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Heavy Metals and Pesticides in Water Bodies: Sources, Impacts, and Remediation Strategies

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Abstract:
Heavy metal and pesticide contamination in water bodies is a pressing global environmental issue, threatening ecosystems, human health, and sustainable development. The resulting effluent (contaminated with heavy metals and pesticides) has a harmful influence on human health, the ecology, and the aquatic environment. Biodegradable and biocompatible insecticides (including plant-based) have recently been offered as environmentally friendly and safe alternatives to synthetic pesticides. Heavy metal pollution in the aquatic environment is on the rise due to industrialization, climate change, and urbanization. This review aims to provide an overview of heavy metals and pesticides in water bodies, their sources, impacts, and mitigation strategies, drawing on recent research.

INTRODUCTION

Water bodies, including rivers, lakes, groundwater, and oceans, serve as perilous resources for drinking, agriculture, and industrial activities (Karapanagioti, 2016; Musie and Gonfa, 2023). However, heavy metals and pesticides pollution has emerged as a significant threat to water quality (Adil *et al.*, 2023). Heavy metals are non-biodegradable, persistent, and toxic at low concentrations, posing risks to aquatic ecosystems and human health (Azeem and Rashid, 2019; Hama Aziz *et al.*, 2023). Pesticides are any chemical or mixture of chemicals used to prevent, eradicate, or control pests. These are synthetic chemicals that may be toxic to the environment and other organisms (Ahmad *et al.*, 2024). Pesticides are widely used for enhancing the production of crops by controlling pest. But these pesticides leach into soil and reach to surface and ground water and therefore dissolve into drinking water (Navarro *et al.*, 2021). Due to their ubiquity in the environment, it poses a significant health risk and known to cause various diseases such as lung cancer, pancreatic cancer and leukemia etc. they also cause weakness and paralysis (Dong *et al.*, 2020). Heavy metals and pesticides are identified in water sources, posing a hazard to water quality and safety (Rad *et al.*, 2022). Furthermore, they would harm the ecological environment and pose potential hazards to humans, despite the fact that an above-standard concentration did not indicate an ecological or health concern. There have been some findings on the non-carcinogenic and carcinogenic dangers of heavy metals and insecticides ingested, inhaled, and applied topically (Dong *et al.*, 2020).

Sources of heavy metals and pesticides in water bodies

Wastewater effluents from industrial processes contain a wide range of toxic heavy metal contaminants, with human and anthropogenic factors being the primary sources of increased environmental toxicity. Heavy metals occur naturally in the Earth's crust and enter water bodies through geological processes such as weathering, erosion, volcanic activity, biogenic processes, and the release of marine salt (Zaynab *et al.*, 2022). For instance, arsenic is often released from arsenic-rich bedrock into groundwater. Similarly, mercury can be mobilized through volcanic emissions and mineral leaching. Spray drifts and agricultural run-off are the major sources of pesticides pollution of soil and water (Schönenberger *et al.*, 2022). The industrial wastes and orchards treated with pesticides also contribute significantly towards pesticides pollution. Food processing industries and pesticide manufacturing industries also release such chemicals in different ecosystems through their effluents wastes. These chemicals are persistent organic pollutants that tend to accumulate in the environment in soil, water or air (Ansari *et al.*, 2024).

Human activities significantly amplify heavy metals and pesticides contamination. Effluents from mining, smelting, electroplating, and textile industries release metals like Cd, Cr, and Pb. For example, tannery effluents in India have been linked to high Cr levels in nearby rivers (Oladimeji *et al.*, 2024). Pesticides, fertilizers, and livestock waste introduce metals like Cu, Zn, and As into water bodies (Alengebawy *et al.*, 2021). Improper disposal of batteries, paints, and electronic waste contributes to Pb and Cd pollution (Dey *et al.*, 2023). Coal combustion and vehicle emissions release Hg and Pb, which settle into water bodies via precipitation (Oladimeji *et al.*, 2024). Organochlorine and other such pesticides cause different disease due to their toxicity. It was also noticed that these pesticides persist in environment for a long time. Therefore in most countries by the World Health Organization these organochlorine and other pesticides have been banned. Recent studies indicate that anthropogenic inputs far exceed natural contributions, with industrial hotspots being the primary drivers of contamination (Haghighizadeh *et al.*, 2024). Water pollution caused by anthropogenic activities due to addition of such contaminants or chemicals that change their natural characteristics. The polluted water is not suitable for human and animals consumption or to support the biotic communities living in water (Edo *et al.*, 2024).

Behavior and fate of heavy metals and pesticides in water bodies

Heavy metals in aquatic environments exist in various forms, dissolved ions, complexes, or particulate matter, depending on factors like pH, redox conditions, and organic matter content. These factors influence their mobility, bioavailability, and toxicity (Martin-Romero *et al.*, 2021). Mercury undergoes biomethylation in anaerobic sediments, forming methylmercury, a highly toxic and bioaccumulative compound (Wu *et al.*, 2024). Arsenic speciation (As(III) vs. As(V)) determines its toxicity, with As(III) being more mobile and toxic (Sadee *et al.*, 2023). Lead and Cadmium tend to adsorb onto sediments, reducing their immediate bioavailability but creating long-term reservoirs of contamination (Zhang *et al.*, 2020). Bioaccumulation and biomagnification amplify heavy metal concentrations through aquatic food chains, affecting higher trophic levels, including fish and humans. The growing population and increased human activities have damaged water quality. Every day, several chemicals are discharged from various sources, polluting the supply of water. The excessive and unregulated use of pesticides on various crop species has a negative impact on beneficial biota such as honey bees, predators, birds, plants, small animals, and people. Furthermore, these repercussions produce an imbalance in the biodiversity of the overall biological system. Pesticides follow a mechanistic pathway that begins with application and continues with photodegradation, absorption by plant components (stem, leaves, or fruit), or soil sorption (Alengebawy *et al.*, 2021).

Ecological and health impacts

Ecological impacts

Heavy metals and pesticides pose a significant threat to aquatic ecosystems, disrupting their balance and causing harm to living organisms. These metals, even at low concentrations, can be toxic and accumulate in the tissues of aquatic life, leading to various adverse effects and impacting the entire food chain (Santhosh *et al.*, 2024). Heavy metals cause damage and malfunction in the tissues of organisms (Hadyait *et al.*, 2018; Iqbal and Ashraf, 2022). Cd and Hg impair reproduction and growth in fish and invertebrates. For example, studies have linked Hg exposure to reduced fish populations (Mondal *et al.*, 2018). Bioaccumulation in primary producers (e.g., algae) transfers metals to higher trophic levels, affecting predators like birds and mammals (Hu *et al.*, 2021). Sedimentation of metals alters benthic environments, reducing biodiversity (Gnanasekaran and Raj, 2023). Pesticides can have a severe harmful influence on ecosystems. They can pollute soil and water, causing biodiversity loss, damaging vital insects such as pollinators, and affecting aquatic life. Pesticides can also disrupt food chains via bioaccumulation and biomagnification, impacting a wide range of creatures, including birds and mammals (Kim *et al.*, 2017; Mahmood *et al.*, 2016).

Health impacts

Consumption of contaminated water or aquatic organisms poses severe health risks. Contamination can introduce harmful pathogens like bacteria and viruses, causing various illnesses, or introduce toxic chemicals like heavy metals and pesticides, which can have long-term health consequences (Lin *et al.*, 2022). It is plausible to presume that ingesting heavy metal-contaminated fruits and vegetables poses a health risk to consumers, since these contaminants may accumulate in various tissues, resulting in both acute and chronic health effects (Azeem and Rashid, 2019; Iqbal and Ashraf, 2023). Lead causes neurological disorders, especially in children, and kidney damage (Sanders *et al.*, 2009). Methylmercury exposure leads to developmental deficits and neurological impairments (Myers and Davidson, 2000). Arsenic is linked to skin lesions, cancers, and cardiovascular diseases, particularly in groundwater-dependent regions. Long-term exposure can lead to these adverse health outcomes, with skin lesions being a classical sign of chronic arsenic toxicity (Shankar *et al.*, 2014). Cadmium is associated with kidney dysfunction and bone fragility. Cadmium, in particular, is known to be nephrotoxic, which means it may harm the kidneys, as well as

having a bad influence on bone health, potentially leading to illnesses such as osteomalacia and osteoporosis. Cadmium-induced kidney impairment can have both direct and indirect effects on bone (Staessen *et al.*, 1999). Pesticide exposure can indeed cause both acute and chronic health problems. Pesticide exposure may cause irritation of the eyes and skin but their most severe effects are on nervous system, causing reproductive problems by interfering with hormonal balance (Shekhar *et al.*, 2024).

Remediation strategies

Great practical and scientific interest lies in the removal of pollutants from environment. Traditional approaches to mitigating heavy metal and pesticide pollution include physical, chemical, and biological methods (Iqbal and Ashraf, 2018). Physical procedures include excavation and soil cleaning, whereas chemical approaches include processes such as chemical reduction and solidification. Adding coagulants (e.g., lime) to precipitate metals as insoluble hydroxides or sulfides. Lime, or calcium hydroxide, is a common reagent for raising the pH of the wastewater, causing metal ions to react and form solid precipitates that can be filtered out. This method is cost-effective but generates sludge (Pohl, 2020). Resins selectively remove metal ions but are expensive and less effective for complex effluents. Techniques like reverse osmosis and nanofiltration remove metals but require high energy and maintenance. Activated carbon and zeolites adsorb metals but have limited capacity and require frequent regeneration (Dehghani *et al.*, 2023; Gahrouei *et al.*, 2024).

Phytoremediation is a suitable technique as it is easy to implement and maintenance. Several plants accumulate metals, offering a low-cost, environmentally friendly solution (Ashraf *et al.*, 2021; Iqbal *et al.*, 2020; Iqbal *et al.*, 2019; Sattar *et al.*, 2018; Sultana *et al.*, 2019a; Sultana *et al.*, 2019b). Microorganisms (e.g., sulfate-reducing bacteria) transform metals into less toxic forms. For instance, bacteria-mediated Hg reduction has been successful in pilot studies (Meyer *et al.*, 2023). Nanoparticles exhibit high adsorption capacities for heavy metals and pesticides (Karnwal and Malik, 2024). Electrocoagulation and electrodialysis offer precise metal and pesticide removal but are energy-intensive (Patel *et al.*, 2024).

Challenges and future directions

While conventional methods are widely used, they often generate secondary waste and are costly at scale. Emerging technologies, though promising, require optimization for field applications and cost reduction. Integrated approaches combining bioremediation, nanotechnology, and policy enforcement are critical for sustainable management.

CONCLUSION

Heavy metal and pesticide contamination in water bodies is a multifaceted challenge requiring urgent action. While natural sources contribute, anthropogenic activities drive the majority of pollution, with severe ecological and health consequences. Advances in remediation technologies, particularly bioremediation and nanotechnology, offer hope, but their scalability and cost-effectiveness need further exploration. Integrated management, combining technological innovation, policy enforcement, and public awareness, is essential to safeguard water resources. Future research should focus on low-cost, sustainable solutions and global cooperation to address this pervasive issue.

CONFLICT OF INTEREST

The authors declare that this article's content has no conflict of interest.

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