Journal of Frontiers in Multidisciplinary Research

Heavy Metal Contamination in Water Resources: Sources, Health Risks, Analytical Detection, and Remediation Strategies-A Review

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Article Info

E-ISSN: 3050-9726
P-ISSN: 3050-9718
Impact Factor (RSIF): 7.34
Volume: 07
Issue: 01
Received: 20-03-2026
Accepted: 19-04-2026
Published: 18-05-2026
Page No: 450-454

Abstract
Concerns of exposure to hazardous heavy metals deactivate safety mechanisms and increase risks to other workers and the surrounding communities. Industrial waste from factories, litter and numerous other hazards contribute to the disruption of ecosystems and public safety. I include the most recent data from 2015 to 2026. As determination of heavy metals is an urgent concern, I highlight recent efforts to develop fast, inexpensive, and effective testing methods. These include: absorption/desorption, membrane separation, chemical precipitation, biosensors, and nanotechnology. While discussing the difficulties in regulating these methods, I focus on the treatment of these contaminants and the safety concerns. I highlight gaps in sustainable water management. This report emphasizes the severe consequences of heavy metal contamination of water on the environment and public health. My goal is to create an efficient synthesis of the latest available data in the field of environmental public health that will serve health and water quality research.

DOI: https://doi.org/10.54660/.JFMR.2026.7.1.450-454

Keywords: heavy metals, water contamination, public health, remediation

1. Introduction

Water is vital to ecological systems, human health, and economic activities. Unfortunately, the rapid industrialization, urbanization, mining, intensified farming, and poor management of waste driven by globalization have made water pollution one of the top global concerns [1,4,6]. Out of the many pollutants that pose a threat to water ecosystems, heavy metals are among the most dangerous due to toxicity, environmental persistence, and tendency to bioaccumulate and biomagnify [2-4]. Heavy metals are metallic elements that have high atomic weights and high densities, and are toxic even in small quantities. The most discussed toxic heavy metals in contaminated water are lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) [2-4]. Such metals come from industrial waste, mining, runoff from farms, urban wastewater, burning fossil fuel, leachate from landfills, poor disposal of hazardous and electronic waste [4,6,7]. Heavy metals, unlike many organic pollutants, do not biodegrade. Because of that, they can amp up in sediment and biological tissue, enter the food chain, and increase the risk to ecosystems and people [2-4, 7]. When people consume contaminated water, food from farming, and fish from aquaculture they suffer heavy metal toxicity, which can result in multiple health conditions ranging from organ failure and cancer to impairment of child development [1-4,7].

The article summarizes a narrative review and examines the existing literature about heavy metal pollution of water sources. Because this revised version is not merely descriptive, it provides some details about the methods related to the existing literature. It evaluates the analytical shortcomings of not only the existing literature, but also the analytical techniques. Finally, this revised version introduces the gaps in literature that may be filled in the future, and focuses on the need for evidence to be able to support future research and policy.

2. Search Strategy and Selection of Literature

This article defines a narrative review based on a targeted literature search. Relevant literature was sourced after a literature search was conducted on Scopus, PubMed, Web of Science, and Google Scholar. Searches were based on terms including, but not limited to, "heavy metal water contamination", "heavy metal sources", "heavy metal health issues", "heavy metal detection", "biosensors", "sensors", and "water pollution remediation". The literature search was conducted within the years 2015 and 2026, and placed additional focus (within the search parameters) on literature within the years 2020 to 2026. Literature within these years was considered timelier, as with the advancements in environmental preservation and the development of remediation technologies.

Literature was selected based on the relevance to one, or many, of the following categories: the sources and pathways of heavy metal contamination, the distribution of heavy metals in the environment and their bioaccumulation, the impact of heavy metals on human health, the techniques of detection and analysis of heavy metals, and the remediation and treatment of heavy metal contamination. Literature was prioritized, as appropriate, based on the author's choice to publish works pertaining to the subject in a peer-reviewed journal, the author's work as a reviewer, International Guidance Documents, and works offering evidence within the region, as appropriate.

Due to the preference for interpretive synthesis over quantitative meta-analysis, the review is of the narrative style. The systematic approach employed for the literature search and selection enhanced the coverage of recent evidence, and the methods added, as appropriate, to the reliability of the synthesis, despite the narrative review's limitations.

3. Sources of Heavy Metal Pollution

Pollution from heavy metals occurs naturally or anthropogenically; however, most polluted environments are heavily impacted by human activities. Principal contributors predominantly are industrial discharges, mining activities, urbanization, agricultural practices, municipal wastes, landfill leachate, and improper domestic and electronic wastes [4, 6].

3.1. Industrial Activities

Around the world, industrial wastewater is a major contributor to the pollution of heavy metals. Industries like electroplating, battery production, leather tanning, textile processing, metal finishing, paint production, and the manufacturing of chemicals can all dump large amounts of toxic metals into the rivers, lakes and even groundwater [4,6,7]. Lead contamination is attributed to the battery and paint industries, while chromium is associated with tanning and dyeing processes. In chlor-alkali plants and e-waste recycling, mercury is involved [4,7].

3.2. Mining Activities

Mining and ore-processing operations contribute to water pollution from acid mine drainage, leaky tailings, and wastewater. It is common to see some toxic metals (like arsenic, cadmium, lead and mercury) get transported to surrounding aquatic environments [4,6]. This problem is even worse in low and middle-income countries because of the weak environmental regulations, and even when environmental regulations exist, monitoring is largely absent [6,7].

3.3. Agricultural Activities

Fertilizers, pesticides, herbicides, and sewage sludge used in agricultural practices contribute heavy metals to water. Cadmium and lead may be present in phosphate fertilizers, and contaminated wastewater can carry other metals to soil, crops, and groundwater [4,6]. Concentrating agronomic activities may therefore contribute to chronic exposure over time.

3.4. Urbanization and Domestic Waste

Urbanization accelerates the problems inherent in the disposal of sewage, municipal wastewater, stormwater, and leachate from landfills. The disposal of household and electronic waste causes elevated concentrations of copper, zinc, nickel, and lead in the adjacent water bodies, especially in the areas of poor waste management. Urbanized areas, therefore, become increasingly important and often overlooked sources of heavy metal pollution.

4. Environmental Distribution and Bioaccumulation

Once present in water systems, heavy metals may remain in water in a dissolved form, adsorb to suspended particles, settle in sediments, or become associated with water biota [2-4]. Their environmental mobility and bioavailability is dependent on several factors including pH, salinity, redox potential, temperature, and presence of organic matters [4, 7].

Bioaccumulation is the process whereby an organism absorbs a metal at a rate faster than elimination. This is worsened by the process of biomagnification in which metal concentrations increase across the different levels of the food chain [2-4]. Fish, shellfish, algae and aquatic plants, can bioaccumulate heavy metals and, after a prolonged period of eating this contaminated aquatic food, a person can be exposed to heavy metals and their toxins [2, 4, 7].

Sediments may also be heavy metals' long-term storage areas. Considering that environmental conditions can change, metals in sediments can be released again to the water column, and hence, cause exposure to heavy metals again [4].

5. Human Health Impacts

Chronic exposure to heavy metals can damage multiple organ systems, even at low concentrations. This includes direct exposure via contaminated drinking water and consumption via the food chain. This is especially true in communities that have limited water sanitation or rely heavily on local water bodies to fulfill their needs [1-4].

5.1. Lead (Pb)

Lead is a powerful neurotoxin that harms both adults and children. Long term exposure can lead to brain, kidney and developmental damage, behavioral issues, high blood pressure, and anemia [1-3]. While everyone is harmed by exposure, the developing nervous system makes children much more vulnerable [1,3].

5.2. Cadmium (Cd)

Cadmium attacks the kidneys and bones. Chronic exposure is linked to kidney damage, bone loss, more bone breaks, lung issues, and cancer [2,3,7]. Cadmium builds in bodies over time, so even small, regular exposure can be dangerous [2,3].

5.3. Mercury (Hg)
Both forms of Mercury, and even more so in its organic form, called Methylmercury can cross the Blood Brain Barrier and the Placental Barrier. Exposure can lead to Neurocognitive disabilities, and can even cause tremors and memory losses along with some sensory and developmental disturbances in children and fetuses [2,3,7].

5.4. Arsenic (As)
Skin tumors, peripheral vascular disease, cardiovascular issues, diabetes, and lung, bladder, and skin cancers have all been associated with exposure to arsenic over an extended period of time [1-3]. Arsenic-contaminated drinking water is an issue of public health concern [1,3].

5.5. Chromium (Cr)
Hexavalent chromium is listed as an extremely dangerous compound and near certain carcinogen. It is known to cause irritation to the respiratory system and liver, skin and other cellular damage, oxidative stress, and damage to DNA. Trivalent chromium is not nearly as toxic as hexavalent chromium [2,3].

5.6. Nickel (Ni)
Nickel exposure is associated with allergic dermatitis, respiratory disorders, nephrotoxicity, and carcinogenic potential at elevated or prolonged exposure levels [2,7].

5.7. Synergistic Effects of Mixed Exposure
Heavy metals usually co-occur in nature, and organisms are almost always exposed to more than one. The multiple exposures can cause toxic effects to be either greater than additive (synergistic) or less than additive (antagonistic), complicating the health risk assessment. This issue is already well-known, and more attention should be paid to it in toxicology and epidemiology studies to a greater extent than what is offered in the current literature [2-4,7].

6. Analytical Detection Techniques
Knowing how to find heavy metals in water paves the way for the development of techniques designed to protect the environment, comply with the law, and ensure the population's well-being. The existing methods of analysis can be more easily compared by costs, speed, analytical demands, sensitivity, procedural complexity, and applicability to field/laboratory studies. [1,4,8].

6.1. Atomic Absorption Spectroscopy (AAS)
The simplicity, cost efficiency, and compatibility of AAS with standard laboratory environments have made it a common choice for routine heavy metal analysis. Despite these advantages, AAS has some limitations, including the requirement for single-element, sequential analysis and being restricted to moderate detection limits. [4,8]

6.2. Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
Among the most modern approaches to trace metal analysis, the application of ICP-MS is characterized by ultra-low detection limits and high sensitivity, as well as the ability to conduct multi-element analyses almost instantaneously. Although this technique is powerful, capital investment, ongoing maintenance, and highly trained personnel are required, reducing its accessibility in resource-limited environments [4,8].

6.3. UV-Visible Spectrophotometry
UV-visible spectrophotometry is used for preliminary screening and colorimetric analyses. Although simple and cost effective, it is generally less sensitive and selective compared to AAS or ICP-MS, which limits its use for detection at trace levels [4,8].

6.4. Biosensors
Biosensors combine biological recognition elements with physicochemical transducers, which provide rapid, dimensionally compact, and specific detection. While sensors can potentially provide real-time tracking of the surroundings, problems associated with long-term viability, calibration, reproducibility, and field-validation remain [8,9].

6.5. Nanotechnology-Based Sensors
Nanotechnology sensors enhance analytical sensitivity using nanoparticles, quantum dots, and nanocomposites. Despite the fact that response rates and detection limits have appreciably improved, concerns regarding standardization, costs, regulatory acceptance, and safety should be addressed before broader applications occur Nd [8, 12, 13].

6.6. Practical Considerations
There isn't one best technique. ICP-MS has the highest analytical performance. However, it is frequently out-of-reach for low-resource laboratories. AAS is a reliable, conventional choice. Biosensors and platforms based on nanotechnology show the potential for distributed monitoring. However, their large-scale use is reliant on better standards, cost reductions, and more realistic field testing for real environmental conditions [8,9,12].

7. Remediation and Water Treatment Strategies
A wide range of technologies has been developed to remove heavy metals from contaminated water. Each approach presents distinct advantages and limitations related to removal efficiency, cost, environmental safety, and operational complexity [5,6,8].

7.1. Adsorption
Adsorption is commonly used to remove heavy metals for both economic and practical reasons. For adsorbents there are many options including activated carbon, zeolites, biochar, clay minerals, and engineered nanomaterials. The method's simplicity and effectiveness are what attract users [6]. The main issue that is encountered during the adsorption method is the cost associated with disposing and renewing the adsorbent [5,9].

7.2. Membrane Filtration
The usage of reverse osmosis, ultrafiltration, and nanofiltration has been well demonstrated in the removal of heavy metal contamination in industrial effluent and wastewaters. They display high efficiency for removal and require minimal to sans chemicals, However in addition to membrane fouling, energy requirement and operational costs, the application of these methods of treatment in developing countries is limited. [5, 8]

7.3. Chemical Precipitation
Chemical precipitation converts dissolved metals to insoluble compounds, which are subsequently removed physically. Its application in many industries is effective, but it often generates large amounts of sludge which need further treatment and safe disposal [5,8,11].

7.4. Phytoremediation
Water hyacinth, duckweed, and vetiver grass are plants used in phytoremediation to absorb and stabilize heavy metals. Though the costs are low and treatment is stable, the biomass which has been contaminated and absorbed requires careful management after treatment [6,7].

7.5. Bioremediation
Bioremediation involves microorganisms, such as bacteria, fungi, and algae, to remove, immobilize, or change toxic metals. Microbial biosorption appears to be a viable remediation method, although some limitations include optimization at the field scale and stability of the process [6,9].

7.6. Nanotechnology-Assisted Treatment
Nanomaterials like carbon nanotubes, graphene oxide, and magnetic nanoparticles exhibit a strong and selective adsorption capacity for heavy metals [12-15]. There are concerns about production costs, the release of nanoparticles into the environment, and toxicology and regulation uncertainties, but these are obstacles for the recommendation of large-scale use [12-15].

7.7. Applicability in Developing Regions
While developed methods of detection and treatment have some scientific merit, their use in under-resourced environments may be hindered by their cost, infrastructure, and maintenance demands, as well as insufficient technical proficiency. Therefore, in many less developed contexts, low-cost adsorption systems, phytoremediation, and bioremediation may be more applicable and scalable alternatives [5,6,8,9].

8. Challenges and Current Limitations
While technology has improved, controlling heavy metal contamination is still a challenge. Operational costs remain very high, facilities are inefficient, most countries have weak laws and regulations, and there is minimal monitoring and insufficient technology. These problems are exacerbated in low- and middle-income countries where urbanization has outpaced development [6,8].

Remediation technologies have been tested under optimal conditions, which is another major challenge for using these technologies. The chemical composition of wastewater is complex, and pollutants are intermingled making operational constraints that much harder. As a result, treatment performance of remediation technologies in most of these studies cannot be translated to real-life applications [6,8,11].

Climate change, coupled with increased industrialization, is likely to worsen the contamination of water bodies. Variations in rainfall and increased severity of droughts and other changes to the hydrology of a region can actually change how and where heavy metals are concentrated in water. As a result of these changes, monitoring will be more difficult, and remediation of contaminated waters will pose even greater challenges [4,6].

9. Research Gaps and Future Directions
There are various notable gaps in the literature when it comes to heavy metal contamination in the literature. First, there is a shortage of region specific studies in the Middle East, Iraq, and other areas of the world that have been underrepresented. This is especially important since the environmental concerns in the regions are extensive. Second, most toxicology studies focus on the exposure of single metals and neglect the exposure of multiple metals. This is especially important when determining the health risk in the given situation.

The third gap is the incorporation of artificial intelligence in the monitoring of heavy metals. This technology has the ability to increase the surveillance systems and improve forecasting and provide alerts in the case of potential risk. The fourth and final gap is the integration of nanotechnology. Most methods attempting to use nanotechnology in the detection and remediation of heavy metals have not been validated outside of the laboratory and especially in low-technology environments.

Research should target the design of smart field sensors and hybrid remediation systems that are complex and adaptable in the field and combine physical, chemical, and biological methods. Special attention should also be given to climate change concerning metal mobility, environmental safety in the use of nanotechnology, and the design of treatment methods that are affordable and innovative.

10. Limitations of This Review
This article is limited in multiple ways due to its nature as a narrative review. The authors used a less rigorous method when it came to choosing the studies to include. Some selection bias was likely, particularly toward cited studies published in English. The risk of bias was not analyzed, and the authors did not introduce evaluation tools. Some of the authors' interpretations of the data rely both on primary sources and review studies. Since other authors have not performed a quantitative meta-analysis, we can describe their work as a critical synthesis and not as a meta-analysis. The limitations should not be considered as cancelling the conclusions, but directing the proper scope of the conclusions.

11. Conclusion
Global water pollution due not the presence of heavy metals endangers both the environment and public health. There are many causes for heavy metal contamination of water, including, but not limited to, industrial activity, mining, urbanization, mismanaged waste, and agriculture. These activities introduce heavy metals to aquatic systems, causing the metals to persist and accumulate. In turn, the metals contaminate and stress ecosystems and humans.

There are numerous advanced techniques available for the measurement and removal of heavy metal contamination in water. Some of the advanced measurement techniques include ICP-MS, nanotechnology, and biosensors. Some of the potential removal techniques include the use of assisted nanotechnology, bioremediation, phytoremediation, and other methods. Despite the advanced measurement and removal techniques available, there are still barriers to remove heavy metal contamination in water on a large scale, including the treatment cost, the technological complexity, safety concerns of the removal techniques, field validations, and limited regulatory frameworks. This revised narrative review prioritizes and synthesizes the current literature on heavy metal contamination of water. This review highlights the importance of low-cost, feasible, and evidence-based methods to ensure that the public's health is protected, regardless of the development status of the country.

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How to Cite This Article

Marwa Mohamed Mahmoud. Heavy Metal Contamination in Water Resources: Sources, Health Risks, Analytical Detection, and Remediation Strategies—A Review. Journal of Frontiers in Multidisciplinary Research. 2026;7(1):450-454. doi:10.54660/.JFMR.2026.7.1.450-454.

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