintenance costs
- Low efficiency at low metal concentrations
- Risk of secondary pollution
- High sensitivity to pH and competing ions

These constraints have prompted the search for more advanced, sustainable, and high-performance materials and technologies (Abdullayev et al., 2024; Gahrouei et al., 2024).

4. Advanced Materials for Heavy Metal Removal

The limitations of traditional methods have accelerated research into advanced materials with greater adsorption capacity, improved selectivity, and enhanced sustainability. Recent developments span nanotechnology, bio-based materials, and hybrid smart systems (Hussein et al., 2025; Kumar et al., 2026; Vidu et al., 2020).

4.1 Nanomaterials

Nanomaterials offer a high surface area, tunable surface chemistries, and superior adsorption performance compared to conventional adsorbents.

Metal Oxide Nanoparticles (Fe_3O_4, TiO_2, ZnO)

Metal oxide nanoparticles, specifically Fe_3O_4, TiO_2, and ZnO, exhibit a significant attraction to heavy metal ions due to the presence of numerous surface hydroxyl groups and reactive sites. Magnetic Fe_3O_4 nanoparticles are especially attractive since they enable easy separation by an external magnetic field (Hussein et al., 2025; Vidu et al., 2020).

Carbon-Based Materials

The exceptional adsorption capabilities of graphene oxide, carbon nanotubes (CNTs), and activated carbon can be attributed to their substantial surface area, π-π interactions, and the presence of functional groups that enhance metal binding (Vidu et al., 2020; Zaimee et al., 2021). Surface modification further increases selectivity and capacity.

Magnetic Nanocomposites

Magnetic nanocomposites combine adsorption efficiency with easy recovery, thereby reducing operational complexity. These materials integrate a magnetic core with a functional shell to improve stability and reusability (Kumar et al., 2026; Zaimee et al., 2021).

Surface Functionalization Strategies

Functionalization with amine, carboxyl, thiol, or sulfonic groups enhances metal-binding affinity and selectivity. Tailoring surface chemistry improves adsorption under different pH and ionic conditions.

4.2 Bio-Based and Green Materials

Sustainable materials derived from natural resources have gained significant attention because they are eco-friendly and cost-effective.

Biosorbents (Algae, Fungi, Bacteria)

Biological materials possess functional groups such as hydroxyl, amino, and carboxyl that bind heavy metals very efficiently. Algae-based nanostructured materials have shown improved adsorption performance (Devi, 2025). The biosorption mechanism and factors influencing it are widely studied (Gupta et al., 2015; Zhang, 2025).

Agricultural Waste-Derived Adsorbents

Agricultural by-products, such as oil palm waste and various biomass residues, present a cost-effective and sustainable option for the adsorption of heavy metals. The principles of a circular economy are upheld by these materials, which also possess significant potential for commercialization (Hamzah et al., 2025; Ganesapillai et al., 2026). Biochar-based adsorbents also exhibit high porosity and good adsorption efficiency (Khamkar & Mehta, 2025).

Biopolymers (Chitosan, Alginate)

Natural polymers such as chitosan and alginate demonstrate strong chelation abilities due to their numerous functional groups. These biodegradable materials offer environmentally friendly treatment options (Gupta et al., 2015; Qasem et al., 2021).

4.3 Hybrid and Smart Materials

Hybrid materials integrate multiple functionalities to enhance performance and selectivity.

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Metal-Organic Frameworks (MOFs)
Metal-organic frameworks (MOFs) exhibit significant porosity and customizable architectures, which render them highly suitable for the selective adsorption of heavy metals. (Zaimee et al., 2021; Kumar et al., 2026).
Covalent Organic Frameworks (COFs)
COFs offer good structural stability and customizable functional groups for target metal binding, representing the next generation of adsorbents (Kumar et al., 2026).
Polymer Nanocomposites
Polymer-based nanocomposites combine mechanical stability with higher adsorption capacity, thereby improving durability and reusability (Gahrouei et al., 2024).

Stimuli-Responsive Materials
Smart materials that can respond to changes in pH, temperature, or magnetic fields allow for controlled adsorption and regeneration, thereby improving operational efficiency (Hussein et al., 2025; Shofia et al., 2025).
Overall, the transition from conventional technology to advanced and sustainable materials demonstrates a paradigm shift toward high-efficiency, eco-friendly, and economically viable solutions for heavy metal removal from wastewater (Abdullayev et al., 2024; Nemeș et al., 2026).

Fig-3: Classification of Advanced Materials for Heavy Metal Removal: Nanomaterials, Bio-Based Adsorbents, and Hybrid Smart Systems

5. Emerging Technologies

The growing limitations of conventional treatment methods have accelerated the development of emerging technologies that offer higher efficiency, selectivity, and sustainability in heavy metal removal (Gahrouei et al., 2024; Nemeș et al., 2026).

5.1 Advanced Oxidation Processes (AOPs)
Advanced oxidation processes involve the generation of highly reactive species such as hydroxyl radicals (•OH), which can transform or immobilizing heavy metal species, especially when combined with reduction pathways. Even though AOPs are more widely applied for organic pollutants, hybrid AOP–adsorption systems have demonstrated better performance in complex wastewater matrices (Shofia et al., 2025). The integration of oxidation and reduction reactions can facilitate valence state transformation, enhancing the subsequent removal efficiency (Onyenanu & Onyenanu, 2025).

5.2 Photocatalytic Removal
Photocatalytic systems use semiconductor materials like TiO_2 and ZnO under light irradiation to generate reactive species that promote redox reactions. In heavy metal remediation, photocatalysis can be used to reduce toxic metal ions (for example, Cr(VI) into Cr(III)) into less harmful and more easily precipitated forms (Vidu et al., 2020; Hussein et al., 2025). Nanostructured photocatalysts have improved light absorption, surface activity, and reusability, making them promising candidates for more sustainable treatment applications.

5.3 Electrocoagulation
Electrocoagulation employs sacrificial electrodes to generate coagulant species in situ, which destabilize dissolved metal ions and facilitate their aggregation and removal. This technique reduces chemical consumption and is very effective across a broader pH range (Oladimeji et al., 2024). However, electrode passivation and energy consumption remain important operational challenges (Onyenanu & Onyenanu, 2025).

5.4 Membrane Bioreactors (MBRs)
Membrane bioreactors integrate biological treatment with membrane filtration, combining biodegradation with physical separation. Although primarily applied to organic contaminants, MBR systems can also assist in heavy metal removal when coupled with biosorption or bioaccumulation mechanisms (Purevjav et al., 2025).

Recent advances in membrane materials, including thin-film nanocomposites, have improved selectivity and fouling resistance (Mohamad et al., 2023).

5.5 Microbial Fuel Cells (MFCs)

An innovative approach is represented by microbial fuel cells, which have the capacity to treat wastewater while concurrently generating electricity. In this system, electroactive microorganisms facilitate redox reactions that contribute to metal ion reduction and removal (Shofia et al., 2025). MFCs offer potential for energy-efficient remediation, aligning with the circular wastewater management concept (Ganesapillai et al., 2026).

5.6 AI-Assisted Treatment Optimization

Artificial intelligence (AI) and machine learning algorithms are increasingly being applied to optimize treatment parameters, predict adsorption performance, and improve operational efficiency. AI-based models assist in process control, material selection, and scaling strategies, which reduce costs and enhance sustainability (Saluja et al., n.d.; Shofia et al., 2025). The integration of AI with nanotechnology-driven systems represents a next-generation approach for heavy metal remediation (Kumar et al., 2026).

6. Removal Mechanisms

Understanding removal mechanisms is very important for designing efficient materials and optimizing treatment systems (Qasem et al., 2021; Zaimee et al., 2021).

6.1 Adsorption (Physical and Chemical Adsorption)

Adsorption is the most widely studied mechanism for heavy metal removal.

- Physical adsorption (physisorption) involves weak van der Waals forces and is generally reversible.
- Chemical adsorption (chemisorption) involves stronger covalent or coordination bonds between metal ions and functional groups on the adsorbent surface.

Nanomaterials and bio-based adsorbents show enhanced adsorption due to high surface area and numerous active sites (Vidu et al., 2020; Gupta et al., 2015).

6.2 Ion Exchange

Ion exchange transpires when ions of metal present in a solution substitute the ions that are exchangeable on the surface of the adsorbent. This mechanism is common in functionalized polymers, zeolites, and biopolymers such as chitosan (Qasem et al., 2021; Zaimee et al., 2021).

6.3 Surface Complexation

v This mechanism is dominant in biosorbents and nanocomposites (Zhang, 2025; Devi, 2025).

6.4 Electrostatic Interaction

The efficiency of adsorption is significantly influenced by the electrostatic attraction that exists between surfaces of adsorbents carrying a negative charge and metal ions that possess a positive charge. This mechanism is highly pH-dependent, as pH affects surface charge and metal speciation (Renu et al., 2017).

6.5 Reduction and Precipitation Mechanisms

Some materials promote redox reactions that convert toxic metal species into less soluble forms, making precipitation easier. For example, photocatalytic and electrochemical systems can reduce Cr(VI) to Cr(III) (Hussein et al., 2025; Vidu et al., 2020).

6.6 Photocatalytic Degradation

In photocatalytic systems, light-induced electron–hole pairs produce reactive species that reduce or immobilize heavy metals. This mechanism increases detoxification and supports a combined oxidation–adsorption strategy (Hussein et al., 2025).**Performance Evaluation**

Evaluating heavy metal removal performance requires systematic investigation of adsorption parameters, equilibrium models, kinetics, and thermodynamics (Nemeș et al., 2026; Qasem et al., 2021).

6.7 Adsorption Parameters

- **Effect of pH:** pH significantly influences metal speciation and surface charge, thereby affecting adsorption capacity (Renu et al., 2017).
- **Contact Time:** Determines the equilibrium time and rate-controlling steps of adsorption (Zaimee et al., 2021).
- **Adsorbent Dosage:** Higher dosage increases available binding sites but may reduce adsorption capacity per unit mass due to site aggregation (Gupta et al., 2015).

- **Initial Metal Concentration:** Influences driving force for mass transfer and saturation behaviour (Qasem et al., 2021).

6.8 Isotherm Models

Isotherm models describe equilibrium interactions between adsorbate and adsorbent:

- **Langmuir Isotherm:** Assumes monolayer adsorption on homogeneous surfaces.
- **Freundlich Isotherm:** Empirical model for heterogeneous surfaces.
- **Temkin Isotherm:** Accounts for adsorbent–adsorbate interactions and heat of adsorption.

These models are widely applied in heavy metal adsorption studies (Renu et al., 2017; Zaimee et al., 2021).

6.9 Kinetic Models

Kinetic models elucidate the mechanisms and rates associated with adsorption processes. T

- he pseudo-first-order model posits that the rate of adsorption is directly proportional to the number of unoccupied sites available.
- In contrast, the pseudo-second-order model indicates that the rate-limiting step is attributed to chemisorption.
- **Intraparticle diffusion model:** Evaluates diffusion-controlled processes.

Such models are essential for understanding adsorption dynamics (Qasem et al., 2021; Gupta et al., 2015).

6.10 Thermodynamic Parameters

Thermodynamic analysis provides insight into feasibility and nature of adsorption processes:

- **$\Delta G°$ (Gibbs Free Energy):** Indicates spontaneity of adsorption.
- **$\Delta H°$ (Enthalpy Change):** Determines whether the process is endothermic or exothermic.
- **$\Delta S°$ (Entropy Change):** Reflects randomness at the solid–solution interface.

Thermodynamic evaluations help assess stability and scalability of advanced adsorbents (Zaimee et al., 2021; Nemeș et al., 2026).

Overall, the integration of emerging technologies, mechanistic understanding, and comprehensive performance evaluation is essential for advancing sustainable heavy metal remediation systems (Abdullayev et al., 2024; Gahrouei et al., 2024).

7. Sustainability and Environmental Impact

The transition towards sustainable wastewater treatment systems are essential to minimize environmental burden while maintaining high removal efficiencies. Recent researches emphasize on the integration of eco-friendly material, circular resource utilizations, and energy-efficient process to ensure long-term environmental protections (Ganesapillai et al., 2026; Kumar et al., 2026).

7.1 Regeneration and Reusability

Regeneration and reusabilities is a critical parameter in assessing the sustainability of adsorbent and advance materials. Efficient regeneration reduce operational cost and waste generations. Magnetic nanocomposite, biochar-based material, and functionalized polymer has demonstrated a promising regeneration performance through chemical, thermal or magnetic recovery method (Hussein et al., 2025; Khamkar & Mehta, 2025). However, repeated regeneration cycle may reduce adsorption capacities due to structural degradations or surface fouling (Zaimee et al., 2021).

7.2 Life Cycle Assessment (LCA)

Life cycle assessment provide a systematic frameworks to evaluate the environmental impact of material and treatment system from raw material extractions to disposals. LCA help to identified energy-intensive step, carbon emission, and waste generation, supporting the development of more greener treatment technology (Ganesapillai et al., 2026). Sustainable nanomaterial must be evaluated not only for it performance but also for environmental footprints across their life span (Kumar et al., 2026).

7.3 Green Synthesis Approaches

Green synthesis strategy aims to minimized hazardous chemical, energy consumptions, and waste during material productions. Biosynthesized nanoparticle and algae-based nanostructured material offer an environmentally-benign alternative to chemically synthesized adsorbent (Devi, 2025). The use of agricultural wastes and biomass-derived material further support sustainable productions pathway (Hamzah et al., 2025).

7.4 CostCost-Effectiveness Analysis

Economic feasibilities remain a decisive factor for industrial adoption. Although advance nanomaterials provide high removal efficiency, production cost and scalability challenge may limits commercialization (Nemeș et al., 2026). Low-cost bioadsorbent and agricultural waste-derived materials has demonstrated competitive adsorption performances with reduced capital investments (Gupta et al., 2015; Hamzah et al., 2025).

7.5 Scale-Up Challenges

Laboratory-scale successes do not always translate to industrial application. Challenge includes material stabilities under real wastewater condition, membrane foulings, regeneration efficiencies, and process integrations (Gahrouei et al., 2024). Additionally, maintaining performances in large-scale continuous system require optimization of hydrodynamic, reactor designs, and operational parameter (Purevjav et al., 2025).

8. Comparative Analyses

A comparative evaluation of different materials and technologies provides insight into their practical applicability and performance efficiency, but many factors are often overlooked in real conditions.

8.1 Comparison of Materials and Technologies

Traditional techniques, including precipitation and ion exchange, are generally regarded as economically viable for the treatment of wastewaters characterized by elevated metal concentrations. However, these methods frequently produce substantial quantities of sludge and additional secondary waste, which necessitate subsequent disposal (Qasem et al., 2021). Membrane technologies are characterized by their elevated selectivity and effective separation performance. Nevertheless, these technologies are associated with increased operational expenses and are susceptible to issues related to fouling (Kapepula & Luis, 2024).

Nanomaterials and hybrid systems show superior adsorption capacities and better selectivity toward specific metal ions, yet they require careful environmental and economic assessment due to possible toxicity, synthesis complexity, and regeneration difficulties (Vidu et al., 2020; Hussein et al., 2025).

8.2 Removal Efficiency (%)

Removal efficiency varies widely depending on the material type, target metal ion, initial concentration, and operating conditions. Nanomaterials, MOFs, and functionalized adsorbents frequently achieve removal efficiencies of more than 90% under optimized laboratory conditions (Zaimee et al., 2021; Kumar et al., 2026). However, their performance usually decreases in complex real wastewater matrices, where competing ions, organic matter, and fluctuating pH reduce the overall removal percentage.

8.3 Adsorption Capacity (mg/g)

Adsorption capacity is one of the main indicators of material performance and is often used to compare adsorbents under similar test conditions. Advanced nanocomposites and biochar-based adsorbents often show higher adsorption capacities compared to conventional materials due to their enhanced surface areas, porosity, and more available functional groups for metal binding (Khamkar & Mehta, 2025; Gupta et al., 2015). Nevertheless, capacities reported in batch tests may not be fully achieved in continuous industrial operations.

8.4 Operational Cost

Operational costs primarily depend on energy consumption, chemical usage, the number of regeneration cycles, labor, and maintenance requirements. Membrane systems and electrochemical methods can provide fast and effective removal, but they usually involve higher energy input, sophisticated equipment, and periodic membrane replacement. On the other hand, biosorption and agricultural waste-based materials offer more cost-effective alternatives, as they use low-cost precursors and require less energy, although their lifetime and regeneration efficiency can be limited (Hamzah et al., 2025; Nemeș et al., 2026).

8.5 Industrial Feasibility

Industrial feasibility requires a balance between efficiency, cost, durability, operational simplicity, and regulatory compliance. Technologies that perform excellently in the lab may fail when scaled up due to hydraulic issues, fouling, or unstable feed quality. Hybrid systems that integrate adsorption, membrane filtration, and AI-based optimization show promise for large-scale deployment, as they can adapt process parameters in real time and improve resource utilization (Shofia et al., 2025; Saluja et al., n.d.). However, their implementation still faces challenges related to capital costs, operator skills, and standardization of design.

9. Challenges and Research Gaps

Despite significant progress, several critical research gaps remain.

9.1 Real Wastewater vs. Synthetic Studies

Many studies are conducted using synthetic metal solutions under controlled laboratory conditions. Real industrial wastewater contains multiple competing ions and organic contaminants that may reduce removal efficiency (Oladimeji et al., 2024). Bridging this gap requires pilot-scale validation on real effluent instead of only lab tests.

9.2 Multi-Metal System Removal

Industrial effluents often contain multiple heavy metals simultaneously. Competitive adsorption and ion interference complicate the removal mechanism, necessitating multifunctional materials with high selectivity (Gahrouei et al., 2024). Current research often focuses on single-metal systems, which do not represent actual conditions.

9.3 Long-Term Stability

Long-term performance, structural stability, and resistance to fouling remain concerns, particularly for nanomaterials and membranes (Purevjav et al., 2025). Many studies only evaluate a few cycles of reuse, so durability over extended operational time is poorly understood.

9.4 Toxicity of Nanomaterials

While nanomaterials increase adsorption efficiency, their potential ecotoxicological impact must be evaluated more carefully. Environmental release and disposal of nanoparticles may pose secondary risks to aquatic organisms and human health (Kumar et al., 2026; Vidu et al., 2020). More studies on life-cycle impact are still lacking.

9.5 Lack of Pilot-Scale Studies

Limited pilot-scale and field-level studies are restricting the commercialization of many promising technologies. To bridge the divide between laboratory research and industrial implementation, it is essential to conduct thorough techno-economic and environmental evaluations. (Nemeș et al., 2026). Without this, scale-up remains very challenging.

10. Future Perspectives

The future of heavy metal remediation is expected to evolve through the adoption of more innovative and sustainable technologies. Some key developments include:

i. Smart Multifunctional Materials: New materials that combine adsorption, catalytic reduction, and magnetic recovery will increase efficiency and recyclability. Tailored designs will improve their effectiveness in complex wastewater environments, where many ions and organic matter are present simultaneously.
ii. Circular Economy Integration: Implementation of circular wastewater management will focus on resource recovery and minimization of waste, promoting the reuse of treated water and valorization of recovered metals in line with sustainable development goals.
iii. Resource Recovery from Wastewater: Future strategies will shift from viewing heavy metals only as pollutants to recognizing them as valuable resources that can be recovered and reused in different industrial applications, reducing dependence on primary mining.
iv. Integration with Industry 4.0 is anticipated to enhance predictive modelling and operational efficiency within heavy metal treatment processes through the application of artificial intelligence, machine learning, and real-time monitoring. The optimization of chemical dosing, energy consumption, and maintenance schedules is achievable through the utilization of these digital tools.
v. Policy and Regulatory Considerations: Stronger regulations and environmental monitoring, together with incentives for green technologies, will encourage the adoption of advanced treatment systems. The management of heavy metals on both regional and global scales necessitates collaboration among researchers, industry stakeholders, and policymakers. Such cooperation is essential for enhancing the effectiveness of strategies aimed at addressing heavy metal contamination.

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