Environmental and Ecological Risks of Heavy Metals in Aquatic Systems: Emphasis on Detection and Management Approaches

Vishal Soni[1]*, Kusumlata Goswami[1], Satendra Singh[2], Krishan Kumar Yadav[1], Prabhutva Chaturvedi[1] and Sujeet Kumar Rai[1]

[1]*College of Fisheries Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana-125004, India*
[2]*Central Institute of Fisheries Education, Panch Marg, Off Yari Road, Versova, Andheri, Mumbai-400061, India*

Corresponding Author
Vishal Soni
Email: vishalsoni68001@gmail.com

OPEN ACCESS

Keywords

Heavy metals, aquatic ecosystem, detection methods, bioremediation, phytoremediation

How to cite this article:

Soni, V., Goswami, K., Singh, S., Yadav, K. K., Chaturvedi, P. and Rai, S. K. 2025. Environmental and Ecological Risks of Heavy Metals in Aquatic Systems: Emphasis on Detection and Management Approaches. *Vigyan Varta* 6(8): 9-16.

ABSTRACT

Heavy metal contamination in aquatic ecosystems poses serious environmental risks due to their persistence, toxicity, and bioaccumulation. This review outlines global regulatory benchmarks (WHO and USEPA) and identifies major sources such as industry, agriculture, wastewater, mining, and natural processes. Metals accumulate in sediments and organisms, causing physiological harm to aquatic life and disrupting food webs through bioaccumulation and biomagnification. Contamination also degrades water quality by altering pH, turbidity, and oxygen levels. Detection methods include AAS, ICP-MS, biosensors, and bioindicators. Remediation strategies involve physicochemical treatments, bioremediation, sediment management, constructed wetlands, and emerging technologies like nanotech and electrochemical processes. Integrated monitoring and mitigation are essential to restore aquatic ecosystem health.

INTRODUCTION

Heavy metals are elements that occur naturally and are characterized by their high atomic mass and a density at least five times higher than that of water. While some heavy metals such as zinc (Zn), copper (Cu), and iron (Fe) are essential in trace amounts for biological functions, others like mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As) are non-essential and highly toxic even at low concentrations (Tchounwou *et al*., 2012). These metals enter aquatic ecosystems through both natural processes and anthropogenic activities such as industrial discharges, agricultural runoff, mining operations, and wastewater effluents (Ali *et al*., 2019). Once introduced into the aquatic environment, heavy metals can persist for long periods and bioaccumulate in aquatic organisms, including fish, molluscs, and crustaceans. Bioaccumulation can lead to biomagnification across trophic levels, posing serious risks to aquatic biodiversity and human health through the consumption of contaminated seafood (Jaishankar *et al*., 2014). The accumulation of heavy metals in aquatic organisms can cause oxidative stress, metabolic disruption, reproductive impairments, and increased mortality rates. Therefore, understanding the behaviour and effects of heavy metals in aquatic biota is crucial for ecosystem health monitoring and the development of effective management strategies.

1. **WHO World Health Organization, USEPA United States Environmental Protection Agency.**

1. Regulatory Standards and Guidelines for Heavy Metals in Water

The table below presents permissible limits of key heavy metals in drinking and surface water, as per guidelines from the World Health Organization (WHO), United States Environmental Protection Agency (USEPA), and Bureau of Indian Standards (BIS).

Table 1

Permissible Limits of Heavy Metals in Water According to WHO, USEPA, and BIS (in mg/L)

Metal	WHO Drinking Water Limit	USEPA Acute Criteria	BIS Drinking Water Limit
Lead (Pb)	0.01	0.065	0.01
Cadmium (Cd)	0.003	0.002	0.003
Mercury (Hg)	0.006	0.0014	0.001
Arsenic (As)	0.01	0.01	0.01

Note. *WHO and BIS values refer to drinking water guidelines; USEPA values represent acute exposure criteria for surface water.*

2. Sources of Heavy Metals in Aquatic Ecosystems

Heavy metals are introduced into aquatic environments through both natural occurrences and human activities. Once introduced, they can persist for long periods and accumulate in sediments and aquatic organisms, leading to ecological and health concerns. The major sources can be categorized as follows:

2.1. Industrial Discharges

Industries are among the primary contributors of heavy metals to aquatic environments. Effluents from sectors such as mining, metal plating, battery manufacturing, textile dyeing, and paper processing often contain high levels of metals like lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg). Improperly treated industrial wastewater results in the direct pollution of adjacent water bodies. (Ghorab, 2018).

2.2. Agricultural Runoff

Heavy metals are introduced into the environment from agricultural practices due to the overuse of phosphate-based fertilizers, chemical pesticides, and organic manure. These agrochemicals may contain arsenic (As), cadmium (Cd), copper (Cu), and zinc (Zn). During rainfall or irrigation, runoff carries these metals into adjacent ponds, lakes, and rivers, impacting both surface and groundwater quality. (Malik *et al*., 2020).

2.3. Domestic and Municipal Wastewater

Urban sewage, when not properly treated, can carry a range of heavy metals such as lead (from plumbing systems), mercury (from household batteries and fluorescent bulbs), and copper (from household cleaning agents and pipes). The increasing urbanization and lack of effective sewage infrastructure in many areas exacerbate this problem. (Malik *et al*., 2020a, 2020b).

2.4. Atmospheric Deposition

Heavy metals can also enter aquatic systems via atmospheric deposition. Emissions from vehicles, coal-fired power plants, and industrial smokestacks release metal particulates into the air. These are subsequently deposited onto land and water surfaces through precipitation (wet deposition) or as dust (dry deposition), contributing to mercury (Hg), arsenic (As), and lead (Pb) loads (Malik *et al*., 2020a).

2.5. Mining and Smelting Activities

Mining operations, especially for metal ores, significantly disturb the earth's crust and expose minerals to weathering. Runoff from mine tailings and acid mine drainage transports heavy metals into surrounding aquatic environments, while smelting operations emit metal-laden fumes and particles, polluting both the air and nearby water sources (Malik *et al*., 2020a, 2020b).

2.6. Leaching from Solid Waste and Landfills

Improperly managed landfills and electronic waste disposal sites can lead to leaching of toxic metals like cadmium, lead, and nickel. Rainwater percolating through waste materials can carry dissolved metals into groundwater and surface water.

2.7. Natural Sources

Although anthropogenic activities are the dominant contributors, some heavy metals occur naturally through geological processes such as volcanic eruptions, rock weathering, and soil erosion. These processes release trace amounts of metals like chromium, nickel, and copper into water bodies over time.

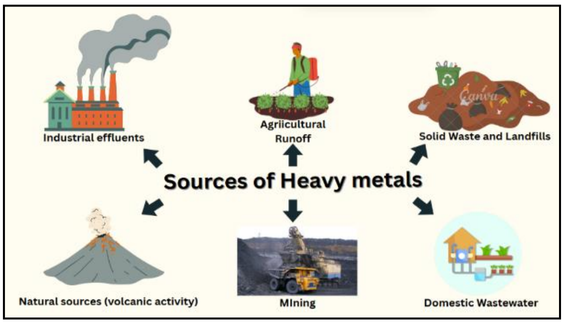

Fig.1 Sources of heavy metals

3. Effects of Heavy Metals on Aquatic Organisms and Ecosystem Health

Heavy metals are some of the most enduring and harmful contaminants found in aquatic environments. Unlike organic pollutants, they do not degrade over time and can accumulate in sediments and organisms, causing long-term damage. Their presence in water bodies poses a serious threat not only to individual aquatic species but also to the stability and functioning of entire ecosystems (Ali *et al*., 2019; Wang *et al*., 2020).

3.1. Toxic Effects on Aquatic Organisms

Heavy metals can severely affect the physiology, behaviour, and survival of aquatic life:

- **Fish:** Exposure to metals like mercury (Hg), cadmium (Cd), and lead (Pb) can impair gill function, reduce growth rates, cause reproductive dysfunction, and damage vital organs such as the liver and kidneys. These metals interfere with enzymatic systems and hormonal balance, leading to chronic stress and potentially mortality (Jaishankar *et al*., 2014).

- **Invertebrates:** Filter-feeding organisms such as mussels, clams, and shrimp readily accumulate metals from water and sediments. High metal concentrations reduce their feeding efficiency, reproduction, and growth, ultimately leading to population declines (Ali *et al*., 2019).

- **Plankton:** Phytoplankton and zooplankton, the foundation of aquatic food webs, are highly sensitive to metal exposure. Their reduced abundance or altered community composition disrupts nutrient cycling and energy flow to higher trophic levels (Tchounwou *et al*., 2012).

- **Bioaccumulation and Biomagnification:** One of the most concerning impacts of heavy metals is their tendency to bioaccumulate in aquatic organisms over time and biomagnify through the food web. For example, small fish and invertebrates absorb metals directly from their environment; predators consuming these organisms accumulate even higher concentrations, eventually reaching toxic levels in top predators like large fish, birds, and mammals (Ali *et al*., 2019).

- **Long-Term Toxicity:** Persistent metals such as mercury, cadmium, and lead cause long-term ecological impacts, including chronic poisoning, reproductive failure, and species declines in contaminated aquatic habitats (Jaishankar *et al*., 2014).

3.2. Impacts on Water Quality

Heavy metals alter key water quality parameters:

- **pH and Chemical Balance:** Metals like aluminum and iron can lower pH, creating acidic conditions harmful to aquatic organisms. Acidification enhances the solubility and toxicity of metals and other pollutants, compounding environmental stress (Wang *et al*., 2020).

- **Turbidity:** Metal ions can bind with organic and inorganic particles, increasing water turbidity. Reduced light penetration limits photosynthesis in submerged plants and phytoplankton, affecting oxygen production and primary productivity (Tchounwou *et al*., 2012).

- **Dissolved Oxygen (DO):** Heavy metal contamination can reduce DO levels by impairing the metabolic activity of aquatic organisms and altering microbial communities involved in decomposition and nutrient cycling (Jaishankar *et al*., 2014).

3.3. Ecosystem-Level Consequences

Beyond individual species, heavy metal contamination impacts overall ecosystem health:

- **Disruption of Food Webs**: Heavy metals accumulate in various trophic levels of aquatic food webs, from phytoplankton to top predators like fish and birds. Filter-feeding invertebrates such as mussels and crustaceans are particularly vulnerable, often accumulating high concentrations of metals through bioaccumulation. As these invertebrates are consumed by higher organisms, metals biomagnify through the food chain, leading to impaired growth, reproduction, and survival among predators. This weakens the entire food web and reduces the ecosystem's diversity and productivity (Wang & Rainbow, 2008).

- **Loss of Biodiversity**: When exposed to metal stress, species that are sensitive often decrease in number or vanish, whereas species that are more tolerant typically become more dominant. This shift in community structure leads to reduced biodiversity and ecological imbalance. For instance, mercury and cadmium exposure are known to reduce amphibian and fish populations, thus homogenizing ecosystems and lowering their resilience to environmental stress (Gall *et al*., 2015).
- **Habitat Degradation**: Contaminated sediments and poor water quality directly degrade critical aquatic habitats such as wetlands, estuaries, and fish spawning grounds. These changes impair the functionality of the ecosystem and reduce the availability of safe habitats for diverse aquatic organisms (Gall *et al*., 2015).
- **Sediment Contamination**: Metals often bind to sediments, acting as long-term sources of contamination. Benthic organisms, which feed or live in sediment layers, ingest these metals and suffer toxic effects. Moreover, activities like storms, trawling, or dredging can disturb the sediments and cause the release of previously settled contaminants, leading to the re-entry of heavy metals into the water column and restarting the contamination cycle. (Burton, 2002).

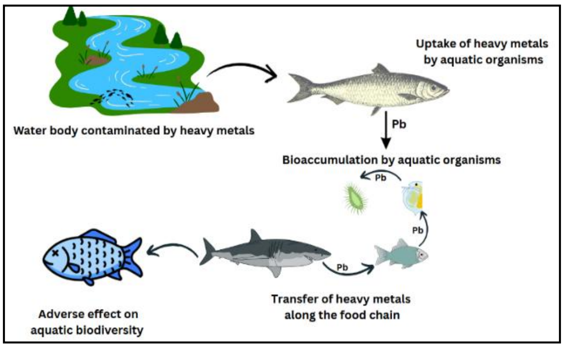

Fig.2 Effects of Heavy metals on aquatic organisms

4. Detection and Monitoring Methods

Accurate detection and continuous monitoring of heavy metals are essential for assessing ecosystem health and guiding mitigation. Advanced analytical and biological methods are used to detect trace metal levels in water, sediment, and biota.

4.1. Atomic Absorption Spectroscopy (AAS)

AAS is one of the most widely used techniques for detecting metal concentrations in water and biological samples. It offers high accuracy and specificity for metals such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu). Samples are typically digested using acids before analysis. Flame AAS is suitable for analyzing higher concentration levels, whereas Graphite Furnace AAS offers greater sensitivity, making it ideal for detecting trace amounts.

4.2. Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

ICP-MS detects multiple metals simultaneously at parts-per-trillion (ppt) levels, making it ideal for environmental monitoring. Its high sensitivity and speed are valuable despite higher costs.

4.3. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

ICP-OES is used to detect and quantify metals based on the light emitted by atoms when excited in a plasma source. While slightly less sensitive than ICP-MS, it is faster and cost-effective for routine monitoring of heavy metals in water, sediments, and organisms.

4.4. Biosensors

Biosensors use biological components (e.g., enzymes, microbes, DNA) to detect metals like arsenic and mercury. They are cost-effective and eco-friendly, with potential for real-time field monitoring, though still under development for widespread use.

4.5. Biological Monitoring (Bioindicators)

Monitoring the accumulation of heavy metals in aquatic organisms such as **mussels**, **algae**, and **fish tissues** provides valuable insight into the bioavailability and long-term ecological impact of metal pollution. These organisms serve as bioindicators, helping assess not only current metal concentrations but also chronic exposure effects. Bioaccumulation studies are often used alongside chemical analyses to offer a comprehensive picture of ecosystem health.

4.6. Remote Sensing and GIS Tools

Remote sensing and GIS enable large-scale monitoring of metal contamination. Satellite imagery and spatial analysis identify pollution sources, track land-use changes, and assess ecosystem vulnerability in near real-time (Kumar, A., & Kumar, R., 2022).

5. Strategies for Removing Heavy Metal Contamination

Mitigating heavy metal contamination in aquatic ecosystems is critical for restoring water quality and safeguarding biodiversity. Due to their non-degradable nature and long-term persistence, heavy metals require strategic and often combined approaches for effective removal. The selection of methods depends on factors such as the type and concentration of metals, the nature of the contaminated medium (water or sediment), and the scale of contamination (Fu & Wang, 2011).

5.1. Physicochemical Methods

These are conventional methods that offer rapid results and are commonly applied in industrial wastewater treatment:

- **Chemical Precipitation**: Involves the addition of chemicals (e.g., lime, sulphides, or hydroxides) to form insoluble metal compounds that settle out of solution. This method is widely used but may generate toxic sludge requiring proper disposal.

- **Ion Exchange**: Uses resins to exchange metal ions in water with benign ions like sodium or hydrogen. Effective for treating low concentrations of metals but requires maintenance and regeneration of resins (Fu & Wang, 2011).

- **Membrane Filtration (e.g., Reverse Osmosis, Nanofiltration)**: Advanced filtration techniques capable of removing metal ions from water. These offer high efficiency but come with higher operational costs and energy demands (Ahluwalia & Goyal, 2007).

5.2. Biological Methods (Bioremediation)

Bioremediation utilizes living organisms primarily microbes and plants to detoxify or immobilize heavy metals. These eco-friendly and sustainable approaches are gaining popularity for in-situ treatment.

- **Microbial Remediation**: Certain bacteria and fungi can absorb, reduce, or transform toxic metals into less harmful forms. For example, certain bacteria like *Pseudomonas* and *Bacillus* spp. can reduce the toxicity and bioavailability of metals such as chromium and lead through uptake and immobilization. White-rot fungi degrade complex pollutants and trap metals in their mycelia. Microbial remediation is a sustainable, mild-condition alternative to chemical methods, though its efficiency depends on metal concentration, environmental factors, and microbial species. Despite limitations, it offers promising long-term solutions for heavy metal pollution in aquatic systems (Wang & Chen, 2009).

- **Phytoremediation**: uses plants, algae, and fungi to absorb and detoxify heavy metals from water, soil, and sediments. Aquatic plants and algae are effective in pollutant uptake, making them ideal for wastewater treatment. Species like *Salsola kali*, *Prosopis*, and *Brassica* thrive in hydroponic and wetland systems due to their metal tolerance. Algae such as *Anabaena*, *Oscillatoria*, *Phormidium*, and *Spirogyra* resist metal stress and remove metals via biosorption (surface binding to hydroxyl, carboxyl, phosphate, and amide groups) and bioaccumulation, which involves the intracellular uptake and storage of metals. Microalgae, though requiring trace metals like Fe, Zn, and Cu for metabolism, can remove excess metals through redox reactions, chelation, gene regulation, and ion exclusion. Phytoremediation is safe, eco-friendly, and cost-effective, though its efficiency is influenced by factors such as pH, temperature, moisture, substrate type, and pollutant distribution (Chaturvedi *et al*., 2025).

5.3. Emerging Technologies

- **Nanotechnology**: Use of metal-binding nanoparticles or nano-adsorbents shows promise for high-efficiency metal removal but is still under research for large-scale applications (Ali *et al*., 2019).
- **Electrochemical Treatments**: Methods like electrocoagulation and electroflotation use electric current to remove dissolved metals. These are effective but may require high energy input and skilled operation.

CONCLUSION

Heavy metal contamination in aquatic ecosystems poses a serious and persistent threat to environmental and human health due to their non-degradable nature and bio accumulative effects. These pollutants originate from industrial, agricultural, domestic, and natural sources, leading to toxic impacts across aquatic food webs, biodiversity loss, and habitat degradation. Detection relies on advanced analytical methods (AAS, ICP-MS), bioindicators, and remote sensing tools, while remediation strategies range from conventional physicochemical treatments to sustainable biological approaches like microbial and phytoremediation. Though effective, each method has limitations in cost, efficiency, or environmental dependency. A holistic approach combining prevention, monitoring, enforcement, and innovative technologies is essential for mitigating heavy metal pollution. Safeguarding aquatic ecosystems from such contamination is vital for ecological integrity and future water security.

REFERENCES

Ahluwalia, S. S., & Goyal, D. (2007). Microbial and plant derived biomass for removal of heavy metals from wastewater. *Bioresource Technology, 98*(12), 2243–2257. https://doi.org /10.1016/j.biortech.2006.10.029

Ali, I., Peng, C., Khan, Z. M., & Naz, I. (2019). Removal of heavy metals from wastewater using nanomaterials: A review. *Environmental Science and Pollution Research, 26*(7), 7257–7278.

https://doi.org/10.1007/s11356-019-04161-3

Bureau of Indian Standards. (2012). *IS 10500:2012 – Drinking water – Specification (Second Revision)*. https://bis.gov.in/

Burton, G. A. (2002). Sediment quality criteria in use around the world. *Limnology, 3*(2), 65–75. https://doi.org/10.1007/s10201-002-8011-x

Chaturvedi, P., Goswami, K., Khalasi, B. R., Soni, V., Sharma, S., & Kanaujiya, S. (2025). Fundamental mechanisms and emerging strategies in phytoremediation of environmental pollutants. *Vigyan Varta, 6*(5), 26–33.

Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management, 92*(3), 407–418. https://doi.org/10.1016/j.jenvman.2010.11.011

Gall, J. E., Boyd, R. S., & Rajakaruna, N. (2015). Transfer of heavy metals through terrestrial food webs: A review. *Environmental Monitoring and Assessment, 187*, 201. https://doi.org/10.1007/s10661-015-4430-3

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009

Kumar, A., & Kumar, R. (2022). Application of GIS and remote sensing in environmental monitoring of heavy metal pollution: A review. *Environmental Science and Pollution Research, 29*, 43901–43916. https://doi.org/10.1007/s11356-021-17811-9

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In Luch, A. (Ed.), *Molecular, clinical and environmental toxicology* (Vol. 101, pp. 133–164). Springer. https://doi.org/10.1007/978-3-7643-8340-4_6

United States Environmental Protection Agency. (2023). *National recommended water quality criteria – Aquatic life criteria table*. https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table

Wang, J., Liu, X., & Zhang, W. (2020). Bioaccumulation of heavy metals in aquatic organisms and human health: A review. *Ecotoxicology and Environmental Safety, 189*, 109913. https://doi.org/10.1016/j.ecoenv.2019.109913

Wang, W.-X., & Rainbow, P. S. (2008). Comparative approaches to understand metal bioaccumulation in aquatic animals. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, 148*(4), 315–323.

World Health Organization. (2017). *Guidelines for drinking-water quality: Fourth edition incorporating the first addendum*. WHO. https://www.who.int/publications/i/item/9789241549950.