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Heavy Metal Pollution in Aquatic Ecosystems: A Review of Toxic Impacts and Remediation Strategies

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Abstract

Heavy metals contamination in aquatic ecosystems is a critical environmental issue with far-reaching implications for ecological health and human safety, Heavy metal pollution in aquatic ecosystems is a pressing environmental concern, posing significant risks to aquatic life and human health. This review summarizes the toxic effects of heavy metals (HMs) on aquatic organisms, ecosystems, and human consumers. The study explores the sources, fate, and transport of HMs in aquatic environments, highlighting their bioaccumulation, biomagnification, and ecological impacts. Remediation strategies, including phytoextraction, bioaugmentation, and chemical treatment, are critically evaluated. Emerging technologies, such as Nano remediation and bioremediation, offer promising solutions. The study showed heavy metal pollution in aquatic ecosystems is a significant environmental challenge that

requires coordinated efforts from governments, industries, and communities to mitigate its impacts and protect water quality and aquatic life. By addressing the sources and effects of heavy metals in aquatic habitats, we can mitigate their impact on the environment and human health, ensuring the sustainability of these vital ecosystems.

Keywords: Heavy Metals, Aquatic Ecosystems, Toxicity, Remediation

Introduction

Global industrialization has advanced and made life easier, but many companies also produce waste that is thrown into the environment, causing toxins to get released into the air, soil, and aquatic bodies, further polluting the surrounding area. Soil contaminated by heavy metals is a serious environmental problem that affects agriculture, human health, and the stability of ecosystems. Due to their toxicity and persistence in the environment, heavy metals like lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) are particularly concerning (Adam, A. B., et al., 2023). Heavy metal pollution in aquatic ecosystems is a major environmental concern worldwide (Musa et al., 2024). Aquatic life and human consumers are at risk from heavy metals like lead, mercury, and cadmium (Sharma et al., 2021). According to Fu et al. (2019), the main causes of heavy metal pollution in aquatic habitats are waste disposal, agricultural runoff, and industrial effluents. Heavy metals can cause negative ecological and health impacts in aquatic animals by bioaccumulating and biomagnifying once they are in the environment (Tchounwou et al., 2012).

Heavy metals are among the most prevalent pollutants in aquatic environments, according to the US Environmental Protection Agency (EPA), and they pose dangers to the environment and human health (Wang et al., 2019). In order to safeguard public health, the World Health Organization (WHO) has also emphasized how critical it is to address heavy metal contamination in aquatic environments (EPA 2020). Heavy metals from building materials, road surfaces, and other sources find their way into aquatic environments through runoff from metropolitan areas. Lead, zinc, and copper are common metals identified in urban runoff (Makepeace, Smith, & Stanley, 1995). Heavy metals are released into the atmosphere via industrial processes, waste incineration, and the burning of fossil

fuels. Both dry deposition and precipitation can deposit these metals into aquatic habitats (Nriagu&Pacyna, 1988).

Heavy metal contamination is mostly caused by industrial processes, especially those involving mining, smelting, manufacturing, and electroplating. These businesses frequently produce wastewater with high metal concentrations that might be hazardous to aquatic life (Alloway, 2013). Heavy metals are released into neighboring rivers, lakes, and streams by agricultural practices that include pesticides, herbicides, and fertilizers. These metals have the ability to build up in soils and eventually find their way into surface and groundwater (Nagajyoti, Lee, &Sreekanth, 2010).

Waste products from mining and ore processing are abundant in heavy metals. Because it releases heavy metals into water bodies, acid mine drainage (AMD), a consequence of sulfide mineral oxidation, is especially dangerous (Hudson-Edwards, 2003). Heavy metals from building materials, road surfaces, and other sources find their way into aquatic environments through runoff from metropolitan areas. Lead, zinc, and copper are common metals identified in urban runoff (Makepeace, Smith, & Stanley, 1995). Heavy metals are released into the atmosphere via industrial processes, waste incineration, and the burning of fossil fuels. Both dry deposition and precipitation can deposit these metals into aquatic habitats (Nriagu&Pacyna, 1988).

Environmental Impacts

Heavy metal pollution is a significant environmental issue that affects the health of aquatic ecosystems, terrestrial ecosystems, and human populations. Heavy metals, including lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr), are persistent pollutants that can have long-lasting effects on the environment due to their toxicity, persistence, and bioaccumulation potential.Heavy metals in aquatic ecosystems have detrimental effects on water quality and biodiversity. They bioaccumulate in the tissues of aquatic life, leading to mortality, physiological stress, and problems with reproduction. High concentrations of metals in top predators can result from bioaccumulation and biomagnification, which can have an effect on entire food webs (Rainbow, 2002). Even at very low quantities, heavy metals are harmful to fish, invertebrates, and other aquatic species, leading to physiological stress, behavioral abnormalities, and even death. Lead and cadmium, for instance, can harm fish larvae's ability to develop and survive (Jezierska&Witeska, 2006). Contamination by heavy metals can modify the makeup of

organisms and decrease biodiversity in aquatic environments by changing their structure and function. According to Luoma and Rainbow (2008), contaminated sediments can act as persistent sources of pollution by gradually reintroducing metals into the water column.Heavy metals bind to sediments, persisting for extended periods and impacting benthic organisms that live and feed on the sediment surface, leading to a decline in benthic biodiversity (Eggleton& Thomas, 2004).

Heavy metals Health Risks on aquatic organism

Even in trace amounts, heavy metals like lead, mercury, cadmium, arsenic, and chromium are harmful to aquatic life. They have the ability to harm cellular structures, impede metabolic processes, and interfere with the activity of enzymes. Heavy metals can enter the bodies of aquatic animals by contact to water, sediment, or food sources. When the rate of metal intake surpasses the rate of excretion, bioaccumulation takes place. Heavy metals have the ability to biomagnify in food webs, which means that at higher trophic levels, their concentrations rise. Over time, predatory fish or mammals that eat polluted prey could accumulate large concentrations of metals. The effects of heavy metals on fertility, irregularities in development, and lower rates of offspring survival can all have an impact on the success of reproduction. They might also prevent growth and lower fitness in the impacted populations. In aquatic species, exposure to heavy metals can change behavior, including feeding and predator avoidance. Hormonal imbalances, immunological suppression, and oxidative stress are a few possible physiological impacts. Heavy metal contamination can disrupt aquatic ecosystems by reducing biodiversity, altering community structure, and impairing ecosystem functions such as nutrient cycling and primary productivity. Aquatic animals contaminated with high levels of heavy metals can pose risks to human health if consumed as seafood. Accumulation of metals in fish or shellfish tissues can lead to health problems such as neurological disorders, kidney damage, and cancer.

The Importance of Aquatic Ecosystems

Aquatic ecosystems, which include oceans, seas, rivers, lakes, wetlands, and estuaries, are vital for the health of the planet and provide numerous benefits to human societies and natural environments. Aquatic ecosystems are home to a vast array of species, many of which are not found anywhere else. This biodiversity is crucial for maintaining ecological balance and resilience. Oceans and other water bodies play a significant role in regulating the Earth's climate. They absorb large amounts of carbon dioxide and heat, helping to

mitigate the impacts of climate change. These ecosystems provide numerous resources, including fish and shellfish, which are vital for food security. They also support industries such as tourism, recreation, and shipping. Wetlands, rivers, and lakes act as natural water filters, removing pollutants and improving water quality. This function is essential for providing clean drinking water and maintaining healthy environments. Wetlands and mangroves act as natural buffers, absorbing excess water and reducing the impact of floods. This helps protect human communities and infrastructure from flood damage. Aquatic ecosystems play a key role in the cycling of nutrients such as nitrogen and phosphorus. These nutrients are essential for the growth of plants and the overall productivity of ecosystems. Many cultures have deep connections to water bodies, which are often considered sacred or integral to cultural practices. Additionally, aquatic environments provide opportunities for recreation and tourism, contributing to human well-being and economic development. Aquatic ecosystems offer invaluable opportunities for scientific research and education. Studying these environments helps scientists understand fundamental ecological processes, biodiversity, and the impacts of human activities.

Sources of Heavy Metal Contamination

Heavy metal contamination were mostly from Industrial Discharges which often release heavy metals like mercury, lead, cadmium, and arsenic into water bodies through waste effluents, Mining Activities which lead to the runoff of heavy metals into nearby rivers and lakes.Agricultural Runoff which washed Pesticides and fertilizers used in agricultural activitiesinto water bodies, metals from urban areas, including those from vehicle emissions and construction activities, Improper disposal of electronic waste, batteries, and other heavy metal-containing products can lead to contamination.

Heavy metals are toxic to aquatic organisms even at low concentrations. They cause a range of adverse effects, including developmental abnormalities, reduced reproductive success, and death. They accumulate in the tissues of aquatic organisms over time, leading to higher concentrations in predators, including humans, through the food chain. Heavy metal contamination can disrupt the balance of aquatic ecosystems, leading to declines in biodiversity and the alteration of species composition.

Human Health Risks

Humans were exposed to heavy metals by eating contaminated fish and shellfish. This exposure can lead to serious health issues, including neurological and developmental problems, kidney damage, and cancer. Heavy metals can leach into groundwater and surface water, posing risks to communities that rely on these sources for drinking water. Heavy metals, such as mercury, cadmium and lead and polychlorinated biphenyls (PCBs), especially the so-called "dioxin-like" PCBs, deserved special attention among these pollutants, as they represent a group of highly toxic substances accumulating in the tissues of marine organisms and being conveyed through the food chain to human Storelli, M. M. (2008).

Heavy Metals of Concern

One of the sustainable development goals (SDG6) is to "ensure availability and sustainable management of water and sanitation for all", with targets concerning water quality, water-use efficiency, and water resources management that should be achieved by 2030 (Kristensen, et al., 2022, NSSDR 2013).Identify the heavy metals of most concern (e.gPb, Hg, Cd, As, Cr, Cu, Zn) and discuss their environmental impact. The presence of priority pollutants (organic or inorganic) in aquatic ecosystems is directly linked to industrial production processes, agriculture, and transport activities that do not meet environmental standards (Chaturvedi et al., 2021) The discharge of effluents with a wide range of inorganic and organic compounds that belong to the priority (PP) and emerging pollutant (EP) classes such as pharmaceuticals and personal care products, pesticides, heavy metals, detergents, and flame retardants provide, even in very small concentrations, eco-toxicological and human health effects and bioaccumulation and degradation characteristics that may influence aquatic biota and the performance and costs of water and wastewater treatment plants (Schwarz,et al., 2021), Wang et al., 2022, Mladenov et al., 2022, Teodosiu et al., 2018). Different acute and chronic health hazards are caused by these potentially toxic elements such as the priority organic and inorganic pollutants due to their bioaccumulation capacity, carcinogenicity, persistent nature, and toxicity (Jiménez-Oyola et al., 2021, Ali et al., 2009. The environmental pollution effects included chiral pollutants with serious long-term health effects (Ali et al., 2009,Basheer, et al., 2018).

Impacts of heavy metal contamination on Aquatic Organisms and Ecosystems

Heavy metal contamination in aquatic environments poses significant threats to aquatic organisms and ecosystems. It can cause acute toxicity, chronic toxicity, physiological stress, immune system suppression, reproductive impairment, growth and developmental abnormalities, behavioral changes, bioaccumulation and biomagnification. Ecosystems also suffer from biodiversity loss, disruption of ecosystem functioning, food web changes, habitat degradation, and water quality degradation. Sensitive species may decline or disappear due to toxic effects, disrupting ecosystem balance and function. To address heavy metal contamination, a comprehensive approach is needed, including strict regulations on industrial discharges and mining operations, remediation techniques like phytoremediation, public awareness and education, and research and monitoring. Effective mitigation requires coordinated regulatory, technological, and educational efforts to reduce contamination and support ecosystem recovery.

Mortality effect of heavy metals contamination on aquatic organisms

Heavy metal contamination in aquatic environments has severe mortality effects on aquatic organisms. This is due to the toxic nature of metals like mercury, lead, cadmium, and arsenic, which can cause both acute and chronic toxicity, High concentrations of heavy metals can lead to rapid death in aquatic organisms. This is often observed in cases of industrial spills or mining accidents where large quantities of heavy metals suddenly enter water bodies(Sharma et al., 2024), Fish and invertebrates are particularly susceptible to acute toxicity, which can result in mass die-offs.

Prolonged exposure to lower concentrations of heavy metals can cause chronic toxicity, leading to gradual deterioration in health and eventual death, Chronic exposure affects physiological systems such as the respiratory, circulatory, and nervous systems, causing long-term damage that can result in mortality over time(Sharma et al., 2024). Heavy metals can interfere with essential physiological processes, such as respiration and osmoregulation. For instance, damage to the gills of fish impairs their ability to extract oxygen from water, leading to hypoxia and death(Sharma et al., 2024). Metals like cadmium and mercury can cause severe kidney and liver damage, impairing the organism's ability to detoxify and excrete wastes, leading to systemic failure and death.

Heavy metals such as mercury and lead are neurotoxic, affecting the nervous system and leading to impaired motor function, loss of coordination, and eventual death.Neurotoxic effects can also impair feeding and predator avoidance behaviors, indirectly leading to higher mortality rates due to predation or starvation(Singh et al., 2023).Heavy metals accumulate in the tissues of aquatic organisms over time. This bioaccumulation can reach toxic levels, particularly in long-lived species.Predatory species at higher trophic levels are especially vulnerable due to biomagnification, where heavy metals become more concentrated as they move up the food chain. This can lead to high mortality rates in top predators like large fish, birds, and mammals(Singh et al., 2023).

Remediation Strategies

Addressing heavy metal pollution in aquatic ecosystems requires a multifaceted approach, including pollution prevention, regulatory enforcement, and remediation technologies, Implementing stringent regulations to control industrial discharges, mining activities, and agricultural practices to reduce the release of heavy metals (Alloway, 2013), Developing advanced water treatment technologies, such as adsorption, chemical precipitation, and phytoremediation, to remove heavy metals from contaminated water bodies (Ali, Khan, &Sajad, 2013), Employing methods like dredging, capping, and in-situ stabilization to manage contaminated sediments and prevent the release of heavy metals (Ghosh et al., 2011), Conducting regular monitoring and risk assessments to identify pollution hotspots, evaluate the effectiveness of remediation efforts, and protect vulnerable ecosystems and populations (Luoma& Rainbow, 2008).

Remediation of heavy metals in aquatic habitats is a critical environmental issue due to the toxic effects of heavy metals on ecosystems and human health. Various techniques are employed to remove or mitigate heavy metals in water bodies. Here are some of the primary methods used for remediation of heavy metals in aquatic habitats. This remediation will help to reduce the contaminations of the heavy metals to water body which will help to maintain the level of water, this process involve both physical and chemical methods these include

Sedimentation, filtering, reverse osmosis, nanofiltration, and ultrafiltration are methods used to remove heavy metals from water bodies. Chemical processes, such as chemical precipitation, coagulation, flocculation, and ion exchange resins, transform heavy metals into less toxic or easily removable forms. Chemical precipitation involves adding chemicals

to form insoluble metal compounds that can be removed by sedimentation or filtration. Coagulation neutralizes charges on particles, causing them to aggregate. Flocculation forms larger aggregates that can be filtered. Ion exchange resins exchange metal ions with non-toxic ions on the resin surface. Biological remediation methods, such as phytoextraction, phytostabilization, bioaugmentation, and biostimulation, utilize the natural capabilities of plants, microorganisms, fungi, and engineered ecosystems to remove or neutralize pollutants. These methods offer sustainable solutions for mitigating contamination in aquatic ecosystems.

Electrochemical processes offer versatile and effective solutions for the remediation of heavy metal contamination in aquatic habitats. Each method has specific applications and advantages, from precipitating and removing metals through electrocoagulation to separating ions with electrodialysis and oxidizing organic contaminants with the Electro-Fenton process. These technologies can often be combined with other physical, chemical, and biological methods to enhance overall remediation efficiency and sustainability, applying an electric current to sacrificial metal electrodes (e.g., iron, aluminum), which dissolve and form coagulants in situ that precipitate heavy metals. Applying an electric current to reduce metal ions to their elemental form, this can then be removed from the water. Combination methods of physical, chemical, and biological could be used to achieve more effective and comprehensive remediation.

Conclusion

Heavy metals are the major source of contamination of soil through anthropogenic sources. In the tannery effluent contaminated sites, the most commonly found heavy metals include chromium and zinc. These metals are highly toxic to the environment and pose a severe threat to the biological systems. Hence, there is a need for remediating the contaminated soil in an eco-friendly manner. Of the various methods for removal of heavy metals that were studied, heavy metal contamination has severe impacts on aquatic organisms and ecosystems, necessitating coordinated regulatory, technological, and educational efforts, biological effects of heavy metal contamination on aquatic organisms, including mortality, sublethal effects, and impacts on reproduction, growth, and development.

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