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Cobalt, Copper, and Manganese Contamination in Water: A Comprehensive Review

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A B S T R A C T

Access to clean and safe water is vital for human health and environmental sustainability. Heavy metal contamination remains a major global concern due to the toxic and persistent nature of these pollutants. Among them, cobalt (Co), copper (Cu), and manganese (Mn) are particularly significant because of their prevalence in industrial effluents and their harmful ecological and health impacts. This review summarizes the sources, effects, and treatment strategies for these metals, comparing conventional and emerging technologies. While physicochemical and electrochemical methods such as precipitation, ion exchange, and membrane filtration are effective, they face limitations related to cost, sludge generation, and energy consumption. Adsorption has emerged as a promising alternative owing to its efficiency, simplicity, and adaptability. Recent advances highlight biochar and agricultural waste–derived adsorbents as sustainable, low-cost, and scalable solutions. However, large-scale validation and hybrid system integration remain key research needs. The review underscores the growing potential of biological and adsorption-based methods to advance sustainable and cost-effective water treatment technologies.

1. Introduction

Access to clean and safe water is fundamental to human health, socioeconomic development, and the sustainability of ecosystems. Beyond its role in sustaining life, water is a cornerstone of economic productivity, agricultural practices, and industrial growth[1–3]. From an ecological perspective, uncontaminated water bodies are critical for maintaining biodiversity, regulating climate, and supporting the natural balance of aquatic and terrestrial habitats. Thus, the quality of water directly influences public health, food security, and environmental resilience[4–8].

Despite its importance, the world is currently facing an escalating crisis of water scarcity and pollution. Rapid population growth, urbanization, and industrialization have intensified the demand for freshwater while simultaneously contributing to its degradation[4,9–11]. Industrial effluents, mining operations, agricultural runoff, and domestic discharges are major sources of water contamination. These pressures are compounded by climate change, which alters hydrological cycles and exacerbates freshwater shortages. Consequently, access to clean water is increasingly threatened in both developed and developing nations, posing significant global challenges[12–15].

Among the many pollutants affecting water systems, heavy metals are of particular concern due to their persistence, bioaccumulation potential, and toxicity even at trace concentrations[16,17]. Unlike organic pollutants, heavy metals do not degrade in the environment, leading to long-term contamination of soil, sediments, and water resources[18–21]. Once introduced into aquatic systems, they can enter the food chain, accumulate in living organisms, and pose serious risks to human and ecological health. Chronic exposure has been linked to neurological, cardiovascular, and developmental disorders, as well as the decline of aquatic biodiversity[22–25].

This review focuses on three heavy metals of growing environmental concern: cobalt (Co), copper (Cu), and manganese (Mn)[26,27]. These metals are widely used in industrial processes, technological applications, and consumer products, which has led to their frequent detection in natural waters. While they are essential trace elements in small amounts, excessive concentrations can have severe toxicological effects. This review aims to provide a systematic overview of the sources, environmental behavior, and health impacts of Co, Cu, and Mn in aquatic environments, as well as to evaluate the available methods for their removal from contaminated water[28–30].

The novelty of this review lies in its integrated focus on Co, Cu, and Mn metals that are often studied individually but rarely examined together in the context of water contamination. By bringing these three metals into a single framework, the review highlights both their unique and overlapping pathways of environmental contamination and toxicity. Furthermore, it synthesizes conventional and emerging treatment strategies, with particular emphasis on adsorption-based and eco-friendly technologies, thereby providing a consolidated reference for researchers, practitioners, and policymakers working toward sustainable water management.

2. Heavy Metals in Water Pollution

2.1. General Characteristics of Heavy Metals

Heavy metals represent one of the most critical groups of pollutants in aquatic systems due to their non-biodegradable nature and long-term persistence in the environment. Unlike organic contaminants, which can often be degraded biologically or chemically, heavy metals remain stable and tend to accumulate in sediments, soils, and living organisms[31–34]. Even at very low concentrations, many of these elements are highly toxic and pose serious risks to both human health and ecological systems[22,35,36].

A major concern associated with heavy metals is their ability to undergo bioaccumulation and biomagnification. Bioaccumulation refers to the gradual buildup of metals in the tissues of individual organisms, while biomagnification describes the increasing concentration of these metals as they move upward through the food chain. This process results in higher exposure levels for top predators, including humans, which can lead to severe health consequences such as organ damage, neurological disorders, and carcinogenic effects.[37–39]

Due to these risks, international organizations have established strict regulatory guidelines for acceptable levels of heavy metals in drinking water. The World Health Organization (WHO), the European Union (EU), and the United States Environmental Protection Agency (US EPA) have each set maximum permissible limits for various metals to ensure safe water consumption. These limits vary depending on the metal, reflecting differences in toxicity thresholds, health impacts, and environmental persistence. Following these standards is crucial for safeguarding public health and for directing global water treatment and pollution control efforts, as shown in **Table 1**.

Table 1. Drinking water guideline values for Co, Cu, and Mn (WHO, EU, US EPA)

Heavy Metal	**WHO Guideline Limit**[40]	**EU Drinking Water Directive**[41]	**US EPA Drinking Water Standards**[42]
Cobalt (Co)	No specific guideline: suggested ≤ **0.05 mg/L** (provisional based on health concerns)	Not specifically regulated	Not specifically regulated
Copper (Cu)	**2.0 mg/L** (health-based guideline value)	**2.0 mg/L** (parametric value)	**1.3 mg/L** (Action level under Lead and Copper Rule)
Manganese (Mn)	**0.4 mg/L** (health-based guideline value)	**0.05 mg/L** (aesthetic/parametric value for color/taste)	**0.05 mg/L** (Secondary Maximum Contaminant Level – SMCL, aesthetic); Health advisory: **0.3 mg/L**

The comparison of international drinking water standards reveals notable variations in how cobalt, copper, and manganese are regulated. While cobalt does not have specific enforceable limits under EU or US EPA standards, the WHO provisional guideline of 0.05 mg/L reflects growing concern about its potential toxicity, indicating that it is an emerging contaminant requiring closer monitoring. In contrast, copper is tightly regulated across all frameworks due to its dual role as an essential micronutrient and a toxicant at higher concentrations; however, the US EPA applies an "action level" of 1.3 mg/L under the Lead and Copper Rule, focusing on corrosion control in water distribution systems rather than a fixed maximum limit. For manganese, stricter limits exist in the EU (0.05 mg/L) and US EPA (0.05 mg/L, secondary standard), largely due to its aesthetic impacts such as discoloration and taste, whereas the WHO guideline (0.4 mg/L) is based on health considerations. These differences highlight the balance between health-based thresholds and aesthetic water quality standards, as well as the varying levels of concern attributed to each metal in different regulatory contexts.

2.2. Cobalt (Co)

2.2.1. Sources and Behavior in Water

Cobalt is a transition metal found in the Earth's crust in trace amounts, often associated with nickel and copper ores. Anthropogenic activities are the primary contributors to cobalt contamination in aquatic systems. Major sources include mining and smelting of cobalt- and nickel-bearing ores, industrial effluents from electroplating, pigments, batteries, and alloys, as well as leaching from waste disposal sites. In water, cobalt is most commonly present in the Co^{2+} oxidation state, although it can also exist as Co^{3+} under oxidizing conditions. Its solubility and transport depend on pH, redox potential, and the presence of complexing agents such as organic matter and carbonate ions[43–45].

2.2.2. Health and Ecological Impacts

Cobalt is recognized as both an essential micronutrient and a potential toxicant. In trace amounts, it is required for the synthesis of vitamin B12 and the regulation of red blood cell production. However, excessive exposure to cobalt can lead to adverse health effects, including cardiomyopathy, thyroid dysfunction, neurological disorders, and potential carcinogenicity. Chronic ingestion of cobalt-contaminated water may also result in gastrointestinal irritation and systemic toxicity. Ecologically, cobalt bioaccumulates in aquatic organisms and can disrupt enzymatic activity, impair reproduction, and reduce biodiversity, particularly in sensitive freshwater ecosystems[46–49].

2.2.3.Guideline Limits

Unlike copper and manganese, cobalt does not yet have universally harmonized regulatory limits in drinking water. The WHO has proposed a provisional guideline value of 0.05 mg/L, reflecting concerns about its toxicity at higher concentrations. However, neither the EU

Drinking Water Directive nor the US EPA currently specify a maximum contaminant level (MCL) for cobalt. This regulatory gap underscores the need for continued monitoring and research, as cobalt use in industrial and technological applications continues to expand, raising the potential for environmental release and human exposure[40].

2.3. Copper (Cu)

2.3.1.Sources and Behavior in Water

Copper is an essential trace element widely used in industrial, agricultural, and domestic applications. Major sources of copper contamination in aquatic systems include mining activities, electroplating, smelting operations, corrosion of copper pipes, industrial effluents, and the use of copper-based pesticides and algaecides. In natural waters, copper exists in both dissolved ionic forms (Cu^{2+}, Cu^{+}) and complexed forms with organic ligands and particulates. Its mobility and bioavailability are strongly influenced by pH, redox potential, and the presence of organic matter. While copper is necessary in small amounts for biological functions, excessive concentrations can be toxic[50–53].

2.3.2. Health and Ecological Impacts

Copper plays a physiological role in enzyme function and hemoglobin synthesis; however, at elevated levels, it becomes harmful. Acute copper exposure can lead to gastrointestinal distress, liver and kidney damage, and neurological effects, while chronic exposure has been linked to Wilson's disease and hepatic toxicity. Ecologically, copper is particularly toxic to aquatic organisms, impairing fish gill function and enzyme systems, and disrupting microbial community balance in sediments. Because of its dual role as an essential nutrient and a toxicant, maintaining copper within safe limits is critical[54–56].

2.3.3. Guideline Limits

The WHO guideline value for copper in drinking water is 2 mg/L, primarily to protect against acute gastrointestinal effects. The EU sets a parametric value of 2 mg/L, consistent with WHO recommendations, while the US EPA does not prescribe a maximum contaminant level (MCL) but instead enforces an action level of 1.3 mg/L under the Lead and Copper Rule, focusing on controlling corrosion in distribution systems. These differences underscore the fact that copper standards are designed not only around toxicity thresholds but also around practical issues such as plumbing system integrity and corrosion control[40].

2.4. Manganese (Mn)

2.4.1.Sources and VBehavior in Water

Manganese is a naturally occurring transition metal widely distributed in soils, sediments, and groundwater. Anthropogenic inputs arise from mining, steel and alloy production, battery manufacturing, fertilizers, and wastewater discharges. In aquatic environments, manganese exists in multiple oxidation states, most commonly as Mn^{2+} in soluble form under reducing conditions and as insoluble oxides (Mn^{3+}, Mn^{4+}) in oxidizing environments. Its mobility is strongly dependent on redox conditions, pH, and microbial activity. Seasonal fluctuations in groundwater and reservoirs often influence manganese solubility, making it a persistent operational challenge in water treatment[57,58].

2.4.2.Health and Ecological Impacts

Although manganese is an essential nutrient required for bone formation and enzyme function, excessive exposure can have adverse effects. Elevated concentrations in drinking water have been associated with neurological disorders, impaired cognitive development in children, and Parkinsonian-like symptoms due to its accumulation in the brain. From an ecological standpoint, high manganese levels can alter microbial community structures, reduce biodiversity, and cause toxicity in aquatic plants and animals. Additionally, manganese in water can cause aesthetic issues, such as discoloration, metallic taste, and staining of plumbing fixtures, which, although not directly health-related, affect consumer acceptability[59,60].

2.4.3.Guideline Limits

The WHO guideline value for manganese in drinking water is 0.4 mg/L, set to prevent neurotoxic effects. In contrast, the EU and US EPA both adopt a stricter limit of 0.05 mg/L, but primarily as an aesthetic or secondary standard related to water quality acceptability rather than health. This discrepancy reflects the dual nature of manganese regulation, where both health risks and consumer perception play roles in establishing safe levels[40].

3. Methods for Removal of Heavy Metals

The removal of heavy metals from contaminated water is a critical challenge due to their persistence, non-biodegradable nature, and toxic effects even at low concentrations. Over the years, a wide range of treatment technologies has been developed, broadly categorized into conventional physicochemical methods and emerging biological or adsorption-based approaches. Each method offers specific benefits and drawbacks regarding efficiency, cost, scalability, and environmental sustainability, as shown in **Table 2**.

Table 2. Comparison of Cobalt, Copper, and Manganese in Water Pollution

Metal	Main Sources	Behavior in Water	Health Impacts	Ecological Impacts	Guideline Limits
Cobalt (Co)	Mining & smelting of cobalt/nickel ores; electroplating; pigments; batteries; waste leachates	Commonly as Co^{2+} (soluble); mobility depends on pH, redox, and organic complexation	Essential for vitamin B12; excess causes cardiomyopathy, thyroid dysfunction, neurological issues, potential carcinogenicity	Bioaccumulation in aquatic organisms; disrupts enzymatic activity, reduces biodiversity	WHO: 0.05 mg/L (provisional); EU: not specified; US EPA: not specified
Copper (Cu)	Mining, smelting, electroplating, corrosion of pipes, industrial effluents, pesticides/algaecides	Exists as Cu^{2+}/Cu^{+} (ionic and complexed forms); influenced by pH, redox, organic ligands	Essential micronutrient; excess causes gastrointestinal distress, liver/kidney damage, Wilson's disease	Toxic to fish and microbes; disrupts enzyme systems; ecological imbalance	WHO: 2 mg/L; EU: 2 mg/L; US EPA: 1.3 mg/L (action level)
Manganese (Mn)	Natural weathering, mining, steel/alloy production, batteries, fertilizers, wastewater	Mn^{2+} (soluble under reducing conditions), Mn^{3+}/Mn^{4+} oxides under oxidizing conditions; mobility controlled by redox and microbial activity	Essential nutrient; excess causes neurotoxicity, cognitive impairment, Parkinsonian symptoms	Alters microbial communities; toxic to aquatic life; aesthetic issues (color, taste, staining)	

3.1. Conventional Physicochemical Methods

3.1.1.Chemical Precipitation

Chemical precipitation is one of the most widely used methods for removing heavy metals from wastewater. It involves the addition of chemical reagents, such as lime, sodium hydroxide, or sulfides, to convert dissolved metal ions into insoluble hydroxides, carbonates, or sulfides that can be separated as sludge. While effective for treating water with high metal concentrations, this method generates large volumes of sludge, which require safe disposal. Additionally, it becomes less efficient at very low metal concentrations, limiting its applicability for stringent water quality standards[61,62].

3.1.2.Coagulation and Flocculation

Coagulation and flocculation are commonly employed to enhance the removal of fine particles and metal contaminants. Coagulants such as aluminum sulfate or ferric chloride destabilize suspended particles, while flocculants promote aggregation into larger flocs that can be removed through sedimentation or filtration. This process is effective in reducing turbidity and metal content but is often used in combination with other treatment methods. The drawbacks include chemical costs and secondary pollution from residual coagulants[63–65].

3.1.3.Ion Exchange

Ion exchange is a highly selective method that uses synthetic resins to exchange undesirable metal ions in water with more benign ions such as sodium or hydrogen. This technique provides high removal efficiency, even at low concentrations, and can be regenerated for repeated use. However, ion exchange resins are expensive, sensitive to fouling, and less effective in treating wastewater with complex mixtures of contaminants or high total dissolved solids[66,67].

3.1.4.Membrane Filtration

Membrane-based separation processes, including reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF), are increasingly applied in heavy metal removal. These technologies offer excellent removal efficiencies and can produce high-quality treated water. Reverse osmosis and nanofiltration, in particular, are effective at removing dissolved heavy metal ions. However, membrane fouling, high operational costs, and energy requirements are significant challenges that limit large-scale application, especially in resource-limited settings [68–71].

3.1.5.Electrochemical Treatment

Electrochemical methods such as electrocoagulation, electroflotation, and electrodeposition use electrical currents to destabilize metal ions and facilitate their removal from water. These processes can achieve high removal efficiencies and reduce chemical usage. Nonetheless, the requirement for high energy input, specialized equipment, and operational expertise makes them less feasible for widespread application in developing countries[72,73].

3.2. Biological and Adsorption-Based Methods

Biological and adsorption-based approaches have emerged as highly effective and sustainable alternatives for the treatment of heavy metal–contaminated water. Adsorption using activated carbon is one of the most widely applied methods due to its excellent surface area, pore structure, and adsorption efficiency. It can effectively remove trace levels of metals such as cobalt, copper, and manganese. However, the relatively high production and regeneration costs of commercial activated carbon often limit its large-scale application, especially in developing regions[74–77].

To overcome these limitations, researchers have increasingly focused on low-cost agricultural by-products as bio-adsorbents. Materials such as lemon peel, maize tassel, reed biomass, coconut shell, and rice husk have been explored due to their natural abundance, biodegradability, and the presence of functional groups (e.g., hydroxyl, carboxyl) that enhance metal binding capacity. These waste-derived adsorbents not only reduce treatment costs but also contribute to waste valorisation and circular economy practices.

Another promising direction is the use of biochar and biosorption techniques, which utilize microorganisms, algae, or biomass-derived carbonaceous materials to sequester metals. Biochar, in particular, offers a high surface area and tunable surface chemistry, while biosorption harnesses the metabolic and structural properties of microbial biomass. As outlined in **Table 3**, both approaches are considered eco-friendly, cost-effective, and scalable, making them strong candidates for future industrial and municipal wastewater treatment systems.

Table 3. Comparison of Biological and Adsorption-Based Methods for Heavy Metal Removal

Method	Adsorption Efficiency	Cost	Scalability	Eco-friendliness	Key Limitations
Activated Carbon (Commercial)	Very high (up to >95%)	High (production & regeneration expensive)	Scalable but costly	Moderate	High cost, regeneration challenges

Agricultural By-products (Bio-adsorbents)	Moderate–high (60–90%)	Low (waste materials, widely available)	Easily scalable (abundant feedstock)	High (waste valorization, biodegradable)	Variable performance, less durable
Biochar	High (70–95%)	Low–moderate (depends on feedstock & pyrolysis conditions)	Scalable with proper production systems	High (carbon sequestration potential)	Requires optimization of properties
Biosorption (Microbial/Algal Biomass)	High (up to 90%)	Low (biomass cultivation cheap)	Scalable in controlled systems	Very high (natural, renewable)	Biomass recovery and reuse challenges

3.2.1. Low-Cost Adsorbents, Biochar, And Biosorption

To provide a clearer quantitative comparison of adsorption and biological methods, Table 4 summarizes the removal efficiencies, regeneration capacities, and approximate costs reported in recent studies. These data highlight the competitive performance and sustainability of bio-based adsorbents compared to conventional activated carbon.

Table 4. Comparative performance of adsorption and biological treatment methods for Co, Cu, and Mn removal.

Treatment Method	Adsorbent/Biological Agent	Target Metal(s)	Removal Efficiency (%)	Regeneration Capacity (cycles)	Approx. Cost (USD/kg adsorbent)	Key Advantages
Activated Carbon	Commercial AC	Co, Cu, Mn	85–98	3–5	2.5–3.0	High surface area, well-established
Biochar	Agricultural waste-derived biochar	Cu, Mn	80–95	4–6	0.3–0.5	Low-cost, sustainable, scalable
Modified Biochar	Biochar with metal oxide or acid modification	Co, Cu	90–99	5–7	0.6–1.0	Enhanced adsorption capacity
Biosorption	Fungal or bacterial biomass	Cu, Co	70–92	2–4	0.2–0.4	Eco-friendly, renewable source
Algal Adsorbent	Dried algal biomass	Mn, Cu	60–85	2–3	0.25–0.35	Biodegradable, nutrient recovery potential
Composite Adsorbent	Biochar–polymer hybrid	Co, Cu, Mn	92–99	6–8	0.8–1.2	High efficiency, good reusability

As shown in Table 4, modified biochar and composite adsorbents exhibit comparable or even superior removal efficiencies to commercial activated carbon, while maintaining lower material costs and improved reusability. This underscores the potential of agricultural and biological waste-derived materials as viable alternatives for heavy metal removal.

3.3. Advanced Treatment Methods

In recent years, advanced technologies have been developed to overcome the limitations of conventional biological and adsorption-based approaches. Among these, membrane filtration processes such as reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) have gained significant attention for their ability to achieve near-complete removal of heavy metals from water. These methods rely on size exclusion and selective permeability, offering high efficiency and consistent performance.

However, their large-scale application is often hindered by high operational costs, energy demand, and membrane fouling, which require frequent maintenance and replacement[68,71,78].

Another promising avenue is the application of nanomaterials for heavy metal removal. Engineered nanomaterials, including metal oxide nanoparticles, carbon nanotubes, and nanocomposites, possess exceptionally high surface areas and tailored surface functionalities, enabling selective and efficient adsorption of metals such as Co, Cu, and Mn. Despite their excellent performance, the stability, potential toxicity, and recovery of nanoparticles remain major challenges that must be addressed before their widespread adoption.

To enhance treatment efficiency while lowering costs, researchers are increasingly focusing on hybrid or integrated processes. These systems merge the strengths of different techniques—for instance, combining adsorption with membrane filtration or coupling biological treatment with advanced oxidation methods. Such integrations frequently produce synergistic outcomes, including higher removal rates, reduced sludge production, and greater overall sustainability. Although many of these approaches are still in the developmental stage, they represent a promising path toward achieving reliable and cost-effective heavy metal remediation, as outlined in **Table 5**.

Table 5. Comparison of Advanced Treatment Methods for Heavy Metal Removal

Method	Removal Efficiency	Cost	Scalability	Eco-friendliness	Key Limitations
Membrane Filtration (RO, NF, UF)	Very high (>95%)	High (energy-intensive, costly membranes)	Scalable with infrastructure	Moderate	Fouling, high energy demand, concentrate disposal
Nanomaterials (Nanoparticles, Nanocomposites, CNTs)	High (80–95%)	Moderate–high (depends on synthesis)	Lab-to-pilot scale; limited full-scale use	Low–moderate (toxicity concerns)	Stability, recovery, environmental risk
Hybrid/Combined Processes	Very high (>90%, synergistic performance)	Moderate–high (depends on methods combined)	Increasing scalability (flexible design)	High (optimized resource use, less sludge)	

A comparative overview of conventional and advanced treatment technologies for heavy metal removal is presented in Table 6. The table summarizes efficiency, scalability, energy requirements, and sustainability aspects to facilitate an integrated understanding of current practices.

Table 6. Comparison of conventional and advanced treatment technologies for heavy metal removal.

Treatment Method	Typical Removal Efficiency (%)	Sludge Generation	Energy Demand	Scalability	Sustainability	Major Limitations
Chemical Precipitation	80–95	High	Moderate	High	Low	Sludge disposal, reagent cost
Ion Exchange	85–98	Low	Moderate	Moderate	Moderate	Resin fouling, regeneration chemicals
Membrane Filtration (RO/NF)	90–99	Low	High	Moderate	Moderate	Fouling, energy-intensive
Electrochemical Treatment	85–97	Low	High	Moderate	Moderate	Electrode corrosion, cost
Adsorption (Activated Carbon)	85–98	Low	Low	High	Moderate	Cost of regeneration

Biochar Adsorption	80–96	Low	Low	High	High	Variability in raw materials
Biological Treatment	70–90	Low	Low	Moderate	High	Sensitive to environmental conditions
Hybrid/Integrated Systems	90–99	Low	Moderate	Moderate	High	Limited large-scale validation

The data in Table 6 indicate that while conventional methods such as precipitation and ion exchange remain effective, they are often limited by sludge generation and operational costs. In contrast, adsorption-based and hybrid systems offer higher sustainability and adaptability, though further large-scale validation is required to confirm their industrial feasibility.

4. Discussion

The comparative evaluation of cobalt, copper, and manganese contamination in aquatic environments highlights both shared challenges and metal-specific concerns. All three metals are characterized by persistence, bioaccumulation potential, and toxicity, yet their regulatory frameworks differ significantly across global guidelines. For example, cobalt currently lacks enforceable limits under EU and US standards, despite its increasing industrial use and emerging recognition as a contaminant of concern. In contrast, copper and manganese are more strictly regulated, with emphasis on both health and aesthetic considerations. This discrepancy underscores the need for harmonized international standards that adequately reflect scientific evidence and health risks.

When treatment approaches are examined, it becomes evident that no single method provides a universal solution. Conventional physicochemical techniques such as precipitation, coagulation–flocculation, and ion exchange remain effective at large scale but generate sludge and incur high operational costs. Membrane processes and nanomaterial-based treatments demonstrate excellent removal efficiencies but face barriers of cost, energy consumption, and material sustainability. On the other hand, adsorption and biological-based approaches particularly those employing low-cost agricultural by-products or biochar offer strong potential due to their eco-friendliness and affordability, though challenges remain in terms of adsorption capacity, regeneration, and stability under variable water chemistries.

A recurring theme across studies is the trade-off between efficiency, cost, and scalability. Advanced methods typically outperform conventional ones in terms of removal efficiency, yet they are rarely feasible in resource-limited settings. Conversely, bio-adsorbents and biosorption techniques are promising for developing regions but require further optimization to achieve industrial-level performance. Hybrid and integrated processes appear to offer a synergistic pathway, combining the strengths of multiple techniques while mitigating their individual weaknesses. However, their complexity and initial setup costs may limit widespread adoption in the short term.

Another critical issue identified is the research gap in real-world applications. Many studies on heavy metal removal are conducted under controlled laboratory conditions, which may not reflect the complex matrices of industrial wastewater or natural aquatic systems. Scaling up requires attention to factors such as competing ions, fluctuating pH, and long-term operational stability. Furthermore, the environmental safety of emerging technologies especially nanomaterials remains insufficiently studied, with concerns about secondary pollution and ecological risks.

In summary, the discussion emphasizes that while significant progress has been made in understanding and mitigating cobalt, copper, and manganese contamination, future research must focus on cost-effective, scalable, and environmentally sustainable technologies, supported by harmonized regulatory frameworks. Bridging the gap between laboratory findings and field applications is essential to ensure that treatment solutions can be translated into practical and impactful outcomes.as summarized in **Table7.**

Table 7. Strengths and Weaknesses of Majors Heavy Metal Treatment Methods.

Treatment Method	Strengths	Weaknesses
Conventional Physicochemical (Precipitation, Coagulation–Flocculation, Ion Exchange, Electrochemical)	Established, reliable; high removal efficiency; suitable for large-scale systems	High chemical/energy demand; sludge generation; costly waste disposal; reduced efficiency at low concentrations
Membrane Filtration (RO, NF, UF)	Very high removal (>95%); consistent performance; effective for multiple contaminants	High capital and operational costs; membrane fouling; energy-intensive; concentrate disposal problem
Nanomaterials (Nanoparticles, CNTs, Nanocomposites)	High selectivity and adsorption efficiency; tunable surface chemistry; effective at trace levels	Expensive synthesis; stability issues; potential toxicity; challenges in recovery and reuse
Adsorption (Commercial Activated Carbon)	High adsorption capacity; proven effectiveness	High production and regeneration costs; less feasible for large-scale continuous use
Bio-adsorbents (Agricultural By-products, Biomass)	Low-cost; widely available; eco-friendly; waste valorization	Variable adsorption performance; limited regeneration; shorter lifespan compared to activated carbon
Biochar and Biosorption (Microbial/Algal Biomass)	Renewable and sustainable; high potential for scale-up; eco-friendly	Process optimization required; biomass recovery challenges; performance variability in complex water matrices
Hybrid/Integrated Processes	Synergistic performance; reduced sludge; higher efficiency	Complex operation; higher initial setup cost; limited large-scale demonstrations

5. Future Perspectives

The growing concern over heavy metal contamination in aquatic systems necessitates the development of more sustainable, cost-effective, and scalable treatment technologies. While significant advances have been made in conventional, adsorption-based, and advanced processes, future research and practice must address existing gaps and emerging challenges.

First, the development of low-cost and renewable adsorbents should remain a priority. Agricultural by-products, biomass-derived activated carbon, and biochar represent promising candidates due to their natural abundance, functional group diversity, and environmental benefits. To enhance their performance, modification techniques such as surface functionalization, chemical activation, and nanomaterial impregnation should be further explored to improve adsorption capacity, selectivity, and regeneration efficiency.

Second, integration of advanced materials with green technologies offers a pathway toward innovative solutions. Nanomaterials and nanocomposites have demonstrated exceptional efficiency at trace concentrations of cobalt, copper, and manganese, but concerns about cost, toxicity, and environmental persistence limit their adoption. Future efforts should focus on designing safe-by-design nanomaterials with minimal ecological risks, coupled with strategies for recovery and reuse to prevent secondary pollution.

Third, hybrid and combined treatment systems are likely to play a central role in the future. By combining complementary methods such as adsorption with membrane filtration or biological treatment with advanced oxidation these systems can achieve synergistic effects, reduce operational costs, and enhance overall sustainability. Pilot-scale and full-scale studies are needed to validate their feasibility under real-world conditions, where complex wastewater matrices and fluctuating environmental parameters present additional challenges.

Fourth, the digitalization and optimization of treatment processes through tools such as machine learning (ML) and artificial intelligence (AI) present new opportunities. Predictive modeling can improve process control, optimize operational parameters, and enable early detection of performance decline. Integrating smart monitoring systems into treatment facilities could significantly enhance efficiency and reduce resource consumption.

Finally, the establishment of harmonized international guidelines and regulatory frameworks is essential to ensure safe levels of cobalt, copper, and manganese in drinking water. As industrial applications of these metals continue to expand, proactive regulation supported by robust scientific evidence will be crucial for protecting both human health and ecosystems.

In summary, the future of heavy metal remediation lies in the intersection of material innovation, process integration, digital technologies, and policy alignment. Advancing research in these areas will ensure that treatment solutions are not only effective but also economically viable and environmentally sustainable.

6. Conclusion

In light of the findings presented in this review, it is evident that heavy metal pollution poses a persistent threat to water quality, human health, and ecological stability. While several conventional treatment techniques have been applied with measurable success, their limitations highlight the urgent need for more sustainable and cost-effective solutions. Adsorption-based methods, particularly those employing bio-adsorbents derived from agricultural residues and biochar, stand out as promising alternatives that combine efficiency with environmental and economic benefits. To consolidate the main insights of this study, the key points are summarized below:

1. Clean and safe water is essential for human health, economic development, and ecosystem balance, yet heavy metal contamination remains a major global concern.
2. Cobalt (Co), copper (Cu), and manganese (Mn) are among the most hazardous metals due to their persistence, bioaccumulation, and toxicity even at low concentrations.
3. Conventional treatment methods (chemical precipitation, ion exchange, membrane filtration, electrochemical processes) are effective but often limited by high cost, energy demand, sludge generation, and operational complexity.
4. Adsorption stands out as a highly efficient and widely applicable method, with activated carbon being the benchmark material.
5. Agricultural by-products (e.g., lemon peel, maize tassel, reed biomass) and biochar have emerged as low-cost, renewable, and eco-friendly alternatives, supporting circular economy practices.
6. Despite their promise, bio-adsorbents often exhibit lower adsorption capacity and regeneration challenges compared to commercial activated carbon, requiring further optimization.
7. Future directions should emphasize the development of hybrid and integrated treatment systems, pilot-scale validation of bio-adsorbents, and improved regeneration strategies to ensure cost-effectiveness and scalability.
8. Overall, adsorption-based methods especially those utilizing bio-adsorbents represent the most sustainable and practical approach for mitigating heavy metal pollution in water, particularly in resource-limited region.

6.1. Study Contributions

This review makes several key contributions to the understanding and management of heavy metal contamination in water systems:

- Comprehensive coverage of target metals: It systematically examines cobalt (Co), copper (Cu), and manganese (Mn), highlighting their sources, environmental behavior, toxicological effects, and treatment challenges.

- Critical assessment of treatment methods: The study compares conventional physicochemical, electrochemical, and biological/adsorption-based methods, identifying their relative strengths, limitations, and practical applicability.

- Emphasis on sustainable solutions: Particular attention is given to adsorption using bio-adsorbents and biochar, showcasing their potential as low-cost, eco-friendly, and scalable alternatives to traditional activated carbon.

- Integration of global perspectives: By referencing international guidelines (WHO, EU, US), the paper places the problem of heavy metal pollution within a global regulatory and health context.

- Framework for future research: The review consolidates key knowledge gaps and proposes directions for advancing bio-adsorbent development, hybrid treatment technologies, and real-scale applications.

Through these contributions, the study provides both a consolidated knowledge base and a forward-looking framework that can support researchers, practitioners, and policymakers in advancing sustainable water treatment strategies.

6.2. Limitations of This Study

While this review provides a comprehensive overview of heavy metal pollution and treatment strategies, certain limitations should be acknowledged:

- Scope of metals: The analysis was restricted to cobalt (Co), copper (Cu), and manganese (Mn). Other hazardous metals such as lead, cadmium, arsenic, and mercury were not addressed, which may limit the generalizability of the findings.
- Literature focus: The study primarily relied on published experimental and review articles. Grey literature, industrial reports, and unpublished case studies were not systematically included, potentially omitting relevant practical insights.
- Comparative analysis constraints: Although treatment methods were compared in terms of strengths and weaknesses, direct quantitative comparisons (e.g., cost per unit volume treated, adsorption capacities across different conditions) were not always possible due to variability in reported data.
- Scale of application: Most evidence summarized in this study comes from laboratory-scale experiments. The performance of bio-adsorbents and hybrid methods under real-world conditions may differ significantly.
- Dynamic regulatory landscape: References to WHO, EU, and US guidelines provide an important context, but water quality regulations are evolving, and this review may not capture the most recent policy changes in all regions.

Recognizing these limitations underscores the need for continued research, more comprehensive data collection, and large-scale validation of emerging technologies to strengthen the applicability of the findings.

6.3. Practical Implications

The insights from this study carry several important implications for practice and policy:

- For engineers and practitioners: The findings highlight the potential of low-cost bio-adsorbents and biochar as scalable alternatives to conventional adsorbents, encouraging their consideration in the design of wastewater treatment systems, particularly in resource-limited contexts.
- For industry: Adoption of agricultural by-products as treatment materials supports waste valorization, reduces disposal costs, and contributes to sustainable production practices aligned with circular economy principles.
- For policymakers and regulators: The review underscores the need to update and harmonize water quality standards globally, while also providing incentives for the development and implementation of eco-friendly

technologies.

- For researchers: The study identifies critical knowledge gaps, including regeneration of bio-adsorbents, hybrid process integration, and pilot-scale validation, that can guide future investigations and funding priorities.

By bridging the gap between research, practice, and policy, the findings of this review can support the development of treatment strategies that are not only scientifically robust but also economically and socially viable.

7. References

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