Heavy Metal Contamination in Coastal Sediments and Its Impact on Aquatic Biodiversity: Sources, Ecological Risks, and Sustainable Management Strategies

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Abstract
The persistence, toxicity and environmental effects of heavy metals have become a very important environmental issue in the coastal sediments. The sources of heavy metals which are found in the industrial effluents, mining, agricultural run-offs, urbanization, shipping and the waste water effluents also gather along the coast and forms sink in the sediments. These metals may be remobilized to the aquatic environment under different environmental conditions and thus of significance to the aquatic organisms. The purpose of this review is to bring together all the available information based on distribution, sources, environmental fate, ecological impacts and risk evaluation of heavy metals in coastal sediments i.e. the impact of heavy metals on aquatic biodiversity. Adverse impacts of cadmium, lead, mercury, arsenic, chromium, copper, zinc and nickel on microorganisms, phytoplankton, benthic invertebrates, fish, mangroves, seagrasses and coral reef systems are pointed out. The ecologic and human health hazards are further enhanced by aquatic food chains by bioaccumulation and biomagnification. The most popular ecological risk assessment tools (Geoaccumulation Index, Enrichment Factor, Pollution Load Index, Potential Ecological Risk Index and Sediment Quality Guidelines), and existing remediation and sustainable management plans are considered. Review also reveals critical research gaps like interaction of climate change, molecular and geospatial technologies to monitor the environment and the role of synergy of a combination of pollutants. Thus, the improvement of the integrated coastal management and long-term monitoring programs will be important to protect and to sustainably manage the aquatic biodiversity and coastal ecosystems.

Keywords: Heavy metals, Coastal sediments, Aquatic biodiversity, Bioaccumulation, Ecological risk assessment, Marine pollution, Sustainable management

1. Introduction

Coastal wetlands are the most prolific and diverse on earth, sustain the greatest number of ecological processes and offer enormous ecosystem services like fisheries, nutrient cycling, shoreline protection, carbon sequestration and recreation. These are estuaries, mangrove forests, tidal and salt marshes, seagrass meadows and coral reefs and they are significant to sustain numerous aquatic species and to sustain biodiversity across the globe. Increased industrialization, urbanization, agricultural intensification as well as improved maritime activities have however contaminated a coastal ecosystem with contaminants, particularly the heavy metals (Rangel-Buitrago et al., 2023; Silva et al., 2024).

The most problematic environmental contaminants are heavy metals (cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), chromium (Cr), copper (Cu), zinc (Zn) and nickel (Ni) since they do not break down and are chemically stable and can survive long in sediments. The heavy metals are not broken down to harmless materials and are deposited in the sediments and can take decades to break and cause ecological hazards at any given time (Luoma & Rainbow, 2008). The sources or sinks of the coastal sediments may include heavy metals. Fine-grained particles that are effective in adsorbing the dissolved metals during transportation include clay minerals, organic matter, and iron-manganese oxides, which are found in rivers, wastewater discharges, industrial effluents, mining activities, atmospheric deposition, and urban runoff. Early effects of sediment on metal levels in the overlying water column tend to be depleting, although redistribution of metal contaminants may occur due to the changes in the environmental conditions (pH, salinity, redox potential, sediment disturbance) that have caused an increase in bioavailability (Birch, 2017; Silva et al., 2024).

The effects of heavy metal contamination are at different troic levels. Chronic exposure results in different levels of stress, growth retardation, reproductive retardation, oxidative injury, immune retardation and death of microbial community, phytoplankton, benthic invertebrates, mollusk, crustaceans, fish and aquatic plants. Bioaccumulation and biomagnification exaggerate these effects, which will concentrate metals in aquatic food chains and endanger the stability of these food chains and human health by consuming seafood (Chapman & Wang, 2001; Rainbow, 2002).

The scientific interest in the contamination of sediments has been on the rise in the past few decades, resulting in a number of regional studies, but because the results are fragmented due to the different places, methods of assessment, types of sediments and sources of pollution (Silva et al., 2024; Zeb et al., 2024). Thus, it is necessary to conduct a comprehensive overview of the available information, to improve knowledge about contamination pathways, ecological effects and management options. This narrative review summarizes the most recent evidence on the prevalence of heavy metal contamination in coastal sediments, on the causes of the contamination, on the disposition of the heavy metals in the environment, on the impact on aquatic biodiversity, on the typical ecological risk assessment approach and on new management options. The review also points out the major research gaps to guide future monitoring and conservation efforts.

2. Heavy Metals of Environmental Concern

2.1 Heavy Metals of Environmental Concern

Heavy metals are naturally occurring elements which may become toxic at concentrations higher than background levels. Micronutrients such as copper, zinc, manganese, cobalt and iron are elements that are necessary in the biological systems but are toxic when found in large quantities which can suppress the biological systems. Cadmium, mercury and lead on the other hand are not known to play any biological role and are very toxic in low concentrations (Luoma & Rainbow, 2008). The most chemically and toxicologically important elements studied in coastal waters are Cd, Pb, Hg, As, Cr, Cu, Zn and Ni due to their persistence, toxicity, ubiquity and sedimentary deposition. The mobility and biological availability of these metals are influenced differently by the oxidation state, the mineralogical sediment characteristics and the environmental conditions (Eggleton & Thomas, 2004).

Mining, phosphate fertilizers, electroplating industries and battery production are the primary sources of cadmium. The main sources of mercury are coal burning, chlor-alkali and small scale artisanal gold mining. Common sources of lead contamination include led gasoline, industrial emissions, battery manufacturing and recycling, urban runoff and paints. Natural erosion and weathering processes supply a little arsenic to coastal systems, and mining and the use of pesticides provide more. Common sources of chromium emissions are the tanning industry, textile industry and the electroplating industry. Sources of copper and zinc release are antifouling paints, shipping activities, municipal wastewater and industrial activities (Huang et al., 2019; Zeb et al., 2024).

2.2 Sources of Heavy Metal Contamination

Several sources have been identified that cause heavy metal contamination. There are natural and anthropogenic sources for the introduction of heavy metals to coastal ecosystems. Natural inputs include weathering of rocks, volcanic eruptions, soil erosion, discharge from groundwater, and transport by rivers. These processes also contribute to background concentrations, but in most parts of the coast generally occur only as a minor source of contamination. The contributions from anthropogenic sources remain the predominant ones. The industrial wastewater is contaminated with various elements, including cadmium, chromium, lead, copper and zinc, which are generally more prevalent in industrial wastewater from mining and metallurgy, electroplating, chemical manufacturing, petroleum refining and textile production (Silva et al., 2024). Agricultural activities contribute metals to the soil from phosphate fertilisers, pesticides, animal wastes and irrigation return flows. Road, roof, construction site, and municipal waste contaminations are transported to estuaries by urban stormwater.

Shipping activities also contribute significantly through antifouling coatings, fuel combustion and ballast water discharge, port maintenance and dredging operations. Heavy metals are present in coastal regions from atmospheric deposition from fossil fuel combustion (Gopal et al., 2023). Sediments are continuously subjected to contamination from different sources and they serve to integrate pollution over long time periods and therefore represent useful records of historical contamination (Ip et al., 2007).

Table 1: Major heavy metals, principal sources, and ecological concerns

Heavy metal	Major anthropogenic sources	Major ecological concerns
Cadmium (Cd)	Mining, fertilizers, batteries	Kidney toxicity, reproductive impairment
Lead (Pb)	Industrial emissions, batteries, urban runoff	Neurological toxicity, reduced growth
Mercury (Hg)	Coal combustion, mining	Biomagnification, neurotoxicity
Arsenic (As)	Mining, pesticides	Carcinogenicity, oxidative stress
Chromium (Cr)	Tanneries, electroplating	DNA damage, developmental toxicity
Copper (Cu)	Antifouling paints, industry	Gill damage, enzyme inhibition
Zinc (Zn)	Urban runoff, wastewater	Metabolic disruption
Nickel (Ni)	Metallurgy, petroleum refining	Reduced reproduction, oxidative stress

3. Distribution and Behaviour of Heavy Metals in Coastal Sediments

The physical, chemical, and biological interactions impact heavy metal environmental behavior in coastal sediments (Table 2). The dissolved metals are particularly absorbed rapidly by suspended particles once discharged into water bodies and subsequently deposited on the bottom. Coastal sediments, therefore, are long term reservoirs of contaminants (Eggleton & Thomas, 2004). The accumulation of metals processes is highly connected with the character of the sediment. The clay and silt fine-grained sediment possesses a greater surface area and adsorption

capacity in comparison to coarse sand. The metals can also be complexified and chelated by organic matter and iron and manganese oxides offer additional adsorption sites.
The mobility of metals is dependent on the environment. Precipitation is likely to happen at high alkalinity, whereas solubility of metals is likely to be favored at low acidicity (Huang et al., 2019). In the deeper layers of sediments, where the environments are reducing, the oxidation of iron and manganese oxides may cause released metals that were previously attached to them again into pore water. Salinity influences metals speciation through ion exchange and complex formation which influences biological uptake.
In addition, the distribution of contaminants is altered by hydrodynamic processes. Storms, tidal currents, dredging, and shipping activities can re-suspend contaminated sediment in the water and increase the levels of dissolved metals and re-expose aquatic organisms to contamination. Rainfall and river discharge are also seasonal and this influences the sedimentation regimes and transports of pollutants.
The concentration of metal actually toxic is an important component of ecological risk assessment and is termed as bioavailability. Exchangeable and carbonate-bound and reducible sediment fractions contain metals that are usually more accessible to the uptake process by biology than those that are tightly bound in mineral lattices. Sequential extraction techniques have thus become significant as a means of measuring environmental risk.

Table 2: Factors influencing heavy metal accumulation and mobility in coastal sediments

Environmental factor	Effect of heavy metals	Ecological implication
Fine particle size	Increased adsorption	Greater contaminant accumulation
Organic matter	Strong metal complexation	Enhanced sediment storage
Low pH	Increased solubility	Greater bioavailability
Reducing conditions	Metal remobilization	Increased toxicity
Salinity changes	Altered speciation	Variable biological uptake
Sediment disturbance	Resuspension	Secondary contamination

4. Ecological Impacts on Aquatic Biodiversity

Atmospheric deposition is another pathway through which heavy metals are transported and is an outcome of fossil fuel burning and is also more widely dispersed along coastal zones (Table 3). The toxicity responses vary according to the type of metal, concentration, length of exposure, and environmental, and sensitivity of species (Chapman, 2007).
The microorganisms are some of the earliest organisms to suffer in controlling nutrient cycles and decomposition of organic matter. High levels of heavy metals lead to a decrease in microbial biomass, shifts in microbial community structure, decreased enzyme activity, and slowed carbon and nitrogen cycling, which affects ecosystem functioning.
Exposure to cadmium, copper, mercury and chromium leads to reduced photosynthesis, chlorophyll destruction, oxidative stress, and reduced primary productivity in phytoplankton. Should a phytoplankton decrease, effects on the upper trophic levels are anticipated.
When aquatic food webs are characterized by low troic levels in the primary producers (phytoplankton), then it can be anticipated that the effects will be cascaded to higher troic levels. Long-term exposure to metals leads to decreased survival, decreased reproductive success, developmental malformations and feeding behavior in zooplankton. Such effects cause a decrease in food availability to young fish and other aquatic food consumers (Li et al., 2022).
Benthic organisms, such as polychaetes, bivalves, gastropods and crustaceans are especially vulnerable, as they need not live away from the polluted sediments. Benthic invertebrates are desirable bioindicators of quality of the sediment, and have good ability to store heavy metals in soft tissues (Rainbow, 2002). Chronic exposure results in decreased growth, reproductive failure, shell deformities, oxidative damage, immune suppression and death.
Metals are absorbed by fish via gills, digestive tract and food. It can lead to liver damage, kidney damage, gill damage, nervous system damage and reproductive system damage, and may also lead to reduced swimming ability, growth rate, fecundity, and resistance to disease. The aquatic food chains can lead to increased amounts of mercury in predatory fish via bio magnification.
Heavy metals can be taken up into mangrove and seagrass roots and leaves to a significant extent in coastal ecosystems. These plants are useful for their role in the ecosystem and can immobilize contaminants, but too much metal will decrease the plants' photosynthetic ability, affect the development of their roots, and have an impact on ecosystem productivity. Sediment-related heavy metals have become an increasing concern to coral reef ecosystems as well (Li et al., 2022). High concentrations have an impact on coral calcification capacity, oxidative stress, larval settlement, and when interacting with other environmental factors, lead to coral bleaching.
Therefore, the ecological effects of sediment contamination are still considered the worst, as bioaccumulation and biomagnification. The metals that are transmitted through the trophic levels eventually reach commercially significant fish and shellfish and this presents a threat to the wildlife consumers and humans.

Table 3: Effects of major heavy metals on aquatic organisms

Heavy metal	Major organisms affected	Principal toxic effects

Cadmium	Fish, mollusks, crustaceans	Kidney damage, reproductive toxicity
Lead	Fish, zooplankton	Neurological impairment, reduced growth
Mercury	Predatory fish	Biomagnification, neurotoxicity
Chromium	Algae, fish	DNA damage, oxidative stress
Copper	Fish, phytoplankton	Gill injury, impaired photosynthesis
Zinc	Aquatic plants, fish	Metabolic disruption
Nickel	Benthic fauna	Reduced reproduction
Arsenic	Fish, invertebrates	Cellular toxicity, oxidative damage

5. Ecological Risk Assessment of Heavy Metal Contamination

Coastal sediments, when contaminated with heavy metals, are ecologically harmful, and a risk assessment is required to better understand the environmental quality, identify pollution hotspots and develop effective management actions. The measurement of the concentration of metals will only measure the amount present in the water, however, the assessment of the concentration of metals and the potential biological effects will provide a fuller picture of ecosystem health as sediments are the long-term reservoir of heavy metals. Various indices and sediment quality guidelines have been created to gauge contamination, identify the source of contamination and estimate the ecological risk (MacDonald et al., 2000).

One of the most common is the Geoaccumulation Index (Igeo) developed by Müller (1969) which relates concentrations of metals found in the soil to natural background concentrations, accounting for natural geologic variability. The index classifies sediments into different classes from least contaminated to most contaminated sediments and may be used for comparison of the sediments between the geographic regions (Muller, 1969).

Two other popular indicators used for sediment contamination are the Contamination Factor (CF) and Pollution Load Index (PLI). The Contamination Factor is an individual metal assessment based on the ratio of metal concentrations to background concentrations; the Pollution Load Index is an integrated assessment and combines the Contamination Factor for multiple metals into an overall assessment of the metal contamination status. A number of these indices have been used extensively in coastal systems to characterize regions of cumulative anthropogenic impacts.

Another approach widely used is the Enrichment Factor (EF), which is used to separate anthropogenic metal inputs from the natural geological sources by dividing metal concentrations by the concentration of a conservative element (Al or Fe). Higher enrichment factors are a sign of major human inputs from industrial processes, mining, effluent discharge, or urban runoff (Alahabadi & Malvandi, 2018).

The Potential Ecological Risk Index (PERI) of Hakanson (1980) is one of the most complete tools of ecological risk assessment due to its incorporation of both contamination level and the relative toxicity of various metals. PERI assigns toxicity response coefficients for each metal, which can be used to estimate the overall ecological risk of the mixed metals. Toxicity coefficients are usually more highly assigned to metals that are more ecologically harmful, such as mercury and cadmium (Birch, 2017).

Sediment Quality Guidelines (SQGs) are also widely used to make predictions of potential biological effects, as are index-based methods. The concentration thresholds used to express adverse biological effects are called guidelines: Effects Range-Low (ERL), Effects Range-Median (ERM), Threshold Effect Concentration (TEC), and Probable Effect Concentration (PEC) (Hakanson, 1980). These measured concentrations are compared to these benchmark values, giving the researcher an idea of the potential threat to benthic organisms and, in turn, helping to determine the ranking of contaminated sites for remediation.

Although these indices provide valuable information, they also have certain drawbacks. Most make use of the total metal concentrations and do not consider all aspects of the speciation, bioavailability, or interactions between more than one contaminant. Therefore, combining chemical, biological, toxicity and ecological data is a more reliable way to assess environmental risks (Chapman, 2007). Table 4 summarizes the commonly applied ecological risk assessment methods used to evaluate heavy metal contamination and associated environmental risks in coastal sediments.

Table 4: Common ecological risk assessment methods used for coastal sediment contamination

Method	Purpose	Advantages	Limitations
Geoaccumulation Index (Igeo)	Measures sediment contamination relative to background	Simple and widely applied	Sensitive to background values
Contamination Factor (CF)	Assesses contamination by individual metals	Easy interpretation	Evaluates single metals only
Pollution Load Index (PLI)	Estimates the overall pollution status	Integrates multiple metals	Does not consider toxicity

Method	Purpose	Advantages	Limitations
Enrichment Factor (EF)	Distinguishes between natural and anthropogenic sources	Useful for source identification	Depends on reference element selection
Potential Ecological Risk Index (PERI)	Evaluates ecological risk considering toxicity	Includes toxicity weighting	Ignores synergistic effects
Sediment Quality Guidelines (SQGs)	Predicts biological effects	Useful for environmental management	Does not account for bioavailability

6. Mitigation and Sustainable Management Strategies

Coping with heavy metal pollution in coastal sediments is a complex task that needs an integrated management plan, which should include both pollution prevention and environmental remediation. Prevention of the release of heavy metals to aquatic environments is the best option for coastal ecosystem protection, as they are not biologically degraded and/or have long persistence.

Pollution prevention should start with the more stringent control of industrial effluent, the better treatment of the "dirty" water, and the better monitoring of the "dirty" water from the mining, agricultural, and urban sectors. Cleaner production technologies, environmentally friendly industrial production, and sustainable agricultural management can significantly reduce the heavy metal input into the coastal water. Environmental monitoring programs should also be established as continuous programs to track trends in contamination and to assess the effectiveness of the management.

Several remediation technologies have been developed to limit sediment contamination. Dredging physically extracts contaminated sediments but can lead to the resuspension of contaminants and disturbance of benthic habitat if not properly managed. Covering sediments that are contaminated prevents metals from moving and causing biological exposure. Effective, but long-term monitoring is required for cap stability.

Biological remediation methods are becoming popular and are known as an environmentally friendly option. Phytoremediation involves the use of aquatic plants, mangroves, and salt marsh plants to take up or hold heavy metals in the sediment. Similarly, bioremediation utilizes microorganisms that can transform, immobilize, or accumulate metals to lower their bioavailability. The environmental impacts of these methods are usually less severe than those of standard engineering techniques, although they are likely to take more time to treat the water.

Current technologies like engineered adsorbents, biochar amendments and nanomaterials have proven to be effective at immobilizing heavy metals and enhancing sediment quality. They can be used on a large scale, but their ecological safety, durability, and economics need to be studied.

Integrated Coastal Zone Management (ICZM) offers a holistic approach to the management of pollution, habitat, sustainable fisheries, and environmental monitoring in the sea and nearshore areas. For it to be successful, it will need the cooperation of several government departments, research institutions, industries, and communities. Coastal Conservation is further enhanced through Public Awareness, Environmental Education, and the involvement of stakeholders in support of practices that are good for the environment.

7. Discussion and Synthesis

The available scientific literature demonstrates that extensive contamination by heavy metals is a global environmental problem that is found in coastal sediments on every continent (Silva et al., 2024). Although contaminations vary according to the region, there are always geographical patterns, among them those associated with the activities of quick industrialisation, urbanisation, intensive farming, shipping and inexplicable wastewater treatment. Overall, coastal regions near industrial complexes, mines, and big river estuaries and high-population cities are linked to the highest levels of heavy metals being in sediments (Gopal et al., 2023).

The ecological reactions of the aquatic organisms are rather similar regardless of the difference in sources of contamination and sediment types in various regions. An increased amount of metals in the environment as time passes may damage the physiology of organisms, reproduction, biodiversity, community composition, and ecosystem resilience. Benthic organisms are considered to be valuable indicators of the environmental quality and they are particularly sensitive to the contaminated sediments because of the exposure they have at all times.

It is also indicated in the literature that the ecological risk might be underestimated by using the concentration of total metal alone, because the toxicity is very dependent on chemical speciation, bioavailability, and environmental conditions. Therefore, a combination of chemical analysis with biological indicators, toxicity testing, and ecological monitoring (an integrated assessment approach) provides a more accurate assessment of sediment (Chapman & Wang, 2001).

Although numerous regional investigations have been conducted worldwide, a lack of consistent analytical methods, background values, ecological indices, and reporting standards makes it difficult to directly compare data across studies. The need for greater methodological standardization would help to improve the assessment done globally and to monitor the environment in the long term.

8. Research Gaps and Future Directions

Despite regardless of the considerable advances in our knowledge of heavy metal contamination of coastal sediments, some major knowledge gaps remain. Firstly, most previous studies focus on contaminant concentrations and relatively little information is available on long-term ecological consequences and ecosystem recovery after remediation. It is therefore important to monitor biodiversity along a longitudinal gradient to assess changes in biodiversity under different environmental conditions.

Secondly, increasing evidence indicates that heavy metals act synergistically with other environmental pressures such as microplastics, pharmaceutical residues, pesticides, enrichment of nutrients, and climate change. All these stressors can interact and have a synergistic effect that is not captured by existing ecological risk assessment models.

Finally, a new generation of molecular biology techniques is opening the door to environmental monitoring opportunities. Environmental DNA (eDNA), metagenomics, transcriptomics, and metabolomics offer useful information on the biological reactions occurring at an early stage, even before the onset of visible ecological impacts. A combination of these with chemical monitoring could significantly enhance ecosystem assessment.

The use of remote sensing, Geographic Information Systems (GIS), Artificial Intelligence, and Machine Learning is also a potential future area of research for pollution hotspot identification, pollution pattern prediction, and decision-making. The technologies need to be further researched in the future to enhance environmental surveillance and coastal management.

Lastly, there is a need for more international cooperation to set up standard monitoring procedures, harmonize ecological risk assessment techniques, and improve global databases of coastal sediment contamination. Such joint initiatives will help in the comparison between regions and evidence-based environmental policy.

9. Conclusion

Sediment contamination is one of the most widespread environmental issues affecting aquatic ecosystems worldwide and is a major concern on the coast. Coastal sediments act as long-term sinks and sources of contaminants and heavy metals are long-term environmental contaminants. Nevertheless, due to the ongoing anthropogenic processes, such as industrialization, mining, farmlands, shipping and urbanization, the burden of heavy metals in coastal ecosystems is still enormous thus presenting an immense pressure on aquatic biodiversity. The impact of heavy metals on microorganisms, primary producers, benthic organisms, fish, aquatic vegetation and higher levels of trophic levels includes oxidative stress, physiological dysfunction, reproductive impairment, bioaccumulation, and biomagnification. These impacts from the environment, in turn, reduce the resilience of ecosystems and can impact fisheries, food security and human health.

Pollution prevention, continual monitoring of the environment, ecological risk assessment, developments of sustainable remediation technology and efficient environmental management are all integrated approaches that are vital to effective management. New molecular tools and state of the art analytical technologies have the potential to improve contamination assessment and provide for better management decisions. Therefore, continued research, international cooperation and implementation of sustainable coastal management are essential to minimize heavy metal contamination, protect marine biodiversity and ensure sustainable coastal management.

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