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An in-depth review of sustainable technologies for heavy metal removal from industrial wastewater: Current approaches and prospective challenges

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ABSTRACT

Water sources contamination with heavy metals is a global source of anxiety. Heavy metals poses a real threat to ecosystems and human health. These metals such as lead, cadmium, and mercury are recognized as highly toxic and persistent pollutants due to their ability to accumulate in biological systems. This research explores and critically assesses cutting-edge technologies for the removal of heavy metals from industrial wastewater, aiming to reduce their harmful environmental and public health effects. The study first outlines the environmental and health hazards associated with these contaminants, followed by an overview of conventional treatment methods—including chemical precipitation, adsorption, ion exchange, and filtration. While these traditional approaches have proven effective, they are often hindered by the need for large quantities of reagents, as well as high operational and waste management costs. To address these limitations, the research shifts focus toward innovative treatment strategies, including nanotechnology, photocatalytic oxidation, advanced membrane technologies, and biological treatments. Recent literature is examined to highlight the performance, advantages, and limitations of these modern techniques. For example, nanomaterials demonstrate exceptional adsorption capabilities due to their high surface area, though challenges such as material recovery and economic viability remain significant. Similarly, membrane-based processes offer high efficiency but are often associated with high operational costs. The study also proposes strategies for overcoming these limitations, such as improving nanomaterial reuse and reducing energy consumption in membrane operations. A comparative analysis of the discussed methods is presented to support practitioners and researchers in selecting appropriate solutions based on factors such as contaminant characteristics, economic constraints, and technological readiness. Ultimately, this work aims to serve as a valuable resource for professionals and scholars engaged in industrial wastewater

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management, promoting informed choices and sustainable heavy metal remediation.

1. Introduction

Industrial wastewater is a major source of environmental pollution, containing a complex mixture of contaminants, notably heavy metals. These metals are widely acknowledged for their high toxicity and detrimental effects on both ecological systems and human health. Managing and treating industrial wastewater presents a considerable environmental challenge, especially in the context of growing industrialization and the associated rise in pollutant discharge. Among the most concerning contaminants are heavy metals such as lead, cadmium, mercury, and chromium, which significantly contribute to water pollution and pose severe risks to aquatic life and public health [1].

Heavy metals possess the ability to bioaccumulate within living organisms, leading to serious long-term toxic effects. Prolonged exposure to lead, for example, has been linked to various health complications such as kidney dysfunction, neurological impairments, and cardiovascular disorders [2]. Mercury, likewise, is considered among the most dangerous heavy metals due to its potent neurotoxicity and its detrimental influence on neurological development [3].

The removal of heavy metals from industrial wastewater relies on a range of technologies aimed at reducing metal concentrations to environmentally safe levels according to what was determined by international environmental organizations and as shown in Table 1. Conventional treatment methods—such as chemical precipitation, adsorption, and filtration—have been widely employed for this purpose [4]. Despite their widespread use, these methods face notable limitations, including suboptimal removal efficiency, high operational and economic costs, and the generation of secondary waste byproducts. In recent years, significant advancements have been made in developing innovative technologies aimed at improving the efficiency and sustainability of industrial wastewater treatment, as demonstrated in Table 2. These emerging approaches include biotechnology, membrane filtration, photocatalysis, and nanotechnology [7]. Among these, nanotechnology has garnered particular attention due to the distinctive characteristics of nanomaterials—such as their large surface area and high chemical reactivity—which make them especially effective in the removal of heavy metals [8].

This study aims to provide a critical evaluation of sustainable strategies for the removal of heavy metals from industrial wastewater, with a particular focus on modern treatment technologies and the associated challenges and opportunities they entail.

The practical implementation of these technologies will be explored through real-world applications and case studies. Furthermore, the research will offer a comprehensive analysis and comparative assessment of the cost-effectiveness and operational efficiency of the different treatment methods.

Table 1. Heavy metals standards in drinking water and surface water [5,6].

Heavy metals	Standards for industrial effluents according to EU	Standards for drinking water according to EU and WHO	Standards of heavy metals dissolved in surface water according to EU Environmental Quality.
Cadmium	0.01-0.1 mg/L	~ 5 µg/L	0.08 µg/L avg/ 0.45 µg/L max
Chromium	0.01- 0.3 mg/L	50 µg/L	_
Copper	0.05 - 0.5 mg/L	2 mg/L	_
Lead	0.05 - 0.3 mg/L	10 µg/L	1.3 µg/L avg/ 14 µg/L max
Mercury	1 - 10 µg/L	1 µg/L	_ (biota: 20 µg/Kg)
Nickel	0.05 - 1 mg/L	20 µg/L	~ 4 µg/L (ecological level)
Zinc	0.1 - 2 mg/L	-	_

Table 2. Recent studies of heavy metals removal from wastewater using different emerging technologies.

Metals	Used technology	Operating conditions and removal rate	Reference
Chromium (Cr)	Electrocoagulation	Current intensity(I) =2.9mA, time(t)=18.1min, and pH=5.6 Removal rate =~98.8%	[9]
Nickle (Ni)	Electrocoagulation	Applied current = 0.31 A, an initial nickel concentration of 10 ppm, time = 18 min, pH = 7, energy consumption of 0.443 Wh/g. Removal efficiency = 95.16%	[10]
Cadmium (Cd), copper (Cu, and zinc (Zn)	Sulfate-reducing biochemical reactors	Two-stage treatment, where basic oxygen furnace slag (slag stage) and microbial SO_4^{2-} reduction (SRBR stage) were incorporated in series Removal rate = ≥96%	[11]
Hexavalent chromium (Cr(VI))	Magnetic biochar (MBC)	Adsorbent dose = 0.4 g/L, pH =2, contact time =120 min, and initial Cr(VI) concentration= 10 mg/L, Adsorption capacity = 36.15 mg/g.	[12]
Cd^{2+}, Pb^{2+} and Zn^{2+} ions	magnetic $Fe_3O_4@SiO_2$-(-NH_2/-COOH) nanoparticles	Adsorption dose = 0.8 g/L, temperature = 30°C and concentrations of Pb^{2+}, Cd^{2+} and Zn^{2+} below 120, 80 and 20 mg/L, respectively. Maximum adsorption capacities for Pb^{2+}, Cd^{2+} and Zn^{2+} were 166.67, 84.03 and 80.43 mg/g.	[13]
Zn^{2+}, Cu^{2+}, Ni^{2+}, and TCr	Electrocoagulation and integrated membrane	pH =8, current density =5 A/dm^2, electrode plate spacing =2 cm, and 35 min of electrolysis time. Removal rate = ≥99%.	[14]
Hexavalent chromium (Cr(VI))	Nanocomposite, polyurethane foam impregnated with zero-valent iron nanoparticles	pH =2 and a dose of 0.5 g/L. Removal rate = 99.98% of Cr^{6+} from tap water, 96.81% from industrial effluent, and 94.57% from treated sewage wastewater.	[15]
Cr, Co, Cu, Fe, Mn, Ni, Pb, Ti and Zn	Hybrid electrocoagulation-ceramic membrane filtration	Electrocoagulation time = 60 min, 20 A, and an initial pH =3. Removal rate = 95–100 %	[16]
Cd^{2+}, Cu^{2+}, Ni^{2+}, Pb^{2+} and Zn^{2}	Fluidized bed sulfidogenic bioreactor	Influent pH 7.0 and 3.0 Removal efficiency ≥ 95% for all the metals except for Ni^{2+} (85%)	[17]
As(III), Ni(II), Cu(II), Pb(II)	Sulfate-reducing bacteria (SRB) with organohalide-respiring bacteria (OHRB)	50–75 µM sulfate Rapid detoxification: Ni(II) =76.87%, Pb(II) =64.01 %, Cu(II) = 86.37 %, As(III) = 95.50 %)	[18]

Although there are many review studies that focus on specific techniques of heavy metals removal from industrial wastewater, there are relatively few that comprehensively discuss all the techniques used, both conventional and modern. Furthermore, this review is unique in that it reviews all the limitations of the utilized techniques and proposes solutions for them.

2. Hazards of heavy metals in industrial wastewater

Heavy metals are naturally occurring high-density elements found in the Earth's crust. However, when released into industrial wastewater, they pose significant threats to both environmental and public health. Among the most frequently encountered heavy metals in industrial effluents are lead, mercury, cadmium, zinc, copper, and chromium, all of which are known for their toxicity and potential to cause long-term ecological and physiological harm.

2.1. Environmental impacts

The introduction of heavy metals into aquatic ecosystems represents a serious environmental threat, resulting in the contamination of both water and sediment. These persistent pollutants exhibit bioaccumulative tendencies, progressively concentrating as they move up the food chain. Consequently, organisms at all trophic levels—from primary producers to apex predators, including humans—are susceptible to exposure. This phenomenon, known as bioaccumulation, can lead to the buildup of toxic metal concentrations in living tissues, ultimately disrupting biodiversity and impairing ecosystem functionality[19].

2.1.1. Pollution of water resources

Freshwater systems represent a vital yet vulnerable resource, increasingly threatened by contamination from heavy metals. The infiltration of these pollutants into rivers, lakes, and groundwater reservoirs degrades water quality and introduces persistent contamination that resists conventional remediation efforts. Of particular concern are highly toxic metals such as cadmium and hexavalent chromium, which exhibit remarkable environmental persistence in aquatic systems [20]. By altering the physicochemical properties of water, these metals disrupt ecological balance, triggering cascading effects across aquatic ecosystems. Additionally, one of the important sources of environmental pollution is the industrial wastewater discharges from plating units especially those from nickel and chromium plating units, acidic and cyanide galvanizing, and acidic and cyanide copper because of the high concentrations of heavy metals and toxic agents [21].

2.1.2. Effects of bioaccumulation

One of the most concerning ecological consequences of heavy metals lies in their propensity for trophic transfer and biomagnification within food webs. A well-documented example involves mercury cycling: inorganic mercury undergoes methylation in aquatic environments, is assimilated by planktonic organisms, and subsequently progresses through successive trophic levels via predator-prey interactions. This bioaccumulation process leads to exponentially higher metal concentrations in apex predators, including humans who consume contaminated seafood. Such biomagnification poses significant public health risks, with documented cases of neurological and developmental disorders linked to chronic exposure [22].

2.1.3. Effects on biodiversity

Heavy metal contamination exerts profound ecological disturbances that progressively erode biodiversity across multiple trophic levels. These persistent pollutants exert toxicological pressures on fundamental ecosystem components, from microbial communities to higher aquatic organisms. A particularly well-characterized case involves lead contamination, which has been shown to inhibit aquatic macrophyte development and significantly impair photosynthetic efficiency [23]. Such physiological disruptions cascade through aquatic ecosystems, compromising primary productivity and destabilizing food web dynamics. Furthermore, chronic exposure induces cumulative toxic effects in aquatic fauna, manifesting as both physiological impairments and heritable genetic damage in fish and invertebrate populations.

2.1.4. Impacts on soil and plants

The contamination of soil with heavy metals originating from wastewater leads to the accumulation of these toxic elements within plant tissues. Cadmium, for example, is easily taken up by plants and can concentrate in the edible parts of crops, ultimately entering the human food chain [24]. Such contamination not only reduces soil fertility but also negatively affects crop productivity, posing significant obstacles to the advancement of sustainable agricultural practices.

2.1.5. Impacts on aquatic ecosystems

Heavy metals impact aquatic ecosystems by disturbing nutrient dynamics and disrupting ecological interactions among various organisms. Their accumulation in aquatic sediments can lead to the contamination of benthic organisms, which play a vital role in maintaining the structure and function of aquatic food webs [4].

2.2. Health Effects

Exposure to heavy metals through contaminated drinking water or food can result in significant health issues:

- **Lead:** Causes severe neurotoxic effects, particularly in children, impairing brain development and leading to reduced cognitive function and behavioral disorders [23].
- **Mercury:** Accumulates in the central nervous system, potentially leading to irreversible neurological disorders [22].
- **Cadmium:** Induces substantial renal damage and is associated with an elevated risk of osteoporosis and cancer [24].

2.3. Economic and social risks:

The infiltration of heavy metals into aquatic systems carries significant socioeconomic consequences, primarily through the degradation of water quality essential for agricultural and industrial applications. Contaminated irrigation water reduces soil fertility and crop yields, directly undermining agricultural productivity. Simultaneously, industrial facilities face escalating operational costs due to the need for advanced water treatment technologies to meet safety standards. These economic burdens are further compounded by substantial public health expenditures, as chronic exposure to heavy metal pollution is associated with increased incidence of debilitating diseases, placing additional strain on healthcare systems and social services [20].

3. Analytical Techniques for Heavy Metal Detection in Industrial Wastewater

The accurate quantification of heavy metals in industrial wastewater represents a critical component in environmental monitoring and remediation efforts. A diverse array of analytical techniques, spanning from classical wet chemistry methods to sophisticated instrumental approaches, enables researchers and practitioners to assess contamination levels and develop targeted treatment protocols.

Among established analytical methods, atomic absorption spectroscopy (AAS) remains a benchmark technique due to its exceptional sensitivity for trace metal detection. As demonstrated by Welz and Sperling (1999) [25], AAS achieves detection limits in the parts-per-billion range for toxic elements including lead, cadmium, and mercury, making it particularly valuable for regulatory compliance monitoring. For more comprehensive analyses, inductively coupled plasma optical emission spectroscopy (ICP-OES) has emerged as a powerful alternative, offering the distinct advantage of multi-element detection capability within a single analytical run [26]. This simultaneous quantification significantly enhances monitoring efficiency in complex wastewater matrices.

High-performance liquid chromatography (HPLC) is widely utilized in the analysis of heavy metals, providing excellent resolution for the separation and identification of various metal species in water samples [27]. In parallel, X-ray fluorescence (XRF) spectroscopy offers the advantage of non-destructive analysis, making it particularly suitable for on-site and field-based applications [28]. Electrochemical techniques, such as voltammetry and amperometry, are also employed due to their high sensitivity and accuracy in detecting trace concentrations of heavy metals [29]. These methods generate reliable data that are essential for evaluating pollution levels and guiding environmental management efforts in affected regions.

Recent advances in analytical science have integrated nanotechnology to further enhance the sensitivity and precision of heavy metal detection. For example, the use of nanoparticles has been shown to improve both the extraction efficiency and quantitative analysis of metals in complex matrices [30]. These emerging techniques offer promising prospects for the development of more advanced, accurate, and efficient analytical methodologies.

4. Conventional Methods for Heavy Metal Removal

Heavy metals like lead, mercury, cadmium, and chromium are significant environmental contaminants, necessitating effective removal technologies from industrial wastewater. Traditional methods for eliminating these metals utilize a combination of chemical and physical processes designed to reduce their concentrations to levels that are safe for both the environment and public health. These methods encompass chemical precipitation, adsorption, ion exchange, and filtration. While each technique is effective, they present challenges related to cost, efficiency, and secondary waste management. Therefore, integrating these methods with modern technologies is crucial for achieving effective and sustainable treatment

4.1. Chemical Precipitation

Chemical precipitation stands as one of the most extensively implemented techniques for heavy metal remediation in industrial wastewater streams. The process fundamentally relies on the introduction of precipitating agents—typically hydroxides (e.g., $NaOH$, $Ca(OH)_2$) or sulfides (e.g., Na_2S, FeS)—which react with dissolved metal ions to form insoluble metallic compounds [4]. These newly formed precipitates subsequently undergo sedimentation, allowing for physical separation from the aqueous phase, as illustrated in Figure 1. A conventional removing method of Cr(VI) from wastewater is the chemical reduction to (Cr^{3+}), which will precipitate as chromium hydroxide [$Cr(OH)_3$] under alkaline conditions [31]. For cyanide-complexed metals, such as zinc cyanide, remediation typically consist of breaking down the complex and precipitating the metal in the form of insoluble metal–ferrocyanide compounds. That can be made by the addition of ferrous sulfate or sulfide-based reagents, which enhance the formation of stable precipitates that can be separated from the treated effluent [32].
Extensive research has demonstrated the particular efficacy of this method for divalent metal species, with removal efficiencies exceeding 90% for chromium (Cr^{3+}), copper (Cu^{2+}), and zinc (Zn^{2+}) across various industrial applications [33-35]. Nevertheless, the technique presents a significant operational challenge through the copious production of metal-laden sludge. This byproduct requires additional processing steps—often involving dewatering, stabilization, and ultimately secure disposal—to prevent secondary environmental contamination and comply with increasingly stringent regulatory standards.

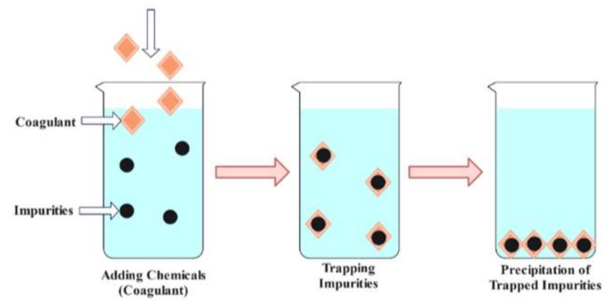

Fig. 1. Simple schematic of chemical precipitation process. Reproduced from [36] under the Creative Commons CC BY 4.0 license.

4.2. Adsorption

The adsorption process has emerged as a robust and versatile approach for the remediation of heavy metal-contaminated water, employing various solid-phase materials such as activated carbon, clay minerals, and zeolites as adsorbents [37]. Among these, activated carbon remains the most widely studied and implemented adsorbent, owing to its exceptionally high surface area and well-developed porous structure, which facilitate superior metal ion uptake [38].
In general, the adsorption mechanism divided into two types physical and chemical. The physical adsorption represented by the adhesion of the adsorbent to the surface of the adsorbate due to the onspecific van der Waals force. The chemical adsorption consist of the construction of ionic or covalent bonds through chemical reactions. On the other hand, biosorption categorized as efficient, not costly, ease of generation, and multiple microorganisms[39, 40], industrial and agricultural waste [41, 42], natural residues [43, 44], and other biological materials have been utilized as bioadsorbents.

4.3. Ion Exchange

Ion exchange represents a well-established remediation technique that employs specialized resins with active functional groups to selectively replace toxic metal ions with benign counterions, typically sodium (Na^{+}) or hydrogen (H^{+}) species [45], as depicted in Figure 2. The method demonstrates particular efficacy in treating wastewater containing trace metal concentrations, while offering the practical benefit of resin regeneration through appropriate elution processes [46]. Nevertheless, the economic viability of this approach may be constrained by the relatively high costs of both the ion-exchange media and the regeneration procedures required for sustained operation. All resins whether natural or synthetic exchange their cations selectively with heavy metals ions present in wastewater. The use of zeolit and purolite C105 for heavy metals (Cu^{2+}, Pb^{2+}, and Ni^{2+}) ions from wastewater was investigated [47]. The maximum removal rates for Cu^{2+}, Ni^{2+}, and Pb^{2+} on zeolite, were averaged to be 97.5 %, 92.5 %, and 87.5 %, respectively; and on purolite C105 were 93.5 %, 96.5%, and 87.5 %, respectively.

The major limitations of ion exchange process were: (1) the production high salty solution which need for recovery, (2) the reduction in efficiency and raise of costs due to the presence of organics, colloids, and oil, (3) ions selectivity of the resin will lead to decrease of efficacy especially in the case of low metals concentrations, and (4) resins regeneration high cost.

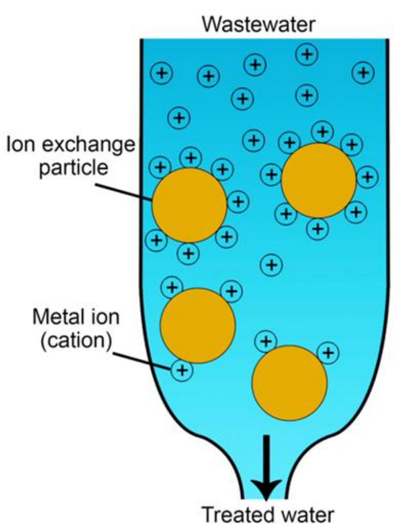

Fig. 2. Simple schematic of ion exchange process. Reproduced from [48] under the Creative Commons CC BY 4.0 license.

4.4. Filtration

Filtration represents a well-established mechanical separation process that effectively removes suspended solids and heavy metal contaminants through porous media such as sand, gravel, or synthetic membranes [49]. Advanced membrane filtration systems, including microfiltration and ultrafiltration, demonstrate enhanced removal efficiency for colloidal particles and dissolved metal species [50].

While these techniques offer reliable contaminant removal, their operational sustainability depends on consistent maintenance protocols and periodic media replacement to maintain optimal performance.

There are many limitations of using this process for heavy metals removal such as: (1) inefficient process for soluble heavy metals removal, (2) require pretreatment process such as chemical precipitation, coagulation/flocculation, or oxidation, (3) near surface loading due to accumulation of metals on the shallow surface layer and that lead to faster headloss development, and (4) probability of release of accumulated metal and return to solution due to pH changes, redox, or aggressive backwashing.

5. Modern Techniques for Heavy Metal Removal

The efficient elimination of heavy metals from industrial effluents represents a critical environmental priority, given their well-documented ecological persistence and adverse effects on human health. In response to these challenges, contemporary research has focused on developing advanced treatment methodologies. Prominent among these emerging technologies are:

- Nanotechnology-based remediation
- Photocatalytic degradation
  *Biotechnological approaches
- Advanced membrane filtration systems
- Electrochemical treatment processes

Each of these innovative techniques offers unique advantages for addressing the complex challenges associated with heavy metal contamination in aqueous systems.

5.1. Nanotechnology

Nanotechnology has emerged as a promising solution for treating heavy metal-contaminated water due to the unique physicochemical properties of nanomaterials. Nanoparticles exhibit exceptionally high surface-area-to-volume ratios, enabling enhanced interactions with metal pollutants [51]. Specific nanomaterials, including iron oxide (Fe_2O_3) and zinc oxide (ZnO) nanoparticles, have demonstrated remarkable efficiency in sequestering toxic metals such as lead (Pb), mercury (Hg), and cadmium (Cd) from aqueous solutions. Furthermore, the surface properties of these nanomaterials can be precisely engineered to target specific contaminants, thereby optimizing removal efficiency[52].

This innovative approach offers significant advantages for wastewater treatment, particularly in meeting growing demands for sustainable and environmentally benign remediation technologies. Nanotechnology-based heavy metal removal operates through multiple mechanisms, including: surface adsorption, chemical precipitation, and redox reactions. These versatile treatment modalities position nanotechnology as a particularly valuable tool for addressing complex water pollution challenges in industrial settings. The technique aligns well with global efforts to develop eco-friendly treatment solutions that balance remediation efficiency with environmental sustainability considerations.

Sorption: The sorption process represents a fundamental mechanism in nanomaterial-mediated heavy metal removal, where metal ions are captured onto nanoparticle surfaces through various physicochemical interactions. Research has particularly focused on engineered nanomaterials such as magnetic iron oxide (Fe_3O_4) and magnesium oxide (MgO) nanoparticles, which have demonstrated exceptional adsorption capacities for toxic heavy metals including lead (Pb^{2+}) and cadmium (Cd^{2+}) ions [53]. These nanomaterials achieve effective contaminant removal through surface complexation, electrostatic attraction, and other interfacial phenomena.

Precipitation: Specific engineered nanomaterials, particularly zinc oxide (ZnO) nanoparticles, have demonstrated remarkable efficacy in facilitating heavy metal precipitation from aqueous solutions. These nanoparticles promote the conversion of soluble metal ions into insoluble metallic compounds through surface-mediated reactions. This transformation process significantly reduces metal toxicity while substantially improving removal efficiency [54].

Reduction: Iron oxide nanoparticles (FeOx NPs) demonstrate significant potential for the reductive transformation of toxic metal ions, converting them into less soluble and environmentally benign species through redox reactions. This chemical reduction process provides an efficient pathway for heavy metal sequestration in wastewater treatment systems [55].

Despite these advantages, several critical limitations hinder the widespread application of nanotechnology for industrial wastewater remediation. Key challenges span three primary domains: (1) technical barriers related to scalability and process control, (2) environmental concerns regarding nanoparticle fate and transport, and (3) economic constraints associated with production and operational costs. The subsequent discussion examines these challenges in detail, with supporting evidence from current literature.

1. Aggregation and Agglomeration: Nanoparticles may aggregate with each other, reducing their effectiveness in removing heavy metals [56].
2. Stability: Maintaining the stability of nanoparticles in solution is a challenge, as their properties can change over time [57].
3. Economic Cost: The manufacture and use of nanoparticles can be expensive, which affects the economic feasibility of their applications on a large scale [58].
4. Treatment and Disposal of Nano waste: Challenges associated with the treatment and disposal of waste resulting from the use of nanoparticles in water treatment [59].
5. Efficiency in Variable Conditions: The effectiveness of nanoparticles may be affected by changing environmental conditions such as pH, temperature, and the presence of organic materials [60].

These challenges underscore the necessity for ongoing research and development to enhance nanotechnology and ensure its efficient and safe application in the removal of heavy metals from industrial wastewater.

Recent advances in nanotechnology have yielded diverse nanomaterials specifically engineered for heavy metal removal applications. These advanced materials fall into three primary categories: (1) carbon-based nanostructures, (2) silica-derived nanomaterials, and (3) functionalized magnetic nanoparticles [61]. Each class exhibits distinct physicochemical properties that determine its metal sequestration capabilities in aqueous environments.

Carbon –Nanomaterials: Carbon nanomaterials, particularly carbon nanotubes (CNTs) and graphene-based adsorbents, have emerged as effective solutions for heavy metal ion sequestration from industrial wastewater. CNTs exist in two principal configurations: single-walled (SWCNTs) and multi-walled (MWCNTs) varieties, both extensively studied for wastewater treatment applications [62, 63]. As illustrated in Figure 3, their unique cylindrical nanostructures feature hollow grooves and interstitial channels that serve as primary adsorption sites. Notably, internal adsorption sites typically reach equilibrium faster than external surfaces under identical operational conditions.

The metal ion adsorption capacity of CNTs depends critically on three physicochemical parameters: (1) hydroxide solubility, (2) electronegativity, and (3) ionic radius. Steric effects become particularly significant, with larger ionic radii reducing adsorption efficiency due to spatial constraints [64- 66].

Graphene nanomaterials demonstrate comparable potential for heavy metal remediation, with two predominant variants: graphene oxide (GO) and reduced graphene oxide (rGO) [67]. Their adsorption efficacy stems from abundant surface functional groups (-OH, -COOH) that enhance metal ion binding through hydrophilic interactions [68]. Multiple studies have confirmed their exceptional adsorption performance [69]. A (GO) nanocomposite that contains chitosan, a biological polymer, combined with a magnetic nanoparticle inorganic material (Fe_3O_4) was successfully synthesized and utilized as adsorbent for Pb(II) from wastewater [70]. The adsorption process was of chemical properties and achieved 63.45 mg /g as maximum adsorption capacity. Other study utilized nanocomposite of Fe_3O_4 nanoparticles grown on the surface of two-dimensional reduced GO nanosheets for the removal of arsenic from wastewater [71]. Maximum adsorption capacity of 8.40 and 8.96 mg/g for arsenic concentrations 0.1 and 10 mg/L, respectively, were achieved.

Functionalized silica nanoparticles: Silica nanoparticles (SiO_2 NPs) have emerged as particularly promising nanomaterials due to their adaptable and exceptional physicochemical properties. According to IUPAC classification, mesoporous silica nanoparticles (MSNs) possess well-defined pore diameters between 2-50 nm, which can be further functionalized with diverse chemical groups [73].

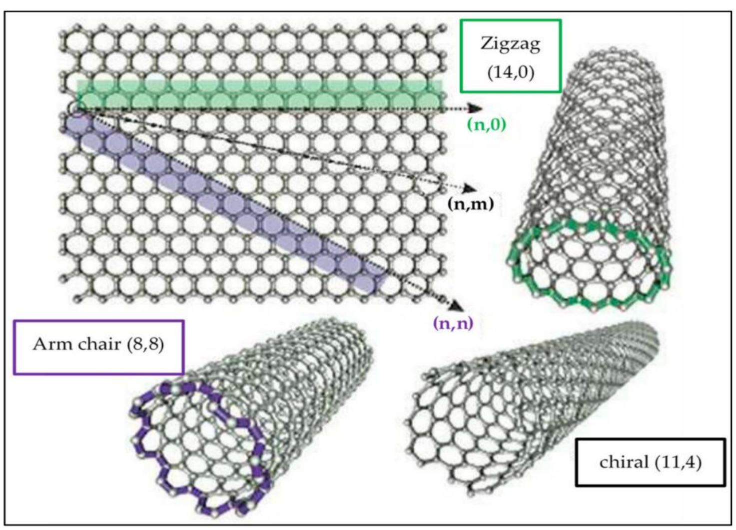

Fig. 3. The structure of carbon nanotube. Reproduced from [72] under the Creative Commons CC BY 4.0 license.

These nanostructures have attracted considerable research interest owing to their:

-Favorable morphological characteristics
-Uniform and adjustable pore architecture
-High surface porosity
-Remarkable chemical stability
-Tailorable surface chemistry

These advantageous properties render MSNs exceptionally suitable for various high-performance applications [74, 75]. Researchers have developed multiple MSN variants, as illustrated in Figure 4, each demonstrating specific utility across different technological domains [74]. A previous study used amine-modifiedmesoporous silica MCM-48 modified with acid and base functional groups for the adsorption of Ce(III), Hg(II), and Cu(II) ions [76]. After 180 min of adsorption, the amine-modified material achieved an adsorption capacity of 97% and 98% for Ce(III), and Hg(II), respectively. In recent years, magnetic nanoparticles have emerged as particularly effective adsorbents for water remediation, demonstrating exceptional capability in removing heavy metal ions, organic pollutants, and biological contaminants from both domestic and industrial wastewater streams [77]. Among these, magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3) nanoparticles exhibit superior corrosion resistance and mechanical stability compared to conventional magnetic materials, making them especially suitable for heavy metal ion extraction [78].

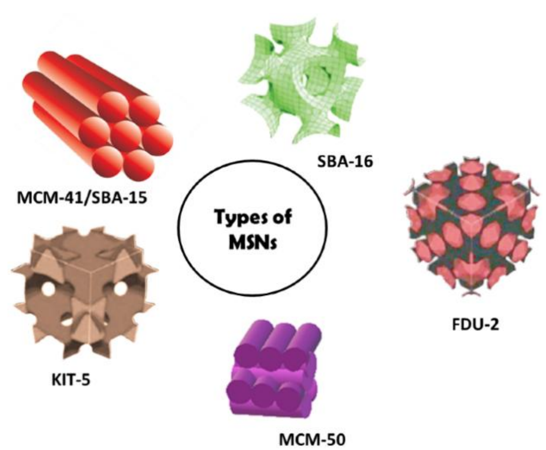

Fig. 4. Depiction of various types of mesoporous silica nanoparticles (MSNs). Reproduced from [74] under the Creative Commons CC BY 4.0 license.

A key advantage of magnetic nanocomposites lies in their facile separation from treated water through magnetic recovery after completing the adsorption process. These composite materials typically incorporate magnetic iron oxide cores as their fundamental component [79]. Figure 5 illustrates the mechanism of heavy metals removal using magnetic nanoparticles. There is a significant additional benefit to using nanomaterials when the nanomaterials are made from waste material that achieves sustainability. As example, moringa and tea extracts were used to made iron nanoparticles adsorbent for the removal of Cu^{2+}, Pb^{2+}, Se^{2+}, Zn^{2+}, and Cr from wastewater [80]. At the optimal conditions (contact time = 45 min, pH = 3, concentration 3.0 mg/L, a adsorbent dose of 0.8 g/L, and 200 rpm at 25 °C), tea magnetic adsorbent achieved removal efficiencies greater than that achieved by moringa magnetic. These efficiencies were 96.5% 99.71%, 96.73%, 93.16%, and 91.83% of Cu, Pb, Se, Zn, and Cr, respectively. Another example was the use of egg shell and fly ash waste with magnetic nanoparticles as efficient, ecofriendly, and not costly adsorbent for cadmium removal from wastewater [81]. Contemporary research in this field demonstrates remarkable diversity in both nanomaterials and technological approaches, providing customized solutions for environmental contamination challenges. Table 3 systematically summarizes recent advancements in nanotechnology-based heavy metal removal, documenting critical parameters including target metal species, nanomaterial composition/technology employed, Removal efficiency metrics, research teams, and publication chronology. This comparative analysis highlights the evolving landscape of nanoscale remediation strategies.

5.2. Photocatalysis

Photocatalysis technology involves the use of photocatalysts such as titanium dioxide (TiO_2), which have the capability to absorb light and transform it into chemical energy. Upon exposure to light, the surface electrons and holes of the photocatalyst become activated, initiating oxidation-reduction reactions. These reactions facilitate the degradation of organic compounds and the conversion of heavy metals into less toxic forms or their precipitation [105, 106]. For instance, photoionization can reduce hexavalent chromium

(Cr^{6+}) to the less harmful trivalent chromium (Cr^{3+}), simplifying its removal from water.
Photocatalysis technology is characterized by several key features:

High pollutant removal efficiency
This technology has demonstrated substantial efficacy in eliminating a diverse array of pollutants, including heavy metals, underscoring its versatility [107].

Environmental sustainability
By utilizing light as an energy source, photoionization reduces the reliance on harmful chemicals, contributing to its environmentally friendly nature [105].

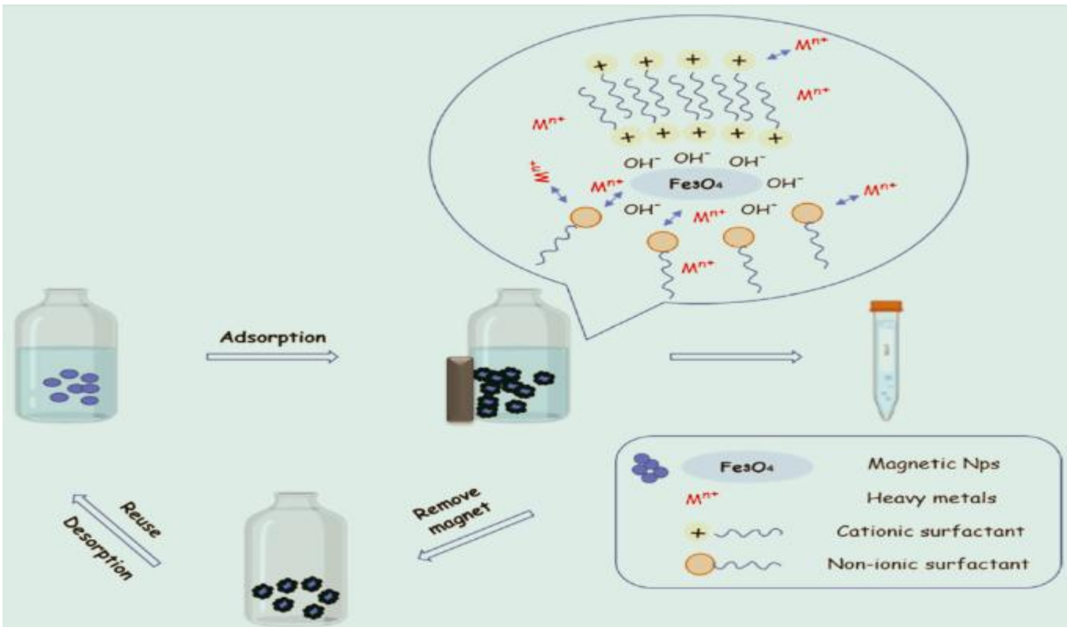

Fig. 5. Simple schematic of heavy metals adsorption using magnetic nanoparticles. Reproduced from [82] under the Creative Commons CC BY 4.0 license.

Table 3. Latest studies in the field of heavy metal removal using nanotechnology techniques.

Removed heavy metal(s)	Utilized nanomaterial or technology	Removal efficiency	Reference No.
Carbon –Nanomaterials			
Lead (Pb)	Functionalized carbon nanotube (CNT-COOH)	99%	[83]
Lead (Pb), Arsenic (As)	Carbon nanotube (single walled)-polysulfone nanocomposite-based membrane.	94%, 87%	[84]
Mercury (Hg)	Carbon nanotube (multiple walled)-CoS	166%	[85]
Lead (Pb) and Copper (Cu)	Carbon nanotube (multiple walled)	97%, 96%	[86]
Lead (Pb), Cadmium (Cd), and Mercury (Hg)	Graphen oxide-embedded calcium alginate	60%, 18%, and 37%	[87]
Copper (Cu), Nickel (Ni)	Reduced graphene oxide-Sulfophenylazo	6%, 6.6%	[88]
Chromium (Cr^{6+})	Oxidized graphene oxide-alphacyclodextrin-polypyrrole	66%	[89]
Chromium (Cr^{3+})	Reduced graphene oxide-Sulfophenylazo	19%	[90]
Cadmium (Cd)	Reduced graphene oxide-Sulfophenylazo	26.7%	[91]
Silica nanoparticles			

Mercury (Hg)	Thiol and Amino functionalized SBA-15 Silica	29%	[92]
Cadmium (Cd)	Amino functionalized silica gel in Tea Polyphenol extracts	99.7%	[93]
Zinc (Zn), Copper (Cu), and Chromium (Cr)	silica-based embedded with NiO and MgO nanoparticles	37.69, 69.68, 209.51 (mg adsorbate per g adsorbent)	[94]
Lead (Pb), Copper (Cu)	Saccharum ravannae-Silica nanoparticles	140.06 mg/ g and 149.25 mg/g	[95]
Lead (Pb)	SBA-15@BDA nanoparticle	112 mg/g (88%)	[96]
lead Pb (II) and chromium Cr (VI)	Nano-SiO_2 fabricated by the sol-gel technique.	82.3% and 78.5% for Pb (II) and Cr (VI)	[97]
lead Pb	Silica/klucel nanocomposite	95% with Max. adsorption capacity of 63.938 mg/g.	[98]
Nano magnetic			
Zinc (Zn)	Thiol-lignocellulosesodium bentonite (TLSB) nanocomposites	35.7%	[99]
Chromium (Cr), Cobalt (Co)	Magnetite nanoparticles modified with thiourea formaldehyde polymer	$\approx 100\%$	[100]
Lead (Pb), Cadmium (Cd)	$NiFe_2O_4$ nanomagnetic	61.4%, 64.3%	[101]
lead (Pb), chromium (CrT), and mercury (Hg)	Amino-functionalized iron oxide magnetic nanoparticles (γ-Fe_2O_3@NH_2)	for Hg^{2+} = 85.6 mg/g, CrT = 90.4 mg/g, and Pb^{2+} = 83.6 mg/g	[102]
Lead (Pb), Cadmium (Cd), and Nickel (Ni)	Carboxyl and thiol-functionalized magnetic nanoadsorbents	64.5, 53.9, and 27.18 mg/g	[103]
Arsenic (As)	Starch-coated magnetite nano-adsorbent	42.88 mg/g	[104]

Flexibility in application

The adaptability of photocatalysts allows for modification to target various pollutants and accommodate different operational conditions, enhancing the technology's versatility [106].

Cost-effectiveness

The use of sunlight as a radiation source significantly lowers operational expenses, rendering it an economical and efficient solution [107].

5.2.1. Technique challenges

Photocatalytic techniques are recognized as advanced methods for water treatment. Nonetheless, these techniques encounter several challenges and limitations that must be addressed for their effective enhancement and application. These challenges include:

1. Photocatalytic efficiency: Photocatalytic efficiency depends on the ability of the photonic material to absorb light and use it effectively to break down pollutants, which may sometimes be limited [108].
2. Photonic Material Degradation: Photonic materials can degrade over time due to constant exposure to light and contaminants, reducing their effectiveness [109].
3. Selectivity of catalysis: Photocatalysis may not be completely selective, meaning it may not be effective in removing all types of heavy metals with the same efficiency [110].
4. Energy requirement: Photocatalytic technologies require continuous light sources, which require significant energy savings and may increase operating costs [111].
5. Effect of environmental conditions: The efficiency of photocatalytic can be affected by environmental conditions such as temperature, pH, and concentration of other ions in the water [112].
6. Secondary waste management: The use of photonic materials may result in the

production of secondary waste that requires additional treatment [113].

7. Light Distribution: Uneven distribution of light within photocatalytic systems can result in uneven efficiency in pollutant removal [114].

5.2.2. Recent Advances in the Photocatalytic Removal of Heavy Metals from Industrial Wastewater

Photocatalysis has emerged as a promising and environmentally sustainable technique for the removal of heavy metals from industrial wastewater, offering considerable potential for large-scale applications. Many researchers with different ideas have tried to develop this technology to find the best removal efficiency of heavy metals with the least negative effects. Josué et al. utilized Niobium Pentoxide, (Nb_2O_5) as a catalyst for Cr(VI) removal. At pH = 2, radiation intensity of 250W, Cr (VI) concentration of 10 mg/L and 1.5 g/L Nb_2O_5 non-calcined, the process achieved highest removal.The research prove that Nb_2O_5 more efficient by 20% than TiO_2 in Cr reduction [115]. Other study utilized a hybrid technique combine photo catalysis (with TiO_2-ZrO_2)with ion exchange (using Lewatit TP207) for selective removal of acidic Cu(II)-Cr(VI) [116]. The results of this study was the separation efficacy of Cu(II)/Cr(VI) was 11,949 with a recovery of 99% for Cu(II) and 96.29% for Cr(VI).

The following highlights key recent developments in this field, as supported by findings from contemporary scientific research:

1. Innovative Photocatalyst Materials:

- **Two-Dimensional (2D) and Three-Dimensional (3D) Materials:** Materials such as graphene oxide and transition metal dichalcogenides have demonstrated remarkable photocatalytic efficiency, primarily attributed to their high surface area and unique electronic structures, which facilitate enhanced interaction with pollutants [117].
- **Metal–Organic Frameworks (MOFs):** MOFs, characterized by their tunable architectures and high porosity, have been effectively employed in the photocatalytic removal of heavy metals from industrial wastewater, offering both structural versatility and high reactivity [118].
- **Perovskite-Based Photocatalysts:** Perovskite materials are increasingly recognized for their significant photocatalytic potential, especially in solar-driven processes. Their favorable optical and electronic properties make them suitable for environmental remediation applications [119].
- **Nanocomposites:** Recent advancements highlight the development of nanocomposites—encompassing carbon-based, polymer-based, and semiconductor-based systems—as efficient platforms for the removal of heavy metals such as mercury, chromium, and arsenic. These materials offer tunable physicochemical characteristics that substantially improve adsorption capabilities and photocatalytic activity [120].
- **Doped Photocatalysts:** The introduction of metal or non-metal dopants into TiO_2 structures has been shown to enhance photocatalytic activity under visible light conditions. For instance, TiO_2 nanorods co-doped with rhodium and antimony have demonstrated exceptional performance in lead removal, largely due to improved light absorption and facilitated charge carrier transport [48].
- **MXenes:** MXene materials, such as $Ti_3C_2O_2$, are gaining increasing attention owing to their extensive surface area and excellent electrical conductivity. These features significantly contribute to their photocatalytic potential for heavy metal reduction. Notably, MXenes have shown a high selectivity in the removal of mercury ions from aqueous environments, positioning them as promising candidates for targeted water purification strategies [121].

2. Integration with Other Technologies:

- **Solar-Enhanced Photocatalysis:** The integration of solar energy into photocatalytic systems has emerged as a key advancement in promoting sustainable and scalable treatment solutions. Solar-driven photoreactors employing TiO_2 and other photocatalysts have demonstrated effective contaminant degradation, achieving quantum yields comparable to those attained under controlled laboratory conditions. This approach not only enhances environmental sustainability but also improves the energy efficiency of large-scale wastewater treatment processes [122].

- **Electro-Photocatalysis:** The combination of photocatalysis with electrochemical methods—referred to as electro-photocatalysis—has been explored to enhance the reduction of metal ions in wastewater. This synergistic integration accelerates reaction kinetics, improves removal efficiency, and optimizes energy utilization. As a result, it represents a promising avenue for future development in both industrial wastewater treatment and broader environmental remediation strategies [121].
- **Advanced Oxidation Processes (AOPs):** AOPs incorporating photocatalysis have been widely applied to generate hydroxyl radicals, which are highly reactive species capable of oxidizing and reducing heavy metal ions. These processes often involve UV light activation of photocatalysts, which substantially increases the efficiency of metal ion removal and enhances the rate of contaminant degradation. Such systems offer a powerful and effective approach to the treatment of heavy metal-contaminated wastewater [107].

5.3. Biotechnology

Biotechnology employs living organisms such as bacteria, fungi, algae, or their metabolic byproducts to aid in the removal of heavy metals from contaminated environments. This method is distinguished by its sustainability and environmental compatibility, presenting a greener and more eco-conscious alternative to conventional chemical and physical treatment techniques [123]. In contrast to traditional approaches, biotechnological processes are capable of efficiently targeting specific contaminants while significantly reducing adverse environmental impacts.

5.3.1. Mechanisms of Biotechnology in Heavy Metal Removal

1. Biosorption

Biosorption utilizes the capacity of microorganisms—such as bacteria, algae, and fungi—to bind heavy metal ions to their cell surfaces or structural components like cell walls. This process capitalizes on the physicochemical properties of microbial biomass to adsorb and immobilize metal ions from aqueous solutions. For instance, Pseudomonas species and microalgae such as Chlorella have demonstrated high biosorption capacities for metals like copper and cadmium [124].

2. Bioprecipitation

Bioprecipitation involves the microbial-mediated transformation of soluble metal ions into insoluble forms through specific biochemical pathways. Sulfate-reducing bacteria, for example, can convert toxic mercury ions into insoluble mercury sulfide. Gadd reported that bacterial strains such as Desulfovibrio are particularly effective in precipitating heavy metals in aquatic environments, thereby facilitating their removal [125].

3. Bioaccumulation

Bioaccumulation refers to the intracellular uptake and storage of heavy metals within microbial cells, where the metals may be sequestered or detoxified. Various studies have shown that algae and fungi can bioaccumulate metals like mercury and zinc within their cellular structures [123]. This process contributes to reducing both the mobility and toxicity of heavy metals in contaminated ecosystems.

5.3.2. Organisms Utilized for Heavy Metal Removal

1. Bacteria

Bacterial species such as Bacillus and Pseudomonas are widely employed in the remediation of heavy metal-contaminated water, particularly for the removal of metals like lead and chromium [4]. These microorganisms facilitate metal removal primarily through biosorption and bioprecipitation mechanisms, utilizing their metabolic and structural capabilities to interact with and immobilize metal ions. The removal of Cr (VI), Cd (II) and Pb (II) was investigated utilizing Microbacterium paraoxydans strain VSVM

IIT(BHU). The bacterial isolate presented a highest removal efficacy of 91.62% Cr (VI), 89.29% Pb (II), and 83.29% Cd (II) at 50 mg/L initial concentration of each metal [126].

2. Algae

Green microalgae, including Chlorella and Spirulina, have demonstrated high efficiency in biosorption processes, especially for metals such as copper and zinc. Their cell walls and internal structures possess functional groups that enable them to effectively adsorb and sequester heavy metals from aqueous environments [124]. The biosorption capacity of zinc (Zn) using Chlorella vulgaris was studied by Malakootian et al., 2016. Under the optimal operating conditions (temperature of 25°C, pH = 7, contact time of 60 min and adsorbent dose of 2g/L), Zn removal rate was reported to be 67.72% for actual wastewater and 90.23% for synthetic one [127].

3. Fungi

Fungal strains like Aspergillus and Trichoderma are effective agents in heavy metal remediation due to the presence of cell wall components capable of binding metal ions, including cadmium and mercury. These fungi also exhibit a strong capacity for bioaccumulation, making them valuable for bioremediation applications in both soil and aquatic systems [128]. Filamentous fungi isolated from the rhizosphere of plants was used to asses the heavy metals (Hg, Pb, Cu, Zn, and Cd) resistance and Hg remediation [129]. The heavy metals resistance of fungi, was in in the following order :Hg > Pb > Zn > Cu > Cd. The results showed an efficient removal of Hg^{2+} (up to 97%) and biosorption capacities (up to 54.9 mg/g).

5.3.3. Benefits of Biotechnology

- **Eco-Friendly**: Biotechnology avoids the use of harmful chemicals, reducing the potential for environmental damage, while also lowering the operational costs of treatment processes [125].
- **Cost-Effective**: The biological agents employed, such as microorganisms, are abundant and inexpensive, making this a cost-efficient solution for industries dealing with heavy metal contamination [124].
- **Adaptability and Versatility**: The organisms or biological derivatives can be engineered or tailored to target specific heavy metals and perform effectively under varying environmental conditions [4].

5.3.4. Challenges and Limitations in Advancing Biotechnological Techniques for Heavy Metal Removal

Despite the promising potential of biotechnology in the remediation of heavy metals from industrial wastewater, several challenges hinder its widespread application and optimization. These limitations, as highlighted in current scientific literature, include the following:

Environmental Stress Resistance

Microorganisms utilized in bioremediation processes often face difficulties in surviving and maintaining functionality under the extreme conditions commonly present in industrial wastewater, such as high acidity, salinity, or heavy metal toxicity [130]. These environmental stressors can limit microbial activity and reduce treatment efficiency.

Metal Selectivity

Biotechnological systems often demonstrate selective affinity toward certain metal ions, which restricts their applicability in treating complex wastewater containing multiple contaminants. Addressing this limitation requires the development of tailored microbial consortia or engineered organisms with broader or tunable metal-binding capabilities [131].

Scale-Up Limitations

Although laboratory-scale studies show considerable potential, translating these findings into industrial-scale operations presents significant technical and economic hurdles. Ensuring consistent performance and cost-effectiveness during scale-up remains a key barrier to practical implementation [132].

Biomass Recovery and Reusability

A critical issue for sustainable application is the efficient recovery and reuse of microbial biomass after biosorption or bioaccumulation. Maintaining the biological integrity and metal-binding functionality of the biomass through multiple treatment cycles remains a considerable technical challenge [133].

5.3.5. Recent Advances in Biotechnological Removal of Heavy Metals from Industrial Wastewater

Recent progress in the biotechnological treatment of industrial wastewater has focused on harnessing diverse microorganisms and integrating emerging technologies to enhance the removal of heavy metals. This review highlights notable developments and innovative approaches in the field.

Bioremediation Strategies

- Microbial Bioremediation

  Various microorganisms, including bacteria, fungi, and algae, have shown significant potential in the detoxification of heavy metals through mechanisms such as biosorption, bioaccumulation, and biotransformation.

  Recent studies have emphasized the promising capabilities of marine-derived microorganisms, which exhibit exceptional resilience in extreme environmental conditions and demonstrate high efficiency in the remediation of metal-contaminated environments [130].
- Nanotechnology-Enhanced Bioremediation

  The integration of nanotechnology into bioremediation has emerged as a powerful approach to improving treatment outcomes.

  Nanoparticles can enhance the performance of microbial systems by increasing the adsorption of metal ions and facilitating their transport to microbial cells, thereby significantly boosting overall remediation efficiency [131].
- Phytoremediation

  The use of plants in conjunction with microbial communities for heavy metal removal has gained increasing attention. Certain plant species possess the capacity to absorb and accumulate metals from contaminated soils and water. When combined with microbial processes, this synergistic approach can substantially improve the efficacy of bioremediation efforts [134].

5.4. Membrane Filtration Technologies for Heavy Metal Removal

Membrane-based separation processes have gained prominence as effective and sustainable solutions for treating heavy metal-contaminated water.

This section evaluates four principal membrane technologies—microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)—focusing on their respective mechanisms, applications, and performance characteristics in heavy metal remediation.

Membrane filtration relies on selective permeability to physically separate contaminants from water.

The effectiveness of each technique depends on membrane pore size, operational pressure, and target pollutant characteristics, allowing for tailored treatment approaches.A simple explanation of these differences is illustrated in Figure 6.

Microfiltration (MF)

MF membranes (0.1–10 μm pore size) primarily remove suspended solids and microbial contaminants. Although limited in direct heavy metal removal, MF demonstrates enhanced performance when integrated with coagulation or adsorption processes [135].

Ultrafiltration (UF)

UF membranes (0.01–0.1 μm) effectively retain macromolecules, colloids, and certain metal complexes, especially when combined with complexing agents. This technology is frequently employed as a pretreatment for NF or RO systems [136].

Nanofiltration (NF)

NF membranes (nanometer-scale pores) selectively remove multivalent heavy metal ions (e.g., Pb^{2+}, Cd^{2+}, Cr^{3+}) while permitting monovalent ion passage, making them particularly suitable for industrial wastewater treatment [137]. A practical study to assess the performance of thin-film composite nanofiltration (NF) hollow-fiber membranes to remove heavy metals from actual electroplating wastewater was conducted. The membrane showed satisfactory stability with a pH of 2.31, and for 0.4 MPa, the removal efficiencies for Cr, Cu, and Ni ions were 95.76%, 95.33%, and 94.99%, respectively [138].

Reverse Osmosis (RO)
RO membranes (0.1–1 nm pores) achieve near-complete dissolved solids removal, including heavy metals. Despite its high efficiency, RO faces operational challenges such as significant energy demands and membrane fouling [139].

Fig. 6. Schematic of the separation capabilities of different membranes. Reproduced from [48] under the Creative Commons CC BY 4.0 license.

5.4.1. Mechanisms of Heavy Metal Removal in Membrane Systems

The removal efficiency of heavy metals through membrane processes is governed by three principal mechanisms:

Size Exclusion
Microfiltration (MF) and ultrafiltration (UF) membranes primarily operate through physical sieving, retaining particulates and macromolecules larger than their pore diameters. While dissolved metal ions typically pass through these membranes due to their small ionic radii, pretreatment with complexation agents can significantly enhance removal efficiency by increasing the effective size of metal species [140].

Electrostatic Interactions
Nanofiltration (NF) and reverse osmosis (RO) membranes exhibit surface charge characteristics that facilitate ion rejection through Donnan exclusion. The high charge density of multivalent heavy metal ions (e.g., Pb^{2+}, Cr^{3+}) enhances their removal efficiency compared to monovalent species. Guo et al. (2022) established that these charge-mediated separation mechanisms in NF systems outperform conventional filtration approaches by 30-40% [73].

Ligand-Assisted Complexation
UF systems achieve improved metal removal when coupled with chelating agents that form stable, high-molecular-weight complexes. Fu and Wang (2011) documented removal efficiencies exceeding 90% for Cu^{2+} and Ni^{2+} using polyelectrolyte-enhanced ultrafiltration, demonstrating the effectiveness of this hybrid approach for industrial wastewater treatment [4].

5.4.2. Challenges and Future Perspectives in Membrane Technology Implementation

Despite the demonstrated efficacy of membrane-based separation systems, several critical challenges must be addressed to optimize their widespread adoption:

Membrane Fouling
The accumulation of particulate and organic matter on membrane surfaces remains a persistent operational challenge, resulting in reduced permeate flux and increased energy demands. Current mitigation strategies, including advanced pretreatment protocols and surface functionalization techniques, show promise in extending membrane service life while maintaining separation efficiency [141].

Economic Viability
The substantial capital expenditure and operational costs associated with membrane systems currently limit their accessibility. Future research directions should prioritize the development of novel, cost-effective membrane materials and streamlined process configurations to enhance economic feasibility [142].

Sustainable Operation
The environmental sustainability of membrane technologies requires improved regeneration protocols and recycling methodologies.

Innovations in membrane cleaning, recovery, and reuse present significant opportunities to reduce waste generation and minimize the ecological impact of these systems [143].

5.4.3. Recent Progress in Membrane Technologies

Recent advancements in membrane technology have focused on enhancing membrane performance through various material and structural modifications. Key developments include:

Polymeric Membranes
Recent studies have demonstrated that functionalization of polymeric membranes with specific chemical groups can significantly improve their selectivity toward heavy metal ions. This enhancement contributes to greater separation efficiency and increased permeability, making polymeric membranes more effective for heavy metal removal [142].

Hybrid Membranes
The integration of different membrane materials or the incorporation of adsorptive components has led to notable improvements in removal efficiency. Chitosan-based membranes, in particular, have shown strong potential due to their high adsorption capacities for various heavy metals, making them suitable candidates for advanced water treatment applications [141].

Nanotechnology-Enhanced Membranes
The application of nanomaterials in membrane fabrication has yielded significant progress in addressing issues such as membrane fouling and limited selectivity.
Membranes embedded with nanomaterials exhibit improved antifouling characteristics and enhanced removal efficiency of heavy metal ions, representing a major step forward in the development of high-performance water purification systems [144].

5.5. Electrochemical Techniques

Electrochemical methods have attracted significant attention for the removal of heavy metals from industrial wastewater due to their high efficiency, cost-effectiveness, and capacity to treat complex and variable waste streams. Among the most prominent electrochemical approaches are electrocoagulation and electrooxidation.
Electrocoagulation involves the destabilization and subsequent precipitation of metal ions, while electrooxidation relies on oxidative processes to degrade or transform contaminants. These techniques offer promising solutions for industrial wastewater treatment, particularly when dealing with diverse contaminant profiles.

5.5.1. Electrochemical Technologies for Heavy Metal Removal

Electrocoagulation is one of the most extensively studied electrochemical techniques for heavy metal remediation. It operates through the dissolution of sacrificial metal anodes, typically composed of iron or aluminum, which generate metal hydroxides during electrolysis. These hydroxides act as coagulants, promoting the aggregation and removal of dissolved metal ions from wastewater [145, 146]. The resulting precipitates adsorb metal ions, thereby enabling the effective removal of a wide range of heavy metal contaminants [147].
A study by Stylianou et al. (2023) demonstrated the effectiveness of electrocoagulation in treating electroplating wastewater, reporting removal efficiencies exceeding 99% for metals such as zinc, copper, and nickel under optimized conditions [148]. Similarly, Mao et al. (2023) emphasized the technique's potential for removing arsenic and chromium, achieving over 90% removal efficiency under favorable operational parameters [147]. These findings affirm electrocoagulation's applicability for industrial wastewater treatment.
A study was conducted on the removal of nickel from synthesized and actual industrial wastewater using electrocoagulation process with zinc anode. The optimal operating conditions (spacing between electrodes = 4 cm, time 90 = min, and the current density= 10 mA/cm^2) achieved maximum removal rate (99.89%) of Ni [149].
In Egypt, other study on factual tannery wastewater was conducted to remove chromium utilizing iron based electrocoagulation process. Using the optimum operating conditions (15 V, 0.4 mA/cm^2, 200 rpm, 330 ppm chromium, 8 iron electrodes with a total surface area of 0.1188 m^2, 3 h), maximum removal rate of chromium was

98.76%. Iron electrode consumption, power, and costs were 0.99 gm/L, 0.0143 kW-h/L, and 160 EGP/kg of chromium removed, respectively [150].

Further advancements have been made by integrating electrocoagulation with complementary processes. Twizerimana and Wu (2024) explored a hybrid approach combining electrocoagulation with adsorption [151]. Their study reported improved efficiency and cost-effectiveness in the removal of heavy metals such as lead and cadmium, highlighting the potential of multi-process strategies to enhance treatment outcomes and reduce operational expenses.

Electrooxidation employs an electric current to generate reactive oxidative species capable of transforming heavy metal ions or degrading associated organic compounds. The process primarily involves the production of hydroxyl radicals, which facilitate the oxidation of metal species into less toxic or more readily removable forms. Additionally, electrooxidation can break down organic-metal complexes, thereby enhancing the overall removal of heavy metals from wastewater [152, 153].

In a study by Shaker et al. (2023), electrooxidation using zinc electrodes achieved a maximum nickel removal efficiency of 99.9% under optimal conditions, underscoring the method's high effectiveness for specific metals [149].

Similarly, Mirshafiee et al. (2024) applied electrooxidation using mixed metal oxide electrodes for the treatment of petrochemical wastewater. Their results indicated a 79% reduction in chemical oxygen demand (COD) and substantial heavy metal removal, supporting the utility of this approach for complex effluent compositions[152].

Additionally, Shaogang et al. (2021) examined the use of electrooxidation in conjunction with Fe(II) ions as a co-agent. Their findings revealed enhanced removal of lead and cadmium, as well as improved sludge dewatering performance [155]. This suggests that integrating electrooxidation into conventional wastewater treatment processes may offer dual benefits: increased contaminant removal and reduced sludge volume, presenting a robust solution for heavy metal remediation in treatment facilities.

5.5.2. Challenges and Limitations

Despite the benefits of electrochemical methods, there are some notable challenges:

- **Energy Costs:** Significant energy requirements, particularly for electrooxidation and electrodeposition, can pose a challenge for large-scale implementations [145].
- **Electrode Degradation:** Electrodes may suffer from fouling or degradation over time, which can decrease their effectiveness and require regular maintenance [156].

5.5.3. Recent Developments

Recent advancements in electrochemical technologies for the removal of heavy metals from wastewater have focused on enhancing treatment efficiency, reducing energy consumption, and improving the performance of electrode materials. Notable developments include the following:

Electrocoagulation: Significant progress has been made in optimizing electrode materials and configurations, leading to improved removal efficiencies. Researchers have explored the use of hybrid electrode systems and refined operational parameters to enhance process performance and adaptability under varying wastewater conditions [157].

Electrooxidation: Innovations in anode materials, particularly the use of boron-doped diamond (BDD) and mixed metal oxides (MMO), have contributed to greater stability and higher treatment efficiency. In addition, recent studies have investigated the integration of electrooxidation with complementary treatment methods, resulting in synergistic effects that improve the overall effectiveness of contaminant removal [158].

6. Comparative Analysis of Emerging Technologies

This section focuses on evaluating the performance, environmental implications, sustainability contributions, and economic feasibility of various advanced technologies used for the removal of heavy metals from industrial wastewater. The technologies under comparison include nanotechnology, Photocatalysis processes, biotechnological approaches, membrane technologies, and electrochemical methods, as summarized in Table 4.

Table 4. Comparative Analysis of Emerging Technologies

Technology	**Efficiency**	**Environmental impact**	**Sustainability and environmental impact**	**Cost**
Nanotechnology	High removal efficiency due to large surface area and reactivity of nanomaterials (e.g., carbon nanotubes, graphene).	Potential concerns regarding the environmental persistence and toxicity of nanoparticles.	Promising for sustainability, especially with green synthesis, but challenges with recycling and regeneration.	High production costs for nanomaterials, though improvements in synthesis are reducing these expenses.
Photocatalysis	Highly efficient under light conditions (e.g., UV light), converting metals to less harmful forms or promoting precipitation.	Generally, environmentally friendly, using renewable light energy, but efficiency can be limited under natural light.	Sustainable, with potential for catalyst reuse, though degradation over time may pose issues.	Photocatalysts like TiO_2 are inexpensive, but system costs increase due to energy demands (artificial light, system maintenance).
Biotechnology	Effective for low-concentration metal removal through bioaccumulation using microorganisms, enzymes, or plants (phytoremediation).	Eco-friendly with minimal environmental impact but managing biological waste and maintaining optimal conditions is a challenge.	Highly sustainable, relying on natural processes, but slow growth and long treatment times can limit scalability.	Low-cost inputs, but operational costs can rise due to long treatment times and need for controlled environments.
Membrane Technologies	High removal efficiency with selective filtration of heavy metals, even at trace concentrations (e.g., nanofiltration, reverse osmosis).	Produces concentrated waste streams; potential for membrane fouling, requiring chemical cleaning.	Sustainable if membrane regeneration and waste management are optimized; high energy demands for some processes.	High capital and operational costs due to energy consumption, membrane replacement, and maintenance
Electrochemical	High efficiency for electrochemically active metals with controllable, precise removal (e.g., electrocoagulation, electrodialysis, electrodeposition)	Can generate sludge or other byproducts, but avoids chemical additives, reducing secondary pollution.	Sustainable with potential for metal recovery and no chemical use, but reliant on electricity, which may limit long-term sustainability if sourced from non-renewables.	High initial investment; operating costs depend on electricity prices, though renewable energy integration can enhance cost-effectiveness

7. Modern Techinques as Supplementary Treatment

The utilizing of modern techniques such as nanotechnology, Photocatalytic degradation, biotechnological approaches, advanced membrane filtration systems, and electrochemical processes as supplementary or tertiary treatment with the conventional methods has become common practice especially for persistent pollutants like heavy metals. This hybrid procedure has been followed in wastewater treatment plants to overcome most of the limitations of the conventional techniques and achieving higher removal efficiencies. Many studies investigated the efficacy of this integrated strategy by utilizing different modern techniques after the conventional processes to remove heavy metals from industrial wastewater and proved its success [14, 159-161].

8. Conclusion

This study highlights that the application of modern technologies for the removal of heavy metals from industrial wastewater represents a promising direction toward achieving effective and sustainable treatment solutions for these hazardous contaminants. While conventional methods—such as chemical precipitation, adsorption, and ion exchange—have demonstrated proven efficacy, they often suffer from drawbacks including high operational costs and substantial chemical usage.

In contrast, advanced techniques such as nanotechnology, photocatalytic oxidation, advanced membrane systems, and biotechnological interventions offer notable advantages in terms of removal efficiency and the potential for pollutant degradation. However, these approaches are not without their challenges, including concerns related to economic feasibility, scalability, energy consumption, and safety.

Each treatment technology presents distinct strengths and limitations. Nanotechnology and membrane-based processes offer high removal efficiencies but raise issues regarding cost-effectiveness and environmental sustainability. Photocatalysis provides a promising green alternative; nevertheless, its high energy requirements can hinder large-scale deployment. Biotechnological methods offer environmentally friendly solutions but remain constrained by difficulties in upscaling.

Electrochemical techniques deliver precision and potential for metal recovery, though their energy demands and byproduct handling require careful management.

The choice of an appropriate treatment method must be guided by the specific characteristics of the wastewater, the operational context, and overarching sustainability objectives. To enhance the performance and viability of these technologies, the study recommends strategies such as improving the recovery of nanomaterials and lowering the production costs of membranes.

Ultimately, this work seeks to inform researchers and practitioners in selecting the most suitable and context-appropriate approaches for the treatment of heavy metal-contaminated water, balancing environmental, economic, and technical considerations to foster integrated and sustainable water treatment solutions.

Author's contribution

The author solely conceived the study, conducted the literature search, synthesized the evidence, and wrote and approved the final manuscript.

Conflict of interest

No potential conflict of interest was reported by the authors.

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