A Review on Heavy Metal Removal Techniques: A Comparative Study of Physical, Chemical, and Biological Techniques

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Abstract— Contamination of water resources with heavy metals poses serious environmental and public health problems due to their toxic, persistent, and bioaccumulative nature. Common heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), nickel (Ni), and chromium (Cr) are abundant in industrial and municipal wastewater. Effective removal of these metals is essential to ensure water quality, protect aquatic ecosystems, and maintain ecological balance. This review provides a comprehensive comparative analysis of three main categories of heavy metal removal methods: physical, chemical, and biological techniques. Physical methods such as membrane filtration, coagulation-flocculation, and adsorption are widely used for their operational simplicity and efficiency. Chemical methods including precipitation, electrochemical treatment, and solvent extraction are effective but may generate secondary contaminants. Biological approaches such as bioremediation and phytoremediation offer environmentally friendly and sustainable alternatives. Additionally, emerging technologies like nanotechnology-based materials and hybrid processing systems are discussed for their potential to improve removal efficiency and sustainability. The comparative evaluation highlights the advantages and limitations of each method in terms of removal efficiency, cost, environmental impact, and scalability. The analysis concludes that hybrid or integrated treatment systems combining multiple methods provide higher efficiency and represent a promising approach for treating complex wastewaters contaminated with heavy metals.

Keywords— heavy metal removal, physical methods, chemical methods, biological methods, wastewater treatment, hybrid systems.

Highlights:

- Comprehensive comparative review of physical, chemical, and biological heavy metal removal methods
- Evaluation of removal efficiency, cost-effectiveness, and scalability of various treatment approaches
- Discussion of advanced nanotechnology and hybrid systems for enhanced treatment performance
- Identification of advantages and disadvantages for each method in complex wastewater treatment.

I.   INTRODUCTION

Heavy metals are naturally occurring elements that become toxic to living organisms when present in excessive concentrations (WHO, 1993; Sahdev et al., 2024). These elements, characterized by high atomic density and toxicity at elevated levels, pose significant environmental challenges. The toxic effects of heavy metals such as lead, mercury, and arsenic have been recognized since ancient times, with systematic scientific investigation beginning in the late 19th century (Yadav et al., 2023). Heavy metals occur naturally in the Earth's crust and are found in sediments, soil, rocks, water, and living organisms. They are

persistent, non-biodegradable, and tend to bioaccumulate in the food chain. Some common heavy metals include copper, silver, zinc, cadmium, gold, and mercury (Mohammed et al., 2011; Yadav et al., 2021).

Water pollution by heavy metals represents one of the most significant environmental challenges of the 21st century. Unlike organic pollutants, heavy metals do not degrade and tend to bioaccumulate in the food chain, creating long-term environmental and health risks. Industrial processes such as mining, electroplating, battery manufacturing, textile processing, leather tanning, and chemical production are primary sources of toxic metals including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), arsenic (As), and nickel (Ni) in water bodies (Tchounwou et al., 2012). Exposure to heavy metals, even at low concentrations, can cause various health problems including neurodegenerative disorders, renal failure, carcinogenic effects, and reproductive issues. Consequently, effective removal of heavy metals from drinking water and wastewater is essential for public safety and environmental protection (Tchounwou et al., 2012).

Over several decades, numerous methods have been developed for heavy metal removal, broadly categorized into physical, chemical, and biological approaches. These methods vary in their advantages and limitations depending on factors such as target metal species, concentration levels, water matrix characteristics, and treatment scale (Tchounwou et al., 2012). Heavy metal contamination originates from various sources including natural processes, industrial activities, agricultural practices, pharmaceutical operations, domestic wastewater, and atmospheric deposition (Tchounwou et al., 2012; He et al., 2005). Point source pollution from mining operations, foundries, smelters, and other industrial facilities represents particularly significant contributions to environmental contamination (Tchounwou et al., 2012; He et al., 2005; Fergusson, 1990; Bradl, 2005).

This review presents a detailed comparison of these three major categories of heavy metal removal methods, focusing on their operational principles, effectiveness, economic feasibility, environmental sustainability, and recent technological advances. By evaluating the strengths and limitations of each approach, this article aims to identify the most effective and sustainable strategies for removing heavy metals from contaminated water systems.

II.   MATERIALS AND METHODS

This review was conducted as a systematic literature analysis to compare the effectiveness of physical, chemical, and biological methods for removing heavy metals from wastewater. Research articles, reviews, and technical reports published between 2010 and 2024 were collected from databases including ScienceDirect, Scopus, SpringerLink, Google Scholar, and ResearchGate. Keywords such as "heavy metal removal," "physical treatment," "chemical treatment," "bioremediation," "phytoremediation," and "hybrid systems" were used to identify relevant studies.

Inclusion criteria required studies focused on metals including Pb, Cd, Hg, As, Ni, and Cr, with clearly described methodologies and reported removal efficiencies. Publications lacking scientific credibility or sufficient data were excluded. Extracted information included treatment principles, performance parameters, removal efficiencies, advantages, limitations, and environmental impacts. The compiled data were systematically compared to assess the performance, cost-effectiveness, and scalability of each method. Emerging technologies, including hybrid approaches and nanotechnology-based systems, were also evaluated for their potential to enhance overall treatment effectiveness.

III.   PHYSICAL METHODS FOR HEAVY METAL REMOVAL

3.1   Membrane Filtration:

Membrane filtration represents a widely used method for wastewater treatment and heavy metal removal. This approach includes processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), with separation mechanisms based on size exclusion, Donnan exclusion, and adsorption (Peters and Shem, 1993; Abdullah et al., 2019; Yadav et al., 2021). RO and NF have demonstrated particular effectiveness in removing metal ions such as Cu^{2+}, Ni^{2+}, Cr(VI), and As(V) (Chan and Dudeney, 2008; Muthukrishnan and Guha, 2008; Sudilovskiy et al., 2008; Taghizadeh et al., 2013; Yadav et al., 2021). Ultrafiltration, especially when combined with micellar-enhanced (MEUF) or polymer-enhanced (PEUF) techniques, improves removal of smaller metal ions (Verbych et al., 2005; Barakat and Schmidt, 2010; Huang et al., 2016; Yadav et al., 2021). These processes typically achieve removal efficiencies exceeding 90% (Vigneswaran et al., 2004; Sato et al., 1977; Yadav et al., 2021).

Research has demonstrated the effectiveness of RO and UF membranes for removing Cu(II), Ni(II), and Zn(II), as well as chromium and cyanide from metal-containing wastewater. Porous nanofiltration membranes have shown particular effectiveness for selective metal removal (Sato et al., 1977; Dutta and De, 2017; Vigneswaran et al., 2004; Huang et al., 2010; Landaburu-Aguirre et al., 2010; Yadav et al., 2021). Despite sometimes higher costs, membrane technology is valued for its

high efficiency, environmental compatibility, and selective separation capabilities, making it a primary technique for treating heavy metal contaminated wastewater (Sato et al., 1977; Bhattacharyya et al., 1978; Dutta and De, 2017; Yadav et al., 2021).

3.2   Coagulation and Flocculation:

Coagulation and flocculation are established physicochemical processes for removing heavy metals from wastewater. Coagulation involves neutralizing the surface charge of colloidal particles, causing destabilization and aggregation. Common coagulants include aluminum sulfate (alum), polyaluminum chloride (PACl), magnesium chloride ($MgCl_2$), and polyethyleneimine (PEI) (Pang et al., 2011; Yadav et al., 2021). Flocculation follows coagulation, where destabilized particles are gently mixed to form larger flocs through bridging with polymeric additives (Tripathy and De, 2006; Yadav et al., 2021). Chitosan, a natural biopolymer, has also demonstrated effectiveness as an eco-friendly coagulant (Yang and Zall, 1984; Yadav et al., 2021).

This integrated process is widely used for drinking water purification and industrial wastewater treatment (Teh and Wu, 2014; Teh et al., 2016; Yadav et al., 2021). According to the U.S. Environmental Protection Agency (1978), lime treatment and coagulation with iron sulfate or alum can achieve up to 98% removal of lead, cadmium, and chromium at optimal pH conditions. Research has shown that iron sulfate achieves approximately 98% chromium removal at pH 6.5-9.3, while $FeCl_3$ enhances removal of Cu, Pb, Zn, and Ni (Johnson et al., 2008; Yadav et al., 2021). Coagulation-flocculation remains an economically viable and effective technique for heavy metal removal in various water treatment applications.

3.3   Ion Exchange:

Ion exchange is a highly effective method for removing heavy metals from wastewater through exchange of metal ions with less harmful ions such as sodium (Na^+) or potassium (K^+) on specialized resin materials. These resins contain functional groups that selectively bind specific metal ions including lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}), and copper (Cu^{2+}). The process is reversible, with saturated resins regenerated using concentrated solutions (typically NaCl or HCl) that displace bound metal ions and restore resin capacity (Dabrowski et al., 2004).

Ion exchange offers advantages including high efficiency, selectivity, and effectiveness at low metal concentrations. The technology finds extensive application in electroplating, metal finishing, and battery manufacturing industries. However, treatment costs can increase significantly for high-volume applications or waters containing complex pollutant mixtures (Inglezakis and Poulopoulos, 2006).

3.4   Adsorption:

Adsorption represents one of the most commonly employed and cost-effective methods for heavy metal removal from contaminated water. This process involves accumulation of metal ions on the surface of solid adsorbents. Activated carbon remains the most widely used adsorbent due to its extensive surface area and high adsorption capacity. However, increasing attention has focused on low-cost natural alternatives including clay minerals, zeolites, and biochar derived from agricultural and industrial wastes (Babel and Kurniawan, 2003).

Adsorption effectiveness depends on multiple factors including adsorbent surface area and porosity, metal species and concentration, contact time, and solution pH. The method has demonstrated particular effectiveness for removing metals such as lead (Pb), copper (Cu), cadmium (Cd), and arsenic (As) from both drinking water and industrial effluents (Ali and Gupta, 2006). Following metal saturation, adsorbents can often be regenerated through chemical or thermal treatment. The simplicity, low energy requirements, and adaptability of adsorption make it suitable for applications in both developed and developing regions (Crini, 2006).

IV.   CHEMICAL METHODS FOR HEAVY METAL REMOVAL

4.1   Neutralization:

Neutralization represents a fundamental technique for treating heavy metal contaminated waters, particularly acid mine drainage and industrial effluents. This process involves pH adjustment using alkaline agents to precipitate dissolved metals as insoluble hydroxides or carbonates. Common neutralizing agents include lime (CaO), limestone ($CaCO_3$), magnesium hydroxide ($Mg(OH)_2$), sodium hydroxide, and industrial byproducts such as fly ash and cement kiln dust. Calcium oxide is particularly effective due to its rapid hydrolysis and strong pH elevation capability, generating hydroxide ions that facilitate metal precipitation. Studies report up to 97% removal of lead (Pb) and 98% removal of antimony (Sb) and sulfate (SO_4) through neutralization processes (Balladares et al., 2018; Yadav et al., 2021).

Innovative approaches include using phosphate-rich minerals like apatite for neutralizing mine wastewater, resulting in metal precipitation and formation of potentially valuable phosphate-containing sediments (Ghirişan et al., 2007; Papassiopi et al., 1996; Conner and Hoeffner, 1998; Yadav et al., 2021). While valued for its simplicity and cost-effectiveness, neutralization requires careful management of resulting sludge and appropriate reagent selection based on water chemistry.

4.2   Chemical Precipitation:

Chemical precipitation represents the most widely used industrial method for heavy metal removal from wastewater. This technique involves converting soluble metal ions into insoluble compounds through pH adjustment or chemical additives, with subsequent removal by sedimentation, filtration, or flotation. Common precipitants include lime, caustic soda, soda ash, sodium bicarbonate, and sodium sulfide (Fu et al., 2007; Lim and Kim, 2013; Yadav et al., 2021).

Process efficiency depends on contaminant type, pH, precipitant dosage, and factors such as particle size and surface charge. Hydroxide and carbonate precipitation represent the most common approaches, with hydroxide precipitation particularly effective around pH 9. Sulfide precipitation demonstrates superior effectiveness for removing zinc, copper, and lead (Wang et al., 2018; Chen et al., 2018; Yadav et al., 2021). Despite high effectiveness, chemical precipitation generates substantial sludge volumes with associated handling and disposal costs. Novel precipitants such as dithiocarbamate derivatives (BDET) have shown promising results under acidic conditions due to their chemical stability (Matlock et al., 2002; Charerntanyarak, 1999; Yadav et al., 2021).

4.3   Electrochemical Treatment:

Electrochemical treatment employs electric current to remove heavy metals through oxidation, reduction, and deposition processes. As contaminated water passes between electrodes, metal ions undergo reduction and deposit on cathode surfaces or form insoluble compounds. Primary electrochemical approaches include electrocoagulation, where sacrificial electrodes (typically iron or aluminum) dissolve to form metal hydroxides that trap heavy metals, and electrowinning, which directly reduces metal ions at the cathode (Chen, 2004).

Electrochemical methods offer advantages including minimal chemical requirements, reduced sludge production compared to conventional precipitation, and potential for metal recovery. Removal efficiencies often exceed 90% for metals such as copper, nickel, and zinc. However, these techniques require significant energy input, electrode maintenance, and capital investment, potentially limiting large-scale applications (Mollah et al., 2004).

4.4   Solvent Extraction:

Solvent extraction represents a highly selective method for heavy metal recovery from wastewater, particularly valuable in industrial applications. This process involves transferring metal ions from aqueous to organic phases through selective chemical interactions. Organic extractants, typically with molecular weights between 210-500 and water-insoluble characteristics, are designed for specific metal recognition and complexation, enabling selective removal of copper, lead, zinc, nickel, and cadmium (Yadav et al., 2023).

Process effectiveness depends on pH, temperature, metal concentration, and extractant chemical structure. Following extraction, metal-loaded organic phases undergo stripping for metal recovery and solvent regeneration. Despite high selectivity and effectiveness, solvent extraction requires careful handling due to potential extractant toxicity and costs that may limit application for high-volume, low-concentration streams (Kislik, 2012).

4.5   Oxidation Processes:

Chemical oxidation employs strong oxidizing agents such as hydrogen peroxide (H_2O_2) and ozone (O_3) to convert heavy metals into less soluble or less toxic forms that can be removed by precipitation or filtration. Ozone has demonstrated particular effectiveness in oxidizing and precipitating metals including nickel, cadmium, and lead. While ultraviolet (UV) radiation is sometimes employed to enhance oxidation reactions, studies indicate limited direct contribution of UV to metal oxidation processes (Karwowska et al., 2022; Yadav et al., 2023).

Advanced Oxidation Processes (AOPs) enhance traditional oxidation through generation of highly reactive hydroxyl radicals (•OH), effective for rapid contaminant degradation. Common AOPs include Fenton oxidation ($H_2O_2 + Fe^{2+}$), electrochemical oxidation, photocatalytic oxidation (typically using TiO_2), and plasma discharge oxidation. These processes offer dual benefits of metal treatment and organic contaminant degradation. However, oxidation methods often require substantial energy inputs and careful control of pH and reagent doses (Du et al., 2020; Yadav et al., 2023).

V.   BIOLOGICAL METHODS FOR HEAVY METAL REMOVAL

5.1   Bioremediation:

Bioremediation employs microorganisms including bacteria, fungi, and algae to detoxify or transform heavy metals in contaminated water and soil. These organisms utilize natural metabolic processes to adsorb, accumulate, or chemically modify metals, reducing their mobility and toxicity. Bioremediation approaches include in situ treatment at contamination sites and ex situ treatment where contaminated materials are removed for processing. Microbial communities may be naturally occurring, artificially introduced (bioaugmentation), or stimulated through nutrient addition (biostimulation). Recent research has demonstrated successful bioremediation of soils contaminated with lead, cadmium, and chromium, highlighting this approach as a cost-effective and environmentally compatible solution (Yadav et al., 2023).

Process effectiveness depends on environmental factors including pH, temperature, oxygen availability, and microbial community characteristics. While generally slower than physical or chemical methods, bioremediation offers advantages for long-term, sustainable remediation with minimal environmental disturbance (Gadd, 2010).

5.2   Phytoremediation:

Phytoremediation utilizes plants to remove, degrade, or immobilize heavy metals from contaminated water and soil. Derived from Greek "phyto" (plant) and Latin "remedium" (restoring balance), this approach leverages specific plant species' natural ability to absorb, accumulate, and detoxify pollutants using solar energy (Vasavi et al., 2010; Sharma et al., 2016; Yadav et al., 2021). The process involves metal ion uptake through roots with subsequent translocation to aerial parts or immobilization in the rhizosphere.

Plants selected for phytoremediation typically exhibit rapid growth, high biomass production, extensive root systems, and metal tolerance. These species are classified as excluders, accumulators, or hyperaccumulators based on their metal handling strategies (Ma et al., 2016; Yadav et al., 2021). Over 400 hyperaccumulator species have been identified, with particular attention to Thlaspi caerulescens and Indian mustard (Brassica juncea) (Ghosh and Singh, 2005; Lasat, 2002; Yadav et al., 2021).

Phytoremediation mechanisms include phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration. Aquatic systems can employ plants like sunflowers and Brassicaceae species for direct metal uptake from water (Rezania et al., 2016; Yadav et al., 2021). Limitations include slow treatment rates and effectiveness primarily at lower metal concentrations. Enhancement strategies include plant growth regulators (Ullah et al., 2015; Yadav et al., 2021) and plant-microbe interactions (Rajkumar et al., 2012; Yadav et al., 2021), positioning phytoremediation as a sustainable alternative to conventional methods.

5.3   Bioaccumulation:

Bioaccumulation employs living organisms such as algae, fungi, and specific bacteria to absorb and concentrate heavy metals from contaminated environments over time. These organisms utilize natural metabolic or passive uptake processes to concentrate metals including lead, cadmium, mercury, and arsenic. Research has demonstrated bioaccumulation effectiveness for treating metal-containing wastewaters, representing a potentially low-cost and environmentally benign remediation approach (Yadav et al., 2023).

Microorganisms employed in bioaccumulation either intracellularly sequester metals or adsorb them to cell walls through mechanisms including biosorption, precipitation, and complexation. Fungi exhibit particularly high bioaccumulation potential due to their extensive surface area and metal binding capacity. This approach minimizes environmental disruption and can facilitate on-site treatment. However, bioaccumulation effectiveness can be limited by environmental variables including pH fluctuations, temperature variations, and co-contaminant presence. Despite these limitations, bioaccumulation represents a promising component of integrated biological treatment systems for heavy metal removal (Yadav et al., 2023).

VI.   EMERGING AND HYBRID TECHNOLOGIES:

Recent advances in heavy metal removal focus on nanotechnology-enhanced materials and integrated hybrid systems. Nanomaterials including carbon nanotubes, metal oxide nanoparticles, and bionanocomposites demonstrate exceptional adsorption capacities and selectivity due to their high surface area-to-volume ratios and tunable surface chemistries (Qu et al., 2013). Hybrid systems combining physical, chemical, and biological approaches offer synergistic benefits, addressing limitations of individual methods. Examples include membrane bioreactors, electrocoagulation coupled with adsorption, and phytoremediation enhanced with soil amendments. These integrated approaches typically achieve higher removal efficiencies

while reducing operational constraints, proving particularly effective for complex industrial wastewaters containing mixed contaminant streams.

VII.   COMPARATIVE ANALYSIS AND DISCUSSION

The evaluation of physical, chemical, and biological heavy metal removal methods reveals distinct performance characteristics, operational requirements, and application domains. Physical methods generally offer high removal efficiencies and operational simplicity but may involve significant energy consumption or material costs. Chemical approaches provide rapid treatment and high effectiveness but often generate secondary waste streams. Biological methods offer environmental sustainability and lower operational costs but typically require longer treatment times and are sensitive to environmental conditions.

TABLE 1
COMPARATIVE SUMMARY OF HEAVY METAL REMOVAL METHODS

Method Category	Specific Technique	Removal Efficiency	Advantages	Limitations	Typical Applications
Physical	Membrane Filtration	90-99%	High efficiency, selective separation, minimal chemical use	Membrane fouling, high energy/cost, concentrate disposal	Industrial wastewater, drinking water
	Adsorption	70-95%	Cost-effective, wide material availability, simple operation	Adsorbent regeneration, selectivity issues, saturation limits	Municipal/industrial wastewater, groundwater
	Coagulation-Flocculation	80-98%	Effective for multiple metals, established technology, scalable	Sludge production, chemical consumption, pH sensitivity	Drinking water, industrial pretreatment
Chemical	Chemical Precipitation	85-99%	High efficiency, simple operation, cost-effective	Sludge volume, chemical consumption, pH control needed	Mining, electroplating, battery manufacturing
	Electrochemical Treatment	90-99%	Minimal chemicals, metal recovery potential, automation compatible	High energy, electrode maintenance, capital cost	Metal finishing, electronics, precious metal recovery
	Solvent Extraction	90-99%	High selectivity, metal recovery, concentrated product streams	Organic solvent use, multi-stage process, cost	High-value metal recovery, concentrated streams
Biological	Bioremediation	60-90%	Environmentally friendly, low cost, minimal secondary waste	Slow process, environmental sensitivity, monitoring needed	Soil/sediment, low-concentration wastewater
	Phytoremediation	50-85%	Solar-powered, soil improvement, carbon sequestration	Seasonal limitations, slow, depth limited	Constructed wetlands, mine tailings, agricultural runoff
	Bioaccumulation	70-95%	High selectivity, low energy, potential resource recovery	Biomass handling, process control, scalability challenges	Low-concentration streams, polishing treatment

Hybrid systems combining multiple approaches demonstrate particular promise for addressing complex contamination scenarios. For instance, combining chemical precipitation with membrane filtration can reduce sludge volumes while enhancing effluent quality. Integrating biological treatment with physical separation can improve overall system resilience and reduce chemical consumption. The selection of appropriate treatment technology depends on specific factors including wastewater characteristics, regulatory requirements, economic considerations, and sustainability goals.

VIII. CONCLUSION AND FUTURE PERSPECTIVES

The comparative analysis of physical, chemical, and biological heavy metal removal methods reveals that no single approach universally addresses all contamination scenarios. Physical methods offer efficiency and reliability but often at higher operational costs. Chemical methods provide rapid treatment but may generate secondary wastes. Biological approaches offer sustainability advantages but typically require longer treatment periods. The optimal technology selection depends on multiple factors including target metals, concentration levels, water chemistry, treatment scale, economic constraints, and regulatory requirements.

Hybrid systems integrating multiple treatment modalities represent the most promising direction for advanced heavy metal removal. These integrated approaches can leverage synergies between different mechanisms, overcoming individual limitations while enhancing overall performance. Future research should focus on developing cost-effective nanomaterials with enhanced selectivity, optimizing hybrid system configurations, improving biological process efficiency through genetic and metabolic engineering, and advancing real-time monitoring and control systems. Additionally, life cycle assessment and techno-economic analysis should guide technology selection and optimization for sustainable water treatment solutions.

As industrial activities continue to expand and water quality standards become increasingly stringent, the development and implementation of efficient, cost-effective, and environmentally sustainable heavy metal removal technologies remain critical for protecting water resources and public health worldwide.

AUTHOR CONTRIBUTIONS

Sahdeva contributed to the conceptualization of the study, data collection, analysis, and preparation of the initial manuscript draft. Dr. Shweta Choubey contributed to supervision, methodology design, critical revision of the manuscript, and overall guidance of the research work. Dr. Ajay Vikram Ahirwar contributed to data interpretation, validation of results, and review and editing of the manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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