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# An insight into the ecological risks and mitigation of heavy metal pollution in aquatic sediments and marine ecosystems

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Aquatic ecosystems are important ecological and socioeconomic zones throughout the world. However, a massive deterioration in the functionality of aquatic zones has been observed globally in recent times due to an enormous rise in environmental pollution with an ever-increasing human population, urbanization, land reformation, and industrialization. However, there is a lack of studies assessing aquatic and sediment pollution and their effects on biogeochemical cycling, the food chain, and the overall wellbeing of species, including humans. Thus, there is an immediate necessity to investigate the status of aquatic sediment pollution, evaluate the associated ecological risks, and estimate the probable pollution sources. Therefore, this review enlightens on the composition, concentrations, sources, and spatial patterns of the distribution of heavy metals affecting the global aquatic sediment pollution; their probable toxic effects on aquatic ecosystems; the modes of transfer through food chains, thereby affecting human health; and the use of aquatic plants for phytoremediation of heavy metals in aquatic ecosystems. This will lead to an understanding of the status and the factors influencing aquatic sediment pollution, which will be useful to monitor and manage the vast aquatic ecosystems and develop strategies for remediation in the near future.

KEYWORDS

**aquatic ecosystem, bioremediation, ecological risks, heavy metals, phytoremediation, pollution, sediments**

# 1 Introduction

Sediments are vital components of any aquatic system. Sediments are supplemented with solids and ions through an array of physicochemical processes that serve as the main source for biogeochemical cycling and nutrient turnovers (Wojtkowska and Bogacki, 2022). However, one of the negative impacts of rapid urbanization is the development of stress on aquatic sediments, resulting in the deterioration of the quality of water, eutrophication, excess flooding, and heavy metal (HM) pollution. HMs are defined as metals or metalloids with a high atomic weight and density that can be toxic, even at low concentrations (Jiang et al., 2021; Haghnazar et al., 2022).

The major problem with HMs is their inefficient elimination through natural decomposition processes due to their long half-lives, non-biodegradability, and lesser self-purification ability (Rezapour et al., 2022). Hence, they attach, settle, and accumulate within the sediments of water bodies by binding to particulate matter. Due to the low solubility of HMs in water, sediments become the highest reservoir/sink for the accumulation of HMs, 99% of which are easily adsorbed within sediment particles, transported through fluvial processes into adjacent rivers, and carried downstream along the course of the river (Varol et al., 2021). Freshwater salts get deposited in the bottom sediments after sinking and do not affect aquatic species, in contrast to HMs, which are mobilized and discharged into the water column under acidic conditions.

Though heavy metals are being incorporated into the aquatic systems (both freshwater and marine ecosystems) through natural physical and chemical weathering of heavy rocks and volcanic eruptions, anthropogenic activities significantly contribute to the increased contamination of HMs in aquatic bodies (Emenike et al., 2020; Redwan and Elhaddad, 2020). Microorganisms also contribute to HMs by transforming mercury (Hg) during certain biochemical activities, thus decreasing the quality of water (Bhat et al., 2022).

The natural biogeochemical cycling of heavy metals is highly perturbed by anthropogenic activities (Haghnazar et al., 2022). Anthropogenic activities that mostly contribute to marine environment pollution through infiltration of HMs into sediments include sludges, electronics, metal, plastic, leather tanning, galvanizing, battery, ointment, adhesive, petroleum, gasoline, paint, dye, textile, wood preservative and pulp processing industries, industrial dusts, smelting, electroplating, power plants, waste incineration, refineries, off-shore natural gas and oil exploration, mining, biomedical wastes, domestic uses, landfills, automobile exhausts, wastewater, acid rains, urban runoff, dumping of solid and soft wastes from aquatic vehicles, alloys, dyes, tires, minerals (phosphates), aquaculture activities, agricultural practices (inorganic pesticides and chemical fertilizers), and natural fields (Ustaoğlu et al., 2021; Yap and Al-Mutairi, 2022; Saidon et al., 2024). The improperly managed electronic waste (e-waste) has been recognized as a recent potential source of threat to humans and the environment by the United Nations Environment Program (UNEP/GPA) and the Global Plan of Action (GPA) due to the presence of HMs like cadmium (Cd), lead (Pb), and mercury (Hg) within electronic devices (Das et al., 2023).

However, the dynamics of accumulating HMs in sediments are controlled by numerous physical, chemical, hydrological, and hydraulic issues, such as the presence of floodplains, lakes, reservoirs, and hydraulic structures that disrupt the natural river flow. Climatic changes, the flow competence of water, land-use structures, pollution types and sources, size of particles, features of the river basin including pH, salinity, content of organic carbon and calcium carbonate, landscape diversity, and geological structures also contribute to HM deposition and pollution in sediments (Rezapour et al., 2022). HMs become the secondary source of pollution for water when they are being released from the sediments with changes in the surrounding environment (pH and Eh) (Zhang et al., 2022).

The characterization of HMs is important for assessing HM load in water (Wu et al., 2021). There is great concern about HM pollution in aquatic sediments, particularly for developing countries, and its present status demands scrutiny to develop probable remedial strategies (Kumar et al., 2020). However, the spatial distribution and the overlapping characteristics make the qualitative and quantitative identification of HMs very challenging. These have resulted in the variability of data and the lack of comprehensiveness in determining the risks associated with HMs in surface sediments (Yap and Al-Mutairi, 2022). To overcome these challenges, a number of chemometric analytical tools like principal component analysis (PCA), positive matrix factorization (PMF), multiple linear regression (MLR), conditional inference tree (CIT), and artificial neural network methods, including Kohonen's self-organizing map, are being employed regularly to assess the composition of the sources and impacts of HMs in aquatic pollution (Cheng et al., 2020; Dash et al., 2020; Wang et al., 2020; Luo et al., 2021).

Therefore, the main goal of this review is to identify and analyze 1) the composition, concentrations, sources, and spatial patterns of distribution of HMs affecting the global aquatic sediment pollution; 2) their probable toxic effects on aquatic ecosystems and the modes of transfer through food chains, thereby affecting human health; and 3) the use of aquatic organisms for bioremediation and phytoremediation for enhanced management of HMs in aquatic ecosystems.

# 2 Sediments and marine ecological cycles

Marine sediments are defined as deposits of insoluble soil matter, rocks, volcanic remains, meteorite debris, and biological remains gathered on the ocean floor and are classified as lithogenous, biogenous, hydrogenous, and cosmogenous depending on their sources. They can be brought by river flow, dust carried by winds, glaciers, or chemical precipitation (Webb, 2019). Soft sediments of marine origin provide valuable contributions to global ecosystem functioning through mineralization of organic compounds and cycling of carbon and nitrogen, thereby affecting the dynamics of marine ecology (Schenone et al., 2025). In the recent era, community-based ecology studies through metagenomics–transcriptomics and very recently metabolomics provide a holistic knowledge on ecosystem functioning in sediments beyond the biogeochemical cycling. This mediates the detailed understanding of the interplay of biogeochemical exchanges, biochemical intermediates synthesized during energy transformation, and biosynthetic metabolism in marine sediments, even beyond the static sequence-based identification of the microbiome (Schenone et al., 2025).

One such integrated study from Australia revealed variations in metabolic criticality involving amino acid metabolism, glycosylation, and phospholipid synthesis from among the species of salt marshes (Schenone et al., 2025). The role of pH and acid volatile sulfide (AVS) in sediments is critical in determining the biogeochemical cycling of methane, nitrogen, and sulfur among the sediment microbiome. Similar metagenomic studies from Antarctic marine sediments have explored the drivers of biogeochemical cycles with respect to nitrogen metabolism under severe climate change (Garber et al., 2021). This study has identified a cluster of genes involved in nitrification, along with sulfur oxidation and carbon utilization. Organotrophy coupled with carbon fixation through the Calvin and tricarboxylic acid cycles is found to be the dominant metabolic pathway in marine sediments. Benthic communities are well-equipped for the utilization of organic matter from the bottom of the sediments. This nitrogen–sulfur biogeochemical cycling supports the thriving of microorganisms as well as higher trophic levels and flux of essential nutrients in bentho-pelagic communities in polar regions. The availability of sulfur in marine sediments drives the process of dissimilatory sulfate reduction (DSR) by anaerobic microbes on surface marine sediments, producing thiosulfate and elemental sulfur. Sulfate reduction, on the other hand, is common in deep anoxic sediments (Jørgensen et al., 2021). The lower organic carbon content in marine sediments of western Antarctica, as compared to the Antarctica peninsula, steers the higher activities of lithotrophic microorganisms in the region (Garber et al., 2021). The biomass of fungi was found to vary directly with the content of particulate organic carbon (POC) and the salinity in the English Channel, as well as in the Pacific and Atlantic Oceans (Amend et al., 2019).

The depths of sediments also influence nutrient processing, thereby determining the vertical stratification of the microbial distribution, with the presence of sulfide- and nitrogen-utilizing microbes in surface sediments, and sulfate-reducing and anaerobic methane-oxidizing microbes in the middle and deep layer sediments (Qian et al., 2023). Fungal density in the water column is inversely proportional to depth. These fungi within water columns contribute to the marine carbon cycle through the processing of organic carbon from phytoplankton (Amend et al., 2019).

The availability of energy for cellular functioning is inversely proportional to the age and depth of the sediments. Hence, cellular metabolic rates decrease within a few meters of the sediment surface. However, an active turnover biomass is observed within a few hundred meters below the seabed. This survival of microbes under energy-deficient deep marine biospheres is attributed to the evolutionary selection of species from surface areas (Starnawski et al., 2017). In comparison to polar sediments, deep trenches called hadal zones, 6,000 m below the sea, where there is a vertical transport of photosynthetic organic compounds, also play an important role in marine ecology. Diverse heterotrophic lineages of microbial communities with high rates of respiration have been reported from the Mussau and Mariana trenches (Liu et al., 2020). A high abundance of n-alkanes has been identified from deep trenches, which might be attributed to the presence of hydrocarbon-degrading microorganisms as potentially active keystone species (Guan et al., 2019; Liu et al., 2020). Therefore, alkane degradation is an important pathway for the turnover of carbon in the sediments of deep marine trenches. During this carbon assimilation, methylated amines (MAs), precursors of methane, produced by methanogenesis, contribute to the greenhouse effect through the release of carbon-active gases and are ubiquitously present in marine sediments (Mausz and Chen, 2019). Methylotrophic methanogens such as Archaea, *Rhodobacteraceae*, and *Pelagibacter* sp. can thrive in sulfate-rich extreme marine environments through decomposition of MAs.

The biological pump contributes to the sinking of organic matter from the surface euphotic zones, where phytoplanktons produce it into meso- and bathypelagic communities in the form of marine snow (Amend et al., 2019). This phenomenon helps in the partitioning of $CO_2$ between the atmosphere and marine sediments, thus transferring sequestered carbon from surface sediments to the deep oceanic floors. However, the variation in the magnitude and depth of mineralization depends on the nearby food webs. For example, the flux of POC is increased by large phytoplankton cells, whereas the feeding of zooplanktons influences the sinking of POC. The abundance of planktons and grazers, as well as the proportion of calcifiers and non-calcifiers, changes the composition and the sinking rate of POC (Birch et al., 2021).

This pump is also shaped by the activities of marine fungi residing in the sediments. The chemical composition of marine snow is also being modified by the fungi through the release of zoospores via the mycoloop. In this way, the fungi establish a trophic connection with the zooplanktons. Besides water columns, the high organic carbon content also steers a wide range of fungal catalytic and antimicrobial compound-synthesizing activities within the oceanic sediments. These secondary metabolites are important for the establishment of fungal association with diatoms, macroalgae, seagrass, and corals, where such symbioses help provide defense against environmental stresses in marine habitats. Genomic studies have revealed the abundant expression of fungal genes associated with the hydrolysis of lipids, proteins, and carbohydrates, as well as the synthesis of antimicrobial compounds in organic carbon-rich sediments from Canterbury and Peru coastal basins (Amend et al., 2019).

Viruses are the other important components that contribute to the marine sediment ecosystem by modifying the composition of the microbial community and the biogeochemical cycles of marine sediments. The dead zones with low/no oxygen in seafloor sediments are formed due to oxygen depletion by microbial decomposition of the decaying and sinking cyanobacterial blooms below the euphotic zone.

Marine sediments are reworked by aquatic organisms through a mechanism called bioturbation, which is believed to be one of the primary drivers for biodiversity, particularly in the aquatic ecosystem. This bioturbation provides numerous ecosystem services like the provision of shelters for organisms, alteration of nutrients, sediment differentiation, production of soil, and influencing species evolution (Hsieh et al., 2023). Shrimps, particularly ghost and mud shrimps, walruses, polychaetes, salmons, and benthic fauna are dominant bioturbators that modify pore water, influence the cycling of nutrients, and process organic matter deposition in the aquatic system. This process ultimately affects the microorganism population of the oceanic beds by modulating the physicochemical properties of the sediments (Cariou et al., 2021). Meiofauna bioturbation has been found to stimulate nitrogen cycling by nitrifying and denitrifying bacteria in soft sediment ecosystems, and the rate of denitrification has doubled in the presence of meiofauna (Fusi et al., 2022). Microfauna, macrofauna, and sesarmid mangrove crabs are identified as principal bioturbating organisms in mangrove sediments. The crabs feed on the leaf litter produced by the mangrove plants and release organic matter through their feces. This then serves as a productive resource in marine and coastal ecosystems (Sarker et al., 2019; Tongununui et al., 2021). Therefore, the diversity and abundance of sesarmid mangrove crabs determine the properties of the sediments through the addition of organic matter. Fiddler crabs, on the other hand, influence the carbon and nitrogen cycling in carbon-rich and nitrogen-poor mangrove sediments through the symbiotic associations with sediment bacteria and their burrowing activities (Booth et al., 2019; Zilius et al., 2020).

## 3 Accumulation of HMs in sediments and their effects on the marine ecosystem

Though marine habitats are one of the principal regulators of ecosystem functioning, they are the most anthropogenically despoiled ecosystems globally (Goode et al., 2020). HMs, defined as metals with atomic numbers and density higher than 20 and 5 g/cm$^3$, respectively, are being incorporated into the biota through specific, easily identifiable point and diffuse widespread non-point sources within marine sediments (Saidon et al., 2024). Both free and combined forms of HMs with carbonate, sulfide, and oxyhydroxide are distributed in aquatic ecosystems (He et al., 2021). The accumulation of HMs occurs in marine biofilms and organic matter through several mechanisms, including precipitation, sedimentation, adsorption, and desorption, potentially affecting the survival of marine life (Islam et al., 2023). Air deposition of HMs is also one of the significant mechanisms for their infiltration into marine sediments from terrestrial runoffs of coastal catchment areas as well as riverside areas and sub-par agricultural regions. The aeolian movement of minute particles forms the primary contributors of HMs in marine sediments, particularly close to dry land masses, at fringing reef regions (Hu et al., 2021).

Due to the biomagnification property of HMs in aquatic ecosystems and coral reefs, marine habitats are one of the most suitable regions to assess the degree of HM pollution in marine ecosystems (Mishra et al., 2019). The feeding on HM-contaminated coral reefs by zooplanktons, fish, crabs, oysters, mussels, sea cucumbers, and shellfish leads to the entry of HMs into the aquatic food chain (Bisht and Negi, 2020; Patterson et al., 2020; Vital et al., 2021).

A vast literature exists on the determination of biomagnifications of HMs in sediments and marine ecosystems all over the world (Hu et al., 2021; Yang et al., 2022). These have proven that the concentration of HMs increases with size and age in large marine organisms and in higher trophic levels, through bioaccumulation and biomagnification processes, indicating that large organisms with a long lifespan and predators on the higher trophic levels of marine ecological pyramids are significantly affected by HMs (Danovaro et al., 2023). The adsorption of HMs within sediments and their mobility through water columns play an important role in the bioaccumulation of HMs within aquatic species along with the rate of metabolism and excretion of HMs within aquatic organisms (Saidon et al., 2024). The bioturbation that distributes HMs within sediments affects the benthic and non-benthic population of the aquatic system, making them the most vulnerable species to be affected by HMs and gradually introducing HMs into the food chain, ultimately affecting human health. As per the literature, a total of 10 million people are affected globally due to HM contamination (Ashraf et al., 2019).

HMs are absorbed into fish gills, amphipod cuticles, and other sensitive organs of aquatic creatures (Saidon et al., 2024). Additionally, the growth of fish larvae is inhibited due to the decrease in the number of benthic organisms in the presence of HMs. The species also become unfit for environmental competition in the long run due to reduced and abnormal growth, locomotor abilities, and behavioral patterns, making them more vulnerable to predation (Taslima et al., 2022).

Oral ingestion, inhalation, and dermal exposure are the three principal entry routes of HMs in humans. Within the human body, they generate reactive oxygen species (ROS) and are deposited in various organs, causing chronic and carcinogenic effects (Rezapour et al., 2022). Additionally, if HMs are not broken down along the pathway and are conserved within the food chain, they tend to increase in concentration along the higher trophic levels, thereby causing biomagnification (Saidon et al., 2024). Therefore, there is a need to increase awareness about the toxic effects and the ecological risks involved in HM pollution among people living in coastal areas and those engaged in coastal activities (Dash et al., 2021).

In developing countries such as those in the Association of Southeast Asian Nations (ASEAN-5)—Indonesia, Malaysia, Philippines, Thailand, and Vietnam—studies have documented the ecological risks of HMs from marine sediments, highlighting the need to investigate the corresponding health risks and to develop effective remediation strategies (Yap and Al-Mutairi, 2022). A review of studies spanning more than 20 years from 1981 to 2021 has reported that copper (Cu), Pb, and zinc (Zn) pose high potential ecological risks in ASEAN-5 countries (Yap and Al-Mutairi, 2022). The studies have highlighted the presence of HMs including Cd, chromium (Cr), Pb, Zn, Cu, and arsenic (As) at different aquatic trophic levels, including the seagrass ecosystem, crustaceans, mollusks, aquatic plants, fishes, bivalves, microalgae, and planktons, and have also reported biomagnification of the same with a trophic magnification factor greater than 1 (Saidon et al., 2024). Studies from Naples Bay showed that marine nematodes constituting 90% of total benthic fauna bioaccumulate As, Cr, manganese (Mn), Zn, and nickel (Ni) from sediments that slowly increases among the deposit feeders and microalgal grazers, followed by predators of microbes and small metazoans, respectively, thereby contributing to the biomagnifications of HMs from sediments to higher trophic levels (Danovaro et al., 2023). The variation of the biomagnification of HMs in different coastal areas has been explained and attributed to multiple factors, including diversity in geographical locations, food web complexities, position of the species within the trophic levels, the cellular composition of the species, physiological requirements of HMs among species, their feeding habits, and detoxification mechanisms (Chernova and Lysenko, 2019). The salinity of sediments is one of the determining factors for HM bioaccumulation in marine ecosystems. Bioaccumulation of Hg and As has been found to be more concentrated among benthic than pelagic populations and also to vary between epipelagic and mesopelagic populations (Ramon et al., 2021).

The organisms living close to the sediments (bottom-feeding fish and sediment-dwelling invertebrates) with higher rates of metabolism and short lifespans and at lower trophic levels have low biomagnifications of HMs (Saidon et al., 2024). However, Boldrocchi et al. showed that gastropods from lower trophic levels and shorter food chains in marine ecosystems have the highest bioaccumulation rates of Cd and Ni (Boldrocchi et al., 2021). In marine ecosystems, planktons are the entry points for the bioaccumulation of HMs, which gradually pass on through the aquatic food web by the species feeding on them. In planktons, although HMs are essential for photosynthesis, high concentrations of the same bind to metallothioneins and disrupt the cellular equilibrium of living cells. Microorganisms, including oligonitrophilic bacteria and actinomycetes, are also negatively impacted by HMs (Hu et al., 2021).

The external factors associated with coastal sediments, including pH, sunlight received, dissolved organic matter, nutrient contents, and salinity, also determine the ultimate rate of bioaccumulation of HMs. A study of zooplanktons from the Baltic Sea showed that bioaccumulation of Zn and Pb in algae decreased due to variations in the bioavailability of metals, the scavenging and biosorption abilities of the zooplankton, the concentration of organic matter, and the hydrochemical characteristics of sediments (Chevrollier et al., 2022). Its low solubility, complex-forming abilities, and occurrence in low concentrations make Pb less likely to biomagnify in marine sediments (Orata and Sifuna, 2023). Even then, these two metals, along with Cr, Cu, and Cd, have been reported in higher concentrations in mollusks and aquatic plants as compared to fishes and crustaceans in a tropical marine seagrass ecosystem in China (Hu et al., 2021). Cu, though essential for life, changes the enzyme actions, interferes with the regulation of ions, upsets the acid–base balance, and causes endocrine disorders in marine species (Bielmyer-Fraser et al., 2018). Cupric ions affect directly or indirectly, causing fatal consequences in aquatic species. The sense of smell is lost due to heavy accumulation of $Cu^{++}$ in fishes along with the tattering of the gills that inhibits the movement of sodium and potassium ions completely (Taslima et al., 2022). The hexavalent Cr is more harmful compared to other forms of Cr, as it is a potent carcinogen causing mutations in proteins within living species (Mortada et al., 2023). Cd that lacks biomagnifying qualities is very highly persistent and stays in organisms for many years after absorption (Zhang et al., 2024). On the other hand, As bioaccumulates in fish, crustaceans, and algae but does not spread along the food chain (Zhang et al., 2024). The vital element iron (Fe) contributes to the primary production by enhancing the growth of phytoplanktons in surface water. The nitrogen-fixing marine diazotrophic algae and cyanobacteria also use Fe, thereby limiting the resource in oligotrophic oceanic regions. However, the high concentration of Fe that may arise from the burning of fuels in marine zones increases the absorption and storage of carbon in aquatic zones, ultimately affecting carbon cycling and the global climate (McAllister et al., 2021). Fe in the distant sea also enhances the release of organic carbon and dimethyl sulfide from marine organisms, which influence the radiative forcing in the atmosphere (Summer et al., 2019). The conversion of soluble $Mn^{+}$ to insoluble $Mn^{+}$ also influences the ecotoxicology of marine sediments due to high solubility, bioavailability, and delayed rate of transition (Summer et al., 2019).

Hg and selenium (Se), particularly in their organic forms, have been reported to be the most abundant HMs associated with aquatic ecosystems due to their high mobility and biotransformation ability (Chernova and Lysenko, 2019). The rate of biomagnification in marine ecosystems is the highest for Hg, with mercury found to biomagnify from low particulate organic matter (POM) trophic levels up to higher-level fish (Byeon et al., 2021). Of these, methylmercury (MeHg), produced from mercuric sulfide through microbial activities in sediments, water columns, and wetlands, can be transferred even to human systems through consumption of aquatic organisms, particularly fish, and is highly neurotoxic (Si et al., 2022). Toxicity increases due to its high water solubility and high power for retention in fatty membranes. Although research is lacking on the oxidation states of Hg among aquatic species, total Hg biomagnifications have been recorded from small zooplanktons to macroplanktons and to fishes in marine ecosystems, particularly enhanced under warm temperatures (Saidon et al., 2024). Although inorganic Hg lacks a biomagnifying property, its volatility can potentially travel throughout the biosphere and remain active for over a year (Slemr et al., 2018). Metal Hg emerges from various inevitable natural geological sources; however, man-made sources, including agricultural practices; mining operations; fossil fuel combustion; electricity-generating power plants; extraction of precious metals; production of numerous commercial products like thermometers, thermostats, barometers, batteries, and dental amalgams; and the discharge of industrial wastewater also contribute highly to the deposition of Hg in marine sediments that need to be controlled and taken care of (Reichelt-Brushett et al., 2017).

The metal Hg has an antagonistic effect on Se, as reported from a survey of Atlantic blue marlin, *Makaira nigricans*, from the North Atlantic Ocean, where high concentrations of Se and low accumulation of Hg were reported between the period of 1975–2021 (Rudershausen et al., 2023). However, like Hg, Se has also been recorded to produce biomagnifications from low to high trophic levels in tropical marine aquatic systems, including mesoplanktons and crustacean species in the South Atlantic food web, as well as from zooplanktons to perch in temperate lakes and invertebrates to fish (C´ordoba-Tovar et al., 2022). In contrast, Se has also been found to decrease among pelagic, benthopelagic, and benthic organisms, as well as from zooplanktons to predatory finfish, bottlenose dolphins, fish, gastropods, and bivalves in marine ecosystems (Babaei et al., 2022). The contrasting phenomena in the distribution of Se in aquatic ecosystems can be attributed to the availability of various oxidative states of Se (like selenate and selenite) at different concentrations. In the marine ecosystem, arsenobetain, another common form of As, has been found to show biomagnification in tertiary consumers such as predatory fish and sharks (Saidon et al., 2024). Silver (Ag) has also emerged as a biocide originating from anthropogenic sources such as smelting, coal combustion, and photographic films, and it can bioconcentrate in fishes, gastropods, crustaceans, algae, and phytoplanktons (Shah, 2021).

The bioaccumulation of toxic HMs in consumable marine species has harmful effects on the entire food chain, particularly humans, as HMs have proven to be carcinogenic (Lehel et al., 2021). Therefore, assessment of the risk of consumption of marine products is important following the guidelines of tolerance levels laid down by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) (De Almeida Rodrigues et al., 2022). The estimated daily intake (EDI) should be calculated by taking into consideration the concentration of the HMs present in marine items and the daily intake rate of those items.

# 4 Management of HMs in sediments by phytoremediation

The traditional methods used previously for HM removal from sediments, including sediment wash, immobilization, and stabilization of pollutants, have negative impacts on sediments and their microbial diversity (Ferrarini et al., 2021). Therefore, bioremediation techniques are highly recommended for the mitigation of HM-induced pollution in marine environments due to their affordability, high efficacy, realistic nature, reliability, and ecological and environmental sustainability (Bala et al., 2022; Liu et al., 2022; Cervantes et al., 2023; Ganesh Kumar et al., 2023). However, it should be noted that the complete removal of HMs from sediments is not possible; however, only the transformation of oxidation states can be done (Bhat et al., 2022). A few of the established methods are discussed briefly below.

## 4.1 Use of microbial species

Metal-resistant bacterial species such as *Pseudomonas* sp., *Microbacterium* sp., *Alcanivorax borkumensis*, *Bacillus* sp., *Dechloromonas aromatica*, *Acinetobacter* sp., *Corynebacterium* sp., and *Ralstonia* sp. and fungi, e.g., *Trametes versicolor*, *Pleurotus* sp., *Phanerochaete* sp., *Phlebia tremellosa*, *Penicillium* sp., *Phanerochaete chrysosporium*, *Methylibium petroleiphilum*, *Mucor* sp., *Inonotus hispidus*, *Hirschioporus laricinus*, *Cryptococcus* sp., *Coriolus versicolor*, *Bjerkandera adusta*, and *Aspergillus* sp., are among the promising agents that have already been used for HM bioremediation, as they can alter HM concentration in marine sediments and help plants tolerate high levels of these HMs (Onder Erguven et al., 2021; Husain et al., 2022; Shourie and Vijayalakshmi, 2022; Sonawane et al., 2022; Maity et al., 2023; Zhao et al., 2023).

## 4.2 Use of bacterial bio-block

The use of bacterial bio-block for the removal of HMs from wastewater, inhibiting the passage of HMs from wastewater treatment plants into aquatic sediments, is a well-established technique for HM removal (Durairaj et al., 2022). The tea-waste bio-block is used as a support material for recruiting bacterial biofilm, notably *Escherichia coli*, *Arthrobacter*, and *Bacillus* sp., to build a batch technique for concurrent biosorption as well as bioaccumulation of Cr (Xia et al., 2022). The halophilic actinomycetes *Nocardiopsis halophila* and *Nocardiopsis rosea* are used as biosorbents for the removal of Cr and Zn in wastewater (El-Gendy and El-Bondkly, 2016). The fungi bio-blocks such as *Penicillium fellutanum* and *Aspergillus* sp. were found to efficiently biosorb Hg, Ni, and Zn (Alabssawy and Hashem, 2024).

## 4.3 Green technology by aquatic plants

Green technology involving phytoremediation has been an effective mechanism to manage environmental pollution issues by extracting HMs from water sources, followed by translocation, bioaccumulation, and degradation of the same within the plant body (Huang et al., 2021). A total of 400 plant species have been identified as effective for phytoremediation to date and have been harnessed for the removal of HM pollution from aquatic sediments and other environments (Das et al., 2023). Since plant genotype plays an important role in phytoremediation ability, the biodiversity among plant species, which regulates metabolic processes, resistance, and mobilization of HMs, is crucial in determining potent candidates for phytoremediation in aquatic sediments. A total of five classes (*Salviniaceae*, *Araceae*, *Cyperaceae*, *Haloragaceae*, and *Poaceae*) of aquatic plants were found to be involved in HM phyto-extraction (Delgado-González et al., 2021). Aquatic plants, including *Cyperus alopecuroides*, *Cyperus sexangularis*, *Eichhornia crassipes*, *Ludwigia stolonifera*, *Stuckenia pectinatus*, *Ranunculus sceleratus*, *Typha domingensis*, *Typha latifolia*, *Scirpus* sp., *Pluchea indica*, *Spirodela intermedia*, *Salvinia* sp., *Phragmites herzogii*, *Potamogeton pectinatus*, *Pistia stratiotes*, *Pteris vittata*, *Nasturtium officinale*, *Myriophyllum* spicatum, *Lemna minor*, *Ceratophyllum demersum*, *Azolla caroliniana*, *Callitriche brutia*, *Ranunculus trichophyllus*, *Callitriche lusitanica*, *Hydrilla verticillata*, *Typha angustifolia*, *Typha capensis*, *Phragmites mauritianus*, *Vossia cuspidata*, and *Azolla pinnata*, have proven proficient in phytoremediation from water and sediments through various mechanisms of extraction, stabilization, volatilization, stabilization, and transformation of HMs, including As, Cd, Cr, Pb, and Hg (Lu et al., 2018; Prasad, 2019; Haldar and Ghosh, 2020; Abdelaal et al., 2021; Farahat et al., 2021; Li et al., 2021; Liu and Tran, 2021; Tshithukhe et al., 2021; Kumar et al., 2022; Nabuyanda et al., 2022; Tripathy et al., 2022). Eid et al. experimentally proved that of these hydrophytes, *Phragmites australis* is capable of accumulating the highest amount of Ni and Cd, while *Echinochloa stagnina* could accumulate the highest amount of Pb from HM-contaminated wetland sediments (Eid et al., 2020). *Phragmites australis* was also found to bioaccumulate and translocate Co, Mo, Pb, Cr, Cu, Fe, Mn, Zn, and Hg in contaminated estuarine sediments in Spain (Cicero-Fernández et al., 2016). The mangrove species *Excoecaria agallocha*, *Avicennia marina*, *Avicennia officinalis*, and *Sonneratia apetala* have also been found to be hyperaccumulators of HMs in sediments (Hossain et al., 2022). In addition, aquatic plants can efficiently remove HMs from water through rhizofiltration, in which they assimilate HMs through their roots and help make the water contaminant-free (Bhat et al., 2022). Cd, Pb, and Cr, which are accumulated in the roots, are efficiently removed by this process. Tobacco, spinach, and sunflower plants proved to be highly proficient in rhizofiltration (Mohan et al., 2021).

### 4.4 Green technology by ornamental and genetically modified plants

Ornamental plants and genetically modified plants used in green technology include *Arabidopsis thaliana*, *Brassica juncea*, *Calendula officinalis, Chlorophytum comosum*, *Melastoma malabathricum*, *Mirabilis jalapa*, and *Polypogon monspeliensis* (Das et al., 2023). Although large-scale application of traditional phytoremediation techniques is unrealistic, the emerging trends of genetically modifying organisms offer a long-lasting and effective means for remediation (Bhat et al., 2022). Intercropping of *Vallisneria natans* and *Hydrilla verticillata* with *Myriophyllum spicatum* was found to be effective in the removal of Cu and Pb from aquatic sediments, decreasing RI to <150 (Li et al., 2023). Phytoremediation includes numerous methods, such as the accumulation of HMs in the form of phytochelatin–metal complexes and their transfer into the aerial parts of plants from the roots (phytoextraction); the breakdown of metal complexes into simple forms using secondary metabolites or transporting proteins on root surfaces (phytostabilization); the conversion of contaminants to volatile substances and their release through aerial parts (phytovolatilization); and the metabolism of pollutants into less toxic compounds with degradation within plant organs (phytodegradation). Makarova et al. demonstrated the phytoextraction of Cd, Cu, and Ni by *Trifolium repens*, where plant growth regulators and the iron chelate and potassium salt of K2HEDP were essential for the phytoextraction of Cd (Makarova et al., 2021). The vegetables were also found to be highly proficient in phytoextraction of Hg and Cd, revealing the health risks involved in eating them from agricultural fields irrigated with wastewater. However, variation in the concentrations of accumulated HMs in the macrophyte *Vossia cuspidate* was observed with respect to both seasons and plant tissues, with higher concentrations being deposited in the roots (Galal et al., 2017). Therefore, it was shown that plant genotype, phytohormones, root architecture, rhizosphere activities, root exudation, redox potentials, organic ligands, metal chelates, edaphic factors (pH, temperature, moisture, vapor pressure, heat flux, texture, cation exchange capacity, nutrient, organic carbon, and phosphorus contents of soil), and other environmental factors influence the rate and chance of phytoremediation of HMs.

### 4.5 Agro-practices

For the facilitation of phytoremediation of HMs in sediments, agro-practices also play an important role, during which the application of stabilizers, fertilizers, and chelators in the soil helps change soil properties and aids in better remediation. For example, *Thlaspi caerulescens* showed the highest Cd and Zn accumulation at low acidic pH of 6.5 to 7.0 (Rosenfeld et al., 2018). Low pH, high moisture, and organic content of the soil increase the mobilization of HMs by chelate formation and increased cation exchange capacity. Agricultural amendments, such as the application of manure, peat, and compost in sediments, and genetic modification of plants and other crop management processes, enhance the rate of bioaccumulation of HMs by plants in sediments (Bhat et al., 2022).

## 5 Current challenges

Phytoremediation offers a number of ways to overcome HM pollution in soil; however, the gaps in knowledge prevail with respect to aquatic systems and sediments due to the lack of research in this field. Therefore, more research is needed to explore diverse plant species for their effective bioremediation possibilities and to design realistic, replicable, and feasible phytoremediation techniques. Also, for the best facilitation of phytoremediation, various factors that influence the process directly or indirectly need to be evaluated, including the HM type, concentration, physicochemical properties of the sediments, and the microbiome associated with the roots. In this regard, the use of various plant species in combination rather than singly may be emphasized for better effectiveness of phytoremediation. Additionally, investigation of plant–microbial synergism and the associated biochemical and metabolic responses is needed to develop more targeted strategies (Khatoon et al., 2024). The challenges associated with the disposal and utilization of plants containing HMs after phytoremediation also need to be addressed. The products obtained after pyrolysis of the plant residues containing HMs after phytoremediation have proven to be an effective technique to reutilize the adsorbed products (Gong et al., 2018). However, since this process produces high amounts of toxic pollutants during the burning of plant biomasses after adsorption of HMs, it may contribute again to environmental pollution (Kumar et al., 2024). Since phytoremediation is an *in situ* process, its application is constrained during the conversion of contaminated space into green space, particularly in highly populated regions with limited spaces. The enhancement of the process is also challenging due to the complexity in plant–microbe interactions and cost issues (Kumar et al., 2024). The slow rate of the process demands a prolonged period of cultivation over generations to consume all the HMs in an affected area. However, simultaneously, the toxicity of HMs resulting in the early deaths of plants leads to high operation costs. This, in turn, requires research for the development of high-tolerant and resilient plant species. The passage of adsorbed HMs from plant species through the food chain to higher trophic levels is also a challenge to overcome (Kumar et al., 2024).

# 6 Conclusion

The exhaustive assessment of aquatic sediments for HMs is of utmost importance to monitor and manage HM pollution of sediments. These data will be helpful for governments and environmentalists in developing specific strategies for remediation, thereby supporting the sustainability of coastal lands around the world. This is possible by maintenance of the mangrove ecosystem as a plausible mechanism toward the amelioration of HM pollution for the betterment of health and the survival of aquatic species. Since the effects of HMs on health hazards throughout the global population is a growing concern, emphasis needs to be given to 1) controlling the sources and pathways of exposure of HMs by regulating the standards of industrial waste management, with priority given to recycling and/or reprocessing of HM wastes; 2) regulating anthropogenic activities, which might be sources for HM release; and 3) decreasing the bioavailability and accessibility of HMs within the living world. Phytoremediation is emerging as a popular technique for bioremediation due to its being cost-effective and least damaging to aquatic systems. Therefore, discussing strategies and the factors influencing phytoremediation for HM management might provide new perspectives on addressing HM-related problems in sediments.

# Author contributions

KK: Validation, Supervision, Writing – review & editing, Funding acquisition. BB: Data curation, Writing – original draft. AK: Writing – review & editing. SH: Software, Data curation, Project administration, Visualization, Funding acquisition, Writing – original draft, Formal analysis, Conceptualization, Methodology, Investigation, Validation, Supervision, Writing – review & editing, Resources.

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# Conflict of interest

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# Generative AI statement

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# Publisher's note

## References


Abdelaal, M., Mashaly, I. A., Srour, D. S., Dakhil, M. A., El-Liethy, M. A., El-Keblawy, A., et al. (2021). Phytoremediation perspectives of seven aquatic macrophytes for removal of heavy metals from polluted drains in the Nile delta of Egypt. *Biol. (Basel)* 10, 560. doi: 10.3390/biology10060560

Alabssawy, A. N., and Hashem, A. H. (2024). Bioremediation of hazardous heavy metals by marine microorganisms: a recent review. *Arch. Microbiol.* 206. doi: 10.1007/s00203-023-03793-5

Amend, A., Burgaud, G., Cunliffe, M., Edgcomb, V. P., Ettinger, C. L., Gutiérrez, M. H., et al. (2019). Fungi in the marine environment: open questions and unsolved problems. *mBio.* 10, e01189–e01118. doi: 10.1128/mBio.01189-18

Ashraf, S., Ali, Q., Zahir, Z. A., Ashraf, S., and Asghar, H. N. (2019). Phytoremediation environmentally sustainable way for reclamation of heavy metal polluted soils. *Ecotoxicol Environ. Saf* 174, 714–727. doi: 10.1016/j.ecoenv.2019.02.068

Babaei, M., Tayemeh, M. B., Jo, M. S., Yu, I. J., and Johari, S. A. (2022). Trophic transfer and toxicity of silver nanoparticles along a phytoplankton-zooplankton-fish food chain. *Sci. Total Environ.* 842, 156807. doi: 10.1016/j.scitotenv.2022.156807

Bala, S., Garg, D., Thirumalesh, B. V., Sharma, M., Sridhar, K., Inbaraj, B. S., et al. (2022). Recent strategies for bioremediation of emerging pollutants: A review for a green and sustainable environment. *Toxics.* 10, 484. doi: 10.3390/toxics10080484

Bhat, S. A., Bashir, O., Ul Haq, S. A., Amin, T., Rafiq, A., Ali, M., et al. (2022). Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. *Chemosphere.* 303, 134788. doi: 10.1016/j.chemosphere.2022.134788

Bielmyer-Fraser, G. K., Patel, P., Capo, T., and Grosell, M. (2018). Physiological responses of corals to ocean acidification and copper exposure. *Mar. pollut. Bulletin* 133, 781–790. doi: 10.1016/j.marpolbul.2018.06.048

Birch, H., Schmidt, D. N., Coxall, H. K., Kroon, D., and Ridgwell, A. (2021). Ecosystem function after the K/Pg extinction: decoupling of marine carbon pump and diversity. *Proc. Biol. Sci.* 288, 20210863. doi: 10.1098/rspb.2021.0863

Bisht, V. S., and Negi, D. (2020). Microplastics in aquatic ecosystem: Sources, trophic transfer and implications. *Int. J. Fish Aquat Stud.* 8, 227–234.

Boldrocchi, G., Spanu, D., Mazzoni, M., Omar, M., Baneschi, I., Boschi, C., et al. (2021). Bioaccumulation and biomagnification in elasmobranchs: a concurrent assessment of trophic transfer of trace elements in 12 species from the Indian Ocean. *Mar. pollut. Bull.* 172, 112853. doi: 10.1016/j.marpolbul.2021.112853

Booth, J. M., Fusi, M., Marasco, R., Mbobo, T., and Daffonchio, D. (2019). Fiddler crab bioturbation determines consistent changes in bacterial communities across contrasting environmental conditions. *Sci. Rep.* 9, 3749. doi: 10.1038/s41598-019-40315-0

Byeon, E., Kang, H. M., Yoon, C., and Lee, J. S. (2021). Toxicity mechanisms of arsenic compounds in aquatic organisms. *Aquat Toxicol.* 237, 105901. doi: 10.1016/j.aquatox.2021.105901

C´ordoba-Tovar, L., Marrugo-Negrete, J., Baró, P.R., and Díez, S. (2022). Drivers of biomagnification of Hg, as and Se in aquatic food webs: a review. *Environ. Res.* 204, 112226. doi: 10.1016/j.envres.2021.112226

Cariou, M., Francois, C. M., Voisin, J., Pigneret, M., Hervant, F., Volatier, L., et al. (2021). Effects of bioturbation by tubificid worms on biogeochemical processes, bacterial community structure and diversity in heterotrophic wetland sediments. *Sci. Total Environ.* 795, 148842. doi: 10.1016/j.scitotenv.2021.148842

Cervantes, P. A. M., Ziarati, P., and de Frutos Madrazo, P. (2023). *Bioremediation Encyclopedia of Sustainable Management* (Springer), 1–8. doi: 10.1007/978-3-030-02006-4_1141-1

Cheng, W., Lei, S., Bian, Z., Zhao, Y., Li, Y., and Gan, Y. (2020). Geographic distribution of heavy metals and identification of their sources in soils near large, open-pit coal mines using positive matrix factorization. *J. Hazard Mater.* 387, 121666. doi: 10.1016/j.jhazmat.2019.121666

Chernova, E. N., and Lysenko, E. V. (2019). The content of metals in organisms of various trophic levels in freshwater and brackish lakes on the coast of the sea of Japan. *Environ. Sci. pollut. Res.* 26, 20428–20438. doi: 10.1007/s11356-019-05198-8

Chevrollier, L.-A., Koski, M., Søndergaard, J., Trapp, S., Aheto, D. W., Darpaah, G., et al. (2022). Bioaccumulation of metals in the planktonic food web in the Gulf of Guinea. *Mar. pollut. Bull.* 179, 113662. doi: 10.1016/j.marpolbul.2022.113662

Cicero-Fernández, D., Peña-Fernández, M., Expósito-Camargo, J. A., and Antizar-Ladislao, B. (2016). Role of *Phragmites australis* (common reed) for heavy metals phytoremediation of estuarine sediments. *Int. J. Phytoremediation* 18, 575–582.

Danovaro, R., Cocozza di Montanara, A., Corinaldesi, C., Dell'Anno, A., Illuminati, S., Willis, T. J., et al. (2023). Bioaccumulation and biomagnification of heavy metals in marine micro-predators. *Commun. Biol.* 6, 1206. doi: 10.1038/s42003-023-05539-x

Das, S., Sultana, K. W., Ndhlala, A. R., Mondal, M., and Chandra, I. (2023). Heavy metal pollution in the environment and its impact on health: exploring green technology for remediation. *Environ. Health Insights.* 17, 11786302231201259. doi: 10.1177/11786302231201259

Dash, S., Borah, S. S., and Kalamdhad, A. S. (2020). Application of positive matrix factorization receptor model and elemental analysis for the assessment of sediment contamination and their source apportionment of Deepor Beel, Assam, India. *Ecol. Indic.* 114, 106291. doi: 10.1016/j.ecolind.2020.106291

Dash, S., Borah, S. S., and Kalamdhad, A. S. (2021). Heavy metal pollution and potential ecological risk assessment for surficial sediments of Deepor Beel, India. *Ecol. Indic.* 122, 107265. doi: 10.1016/j.ecolind.2020.107265

De Almeida Rodrigues, P., Ferrari, R. G., Kato, L. S., Hauser-Davis, R. A., and Conte-Junior, C. A. (2022). A systematic review on metal dynamics and marine toxicity risk assessment using crustaceans as bioindicators. *Biol. Trace Elem. Res.* 200, 881–903. doi: 10.1007/s12011-021-02685-3

Delgado-González, C. R., Madariaga-Navarrete, A., Fernández-Cortés, J. M., Islas-Pelcastre, M., Oza, G., Iqbal, H. M. N., et al. (2021). Advances and applications of water phytoremediation: A potential biotechnological approach for the treatment of heavy metals from contaminated water. *Int. J. Environ. Res. Public Health* 18, 5215. doi: 10.3390/ijerph18105215

Durairaj, A., Maruthapandi, M., Luong, J. H. T., Perelshtein, I., and Gedanken, A. (2022). Enhanced UV protection, heavy metal detection, and antibacterial properties of biomass-derived carbon dots coated on protective fabrics. *ACS Appl. Bio Mater.* 5, 5790–5799. doi: 10.1021/acsabm.2c00798

Eid, E. M., Galal, T. M., Sewelam, N. A., Talha, N. I., and Abdallah, S. M. (2020). Phytoremediation of heavy metals by four aquatic macrophytes and their potential use as contamination indicators: a comparative assessment. *Environ. Sci. pollut. Control Ser.* 27, 12138–12151. doi: 10.1007/s11356-020-07839-9

El-Gendy, M. M., and El-Bondkly, A. M. (2016). Evaluation and enhancement of heavy metals bioremediation in aqueous solutions by *Nocardiopsis* sp. MORSY1948, and *Nocardia* sp. MORSY2014. *Braz. J. Microbiol.* 47, 571–586. doi: 10.1016/j.bjm.2016.04.029

Emenike, P. C., Tenebe, I. T., Neris, J. B., Omole, D. O., Afolayan, O., Okeke, C. U., et al. (2020). An integrated assessment of land-use change impact, seasonal variation of pollution indices and human health risk of selected toxic elements in sediments of River Atuwara, Nigeria. *Environ. pollut.* 265, 114795. doi: 10.1016/j.envpol.2020.114795

Farahat, E. A., Mahmoud, W. F., and Fahmy, G. M. (2021). Seasonal variations of heavy metals in water, sediment, and organs of *Vossia cuspidata* (Roxb.) Griff. in River Nile ecosystem: implication for phytoremediation. *Environ. Sci. pollut. Res. Int.* 28, 32626–32633. doi: 10.1007/s11356-021-13033-2

Ferrarini, A., Fracasso, A., Spini, G., Fornasier, F., Taskin, E., Fontanella, M. C., et al. (2021). Bioaugmented phytoremediation of metal-contaminated soils and sediments by hemp and giant reed. *Front. Microbiol.* 12, 645893. doi: 10.3389/fmicb.2021.645893

Fusi, M., Booth, J. M., Marasco, R., Merlino, G., Garcias-Bonet, N., Barozzi, A., et al. (2022). Bioturbation intensity modifies the sediment microbiome and biochemistry and supports plant growth in an arid mangrove system. *Microbiol. Spectr.* 10, e0111722. doi: 10.1128/spectrum.01117-22

Galal, T. M., Gharib, F. A., Ghazi, S. M., and Mansour, K. H. (2017). Phytostabilization of heavy metals by the emergent macrophyte *Vossia cuspidata* (Roxb.) Griff.: A phytoremediation approach. *Int. J. Phytoremediation.* 19, 992–999. doi: 10.1080/15226514.2017.1303816

Ganesh Kumar, A., Manisha, D., Nivedha Rajan, N., Sujitha, K., Magesh Peter, D., Kirubagaran, R., et al. (2023). Biodegradation of phenanthrene by piezotolerant Bacillus subtilis EB1 and genomic insights for bioremediation. *Mar. pollut. Bull.* 194, 115151. doi: 10.1016/j.marpolbul.2023.115151

Garber, A. I., Zehnpfennig, J. R., Sheik, C. S., Henson, M. W., Ramírez, G. A., Mahon, A. R., et al. (2021). Metagenomics of antarctic marine sediment reveals potential for diverse chemolithoautotrophy. *mSphere.* 6, e0077021. doi: 10.1128/mSphere.00770-21

Gong, X., Huang, D., Liu, Y., Zeng, G., Wang, R., Wei, J., et al. (2018). Pyrolysis and reutilization of plant residues after phytoremediation of heavy metals contaminated sediments: For heavy metals stabilization and dye adsorption. *Bioresour Technol.* 253, 64–71. doi: 10.1016/j.biortech.2018.01.018

Goode, K. L., Dunphy, B. J., and Parsons, D. M. (2020). Environmental metabolomics as an ecological indicator: metabolite profiles in juvenile fish discriminate sites with different nursery habitat qualities. *Ecol. Indic.* 115, 106361. doi: 10.1016/j.ecolind.2020.106361

Guan, H. X., Chen, L. Y., Luo, M., Liu, L. H., Mao, S. Y., Ge, H. M., et al. (2019). Composition and origin of lipid biomarkers in the surface sediments from the southern Challenger Deep, Mariana Trench. *Geosci. Front.* 10, 03 51–03360. doi: 10.1016/j.gsf.2018.01.004

Haghnazar, H., Johannesson, K. H., González-Pinzón, R., Pourakbar, M., Aghayani, E., Rajabi, A., et al. (2022). Groundwater geochemistry, quality, and pollution of the largest lake basin in the Middle East: Comparison of PMF and PCA-MLR receptor models and application of the source-oriented HHRA approach. *Chemosphere.* 288, 132489. doi: 10.1016/j.chemosphere.2021.132489

Haldar, S., and Ghosh, A. (2020). Microbial and plant-assisted heavy metal remediation in aquatic ecosystems: a comprehensive review. *3 Biotech.* 10, 205. doi: 10.1007/s13205-020-02195-4

He, N., Liu, L., Wei, R., and Sun, K. (2021). Heavy metal pollution and potential ecological risk assessment in a typical mariculture area in western Guangdong. *Int. J. Environ. Res. Public Health.* 18, 11245. doi: 10.3390/ijerph182111245

Hossain, M. B., Masum, Z., Rahman, M. S., Yu, J., Noman, M. A., Jolly, Y. N., et al. (2022). Heavy metal accumulation and phytoremediation potentiality of some selected mangrove species from the world's largest mangrove forest. *Biol. (Basel)* 11, 1144. doi: 10.3390/biology11081144

Hsieh, S., Łaska, W., and Uchman, A. (2023). Intermittent and temporally variable bioturbation by some terrestrial invertebrates: implications for ichnology. *Naturwissenschaften.* 110, 11. doi: 10.1007/s00114-023-01833-0

Hu, H., Han, L., Li, L., Wang, H., and Xu, T. (2021). Soil heavy metal pollution source analysis based on the land use type in Fengdong District of Xi'an, China. *Environ. Monit Assess.* 193, 643. doi: 10.1007/s10661-021-09377-4

Hu, C., Shui, B., Yang, X., Wang, L., Dong, J., and Zhang, X. (2021). Trophic transfer of heavy metals through aquatic food web in a seagrass ecosystem of Swan Lagoon, China. *Sci. Total Environ.* 762, 143139. doi: 10.1016/j.scitotenv.2020.143139

Huang, D., Xiao, R., Du, L., Zhang, G., Yin, L., Deng, R., et al. (2021). Phytoremediation of poly- and perfluoroalkyl substances: a review on aquatic plants, influencing factors, and phytotoxicity. *J. Hazard Mater.* 418, 126314. doi: 10.1016/j.jhazmat.2021.126314

Husain, R., Vikram, N., Yadav, G., Kumar, D., Pandey, S., Patel, M., et al. (2022). "Microbial bioremediation of heavy metals by marine bacteria," in *Elseviere Books*, 177–203. doi: 10.1016/B978-0-323-85839-7.00014-1

Islam, M. S., Islam, A. R. M. T., Ismail, Z., Ahmed, M. K., Ali, M. M., Kabir, M. H., et al. (2023). Effects of microplastic and heavy metals on coral reefs: A new window for analytical research. *Heliyon.* 9, e22692. doi: 10.1016/j.heliyon.2023.e22692

Jiang, Y., Gui, H., Chen, C., Wang, C., Zhang, Y., Huang, Y., et al. (2021). The characteristics and source analysis of heavy metals in the sediment of water area of urban scenic: A case study of the delta park in Suzhou City, Anhui Province, China. *Pol. J. Environ. Stud.* 30, 2127–2136. doi: 10.15244/pjoes/127279

Jørgensen, B. B., Findlay, A. J., and Pellerin, A. (2021). The biogeochemical sulfur cycle of marine sediments. *Front. Microbiol.* 10, 849.

Khatoon, Z., Orozco-Mosqueda, M. D. C., and Santoyo, G. (2024). Microbial contributions to heavy metal phytoremediation in agricultural soils: A review. *Microorganisms.* 12, 1945. doi: 10.3390/microorganisms12101945

Kumar, A., Dadhwal, M., Mukherjee, G., Srivastava, A., Gupta, S., and Ahuja, V. (2024). Phytoremediation: sustainable approach for heavy metal pollution. *Scientifica (Cairo)* 2024, 3909400. doi: 10.1155/2024/3909400

Kumar, V., Sharma, A., Pandita, S., Bhardwaj, R., Thukral, A. K., and Cerda, A. (2020). A review of ecological risk assessment and associated health risks with heavy metals in sediment from India. *Int. J. Sediment Res.* 35, 516–526. doi: 10.1016/j.ijsrc.2020.03.012

Kumar, S., Thakur, N., Singh, A. K., Gudade, B. A., Ghimire, D., and Das, S. (2022). *Aquatic macrophytes for environmental pollution control phytoremediation technology for the Removal of Heavy Metals and Other Contaminants From Soil and Water* (Elsevier), 291–308.

Lehel, J., Yaucat-Guendi, R., Darnay, L., Palotá, P., and Laczay, P. (2021). Possible food safety hazards of ready-to-eat raw fish containing product (sushi, sashimi). *Crit. Rev. Food Sci. Nutr.* 61, 867–888. doi: 10.1080/10408398.2020.1749024

Li, Y., Song, Y., Zhang, J., and Wan, Y. (2023). Phytoremediation competence of composite heavy-metal-contaminated sediments by intercropping *Myriophyllum spicatum* L. with two species of plants. *Int. J. Environ. Res. Public Health* 20, 3185.

Li, J., Zheng, B., Chen, X., Li, Z., Xia, Q., Wang, H., et al. (2021). The use of constructed wetland for mitigating nitrogen and phosphorus from agricultural runoff: a review. *Water.* 13, 476. doi: 10.3390/w13040476

Liu, X., He, L., Zhang, X., Kong, D., Chen, Z., Lin, J., et al. (2022). Bioremediation of petroleum-contaminated saline soil by *Acinetobacter baumannii* and *Talaromyces* sp. and functional potential analysis using metagenomic sequencing. *Environ. pollut.* 311, 119970.

Liu, Z., and Tran, K.-Q. (2021). A review on disposal and utilization of phytoremediation plants containing heavy metals. *Ecotoxicol Environ. Saf* 226, 112821. doi: 10.1016/j.ecoenv.2021.112821

Liu, R., Wang, Z., Wang, L., Li, Z., Fang, J., Wei, X., et al. (2020). Bulk and active sediment prokaryotic communities in the Mariana and Mussau trenches. *Front. Microbiol.* 11, 1521. doi: 10.3389/fmicb.2020.01521

Lu, G., Wang, B., Zhang, C., Li, S., Wen, J., Lu, G., et al. (2018). Heavy metals contamination and accumulation in submerged macrophytes in an urban river in China. *Int. J. Phytoremediation.* 20, 839–846. doi: 10.1080/15226514.2018.1438354

Luo, P., Xu, C., Kang, S., Huo, A., Lyu, J., Zhou, M., et al. (2021). Heavy metals in water and surface sediments of the Fenghe River Basin, China: Assessment and source analysis. *Water Sci. Technol.* 84, 3072–3090. doi: 10.2166/wst.2021.335

Maity, J. P., Chandra Samal, A., Rajnish, K., Singha, S., Sahoo, T. R., Chakraborty, S., et al. (2023). Furfural removal from water by bioremediation process by indigenous *Pseudomonas putida* (OSBH3) and *Pseudomonas aeruginosa* (OSBH4) using novel suphala media: an optimization for field application. *Groundwater Sustain Dev.* 20, 100895. doi: 10.1016/j.gsd.2022.100895

Makarova, A., Nikulina, E., Avdeenkova, T., and Pishaeva, K. (2021). The improved phytoextraction of heavy metals and the growth of *Trifolium repens* L.: The role of K2HEDP and plant growth regulators alone and in combination. *Sustainability.* 13, 2432.

Mausz, M. A., and Chen, Y. (2019). Microbiology and ecology of methylated amine metabolism in marine ecosystems. *Curr. Issues Mol. Biol.* 33, 133–148. doi: 10.21775/cimb.033.133

McAllister, S. M., Vandzura, R., Keffer, J. L., Polson, S. W., and Chan, C. S. (2021). Aerobic and anaerobic iron oxidizers together drive denitrification and carbon cycling at marine iron-rich hydrothermal vents. *ISME J.* 5), 1271–1286. doi: 10.1038/s41396-020-00849-y

Mishra, S., Bharagava, R. N., More, N., Yadav, A., Zainith, S., Mani, S., et al. (2019). Heavy Metal Contamination: An Alarming Threat to Environment and Human Health. *Environ. Biotechnol. Sustain. Fut*, (Singapore: Springer) 103–125. doi: 10.1007/978-981-10-7284-0_5

Mohan, I., Goria, K., Dhar, S., Kothari, R., Bhau, B., and Pathania, D. (2021). Phytoremediation of heavy metals from the biosphere perspective and solutions. *Pollutants Water Management: Resources Strategies Scarcity.* 16, 95–127.

Mortada, W. I., El-Naggar, A., Mosa, A., Palansooriya, K. N., Yousaf, B., Tang, R., et al. (2023). Biogeochemical behaviour and toxicology of chromium in the soil-water-human nexus: A review. *Chemosphere.* 331, 138804. doi: 10.1016/j.chemosphere.2023.138804

Nabuyanda, M. M., Kelderman, P., van Bruggen, J., and Irvine, K. (2022). Distribution of the heavy metals Co, Cu, and Pb in sediments and *Typha* spp. and *Phragmites mauritianus* in three Zambian wetlands. *J. Environ. Manage.* 304, 114133.

Onder Erguven, G., Tatar Serdar, O., and Yildirim, N. C. (2021). Evaluation of the efficiency of chlorpyrifos ethyl remediation by *Methylobacterium radiotolerans* and *Microbacterium arthrosphaerae* using response of some biochemical biomarkers. *Environ. Sci. pollut. Res.* 28, 2871–2879. doi: 10.1007/s11356-020-10672-9

Orata, F., and Sifuna, F. (2023). "Uptake, bioaccumulation, partitioning of lead (Pb) and cadmium (Cd) in aquatic organisms in contaminated environments," in *Lead, Mercury and Cadmium in the Aquatic Environment: Worldwide Occurrence, Fate and Toxicity*, vol. 166. doi: 10.1201/9781003186441

Patterson, J., Jeyasanta, K. I., Sathish, N., Edward, J. K. P., and Booth, A. M. (2020). Microplastic and heavy metal distributions in an Indian coral reef ecosystem. *Sci. Total Environ.* 744, 140706. doi: 10.1016/j.scitotenv.2020.140706

Prasad, M. N. V. (2019). "Prospects for manipulation of molecular mechanisms and transgenic approaches in aquatic macrophytes for remediation of toxic metals and metalloids in wastewaters," in *Transgenic Plant Technology for Remediation of Toxic Metals and Metalloids* (Elsevier), 395–428. doi: 10.1016/B978-0-12-814389-6.00021-3

Qian, L., Yu, X., Gu, H., Liu, F., Fan, Y., Wang, C., et al. (2023). Vertically stratified methane, nitrogen and sulphur cycling and coupling mechanisms in mangrove sediment microbiomes. *Microbiome.* 11, 71. doi: 10.1186/s40168-023-01501-5

Ramon, D., Morick, D., Croot, P., Berzak, R., Scheinin, A., Tchernov, D., et al. (2021). A survey of arsenic, mercury, cadmium, and lead residues in seafood (fish, crustaceans, and cephalopods) from the south-eastern Mediterranean Sea. *J. Food Sci.* 86, 1153–1161. doi: 10.1111/1750-3841.15627

Redwan, M., and Elhaddad, E. (2020). Assessment the seasonal variability and enrichment of toxic trace metals pollution in sediments of Damietta branch, Nile River, Egypt. *Water.* 12, 3359. doi: 10.3390/w12123359

Reichelt-Brushett, A. J., Stone, J., Howe, P., Thomas, B., Clark, M., Male, Y., et al. (2017). Geochemistry and mercury contamination in receiving environments of artisanal mining wastes and identified concerns for food safety. *Environ. Res.* 152, 407–418. doi: 10.1016/j.envres.2016.07.007

Rezapour, S., Asadzadeh, F., Nouri, A., Khodaverdiloo, H., and Heidari, M. (2022). Distribution, source apportionment, and risk analysis of heavy metals in river sediments of the Urmia Lake basin. *Sci. Rep.* 12, 17455. doi: 10.1038/s41598-022-21752-w

Rosenfeld, C. E., Chaney, R. L., and Martínez, C. E. (2018). Soil geochemical factors regulate Cd accumulation by metal hyperaccumulating *Noccaea caerulescens* (J. Presl & C. Presl) FK Mey in field-contaminated soils. *Sci. Total Environ.* 616, 279–287. doi: 10.1016/j.scitotenv.2017.11.016

Rudershausen, P. J., Cross, F. A., Runde, B. J., Evans, D. W., Cope, W. G., and Buckel, J. A. (2023). Total mercury, methylmercury, and selenium concentrations in blue marlin *Makaira nigricans* from a long-term dataset in the western north Atlantic. *Sci. Total Environ.* 858, 159947. doi: 10.1016/j.scitotenv.2022.159947

Saidon, N. B., Szabó, R., Budai, P., and Lehel, J. (2024). Trophic transfer and biomagnification potential of environmental contaminants (heavy metals) in aquatic ecosystems. *Environ. pollut.* 340, 122815. doi: 10.1016/j.envpol.2023.122815

Sarker, S. K., Matthiopoulos, J., Mitchell, S. N., Ahmed, Z. U., Mamun, M. B. A., and Reeve, R. (2019). 1980s-2010s: The world's largest mangrove ecosystem is becoming homogeneous. *Biol. Conserv.* 236, 79–91. doi: 10.1016/j.biocon.2019.05.011

Schenone, S., Hewitt, J. E., Hillman, J., Gladstone-Gallagher, R., Gammal, J., Pilditch, C., et al. (2025). Seafloor sediment microtopography as a surrogate for biodiversity and ecosystem functioning. *Ecol. Appl.* 35, e3069. doi: 10.1002/eap.3069

Shah, S. B. (2021). "Heavy metals in the marine environment—An overview," in *Heavy Metals in Scleractinian Corals* (Springer, Cham). SpringerBriefs in Earth Sciences.

Shourie, A., and Vijayalakshmi, U. (2022). Fungal diversity and its role in mycoremediation. *Geomicrobiol J.* 39, 426–444. doi: 10.1080/01490451.2022.2032883

Si, L., Branfireun, B. A., and Fierro, J. (2022). Chemical oxidation and reduction pathways of mercury relevant to natural waters: a review. *Water* 14, 1891. doi: 10.3390/w14121891

Slemr, F., Weigelt, A., Ebinghaus, R., Bieser, J., Brenninkmeijer, C. A. M., Rauthe-Schoch, A., et al. (2018). Mercury distribution in the upper troposphere and lowermost stratosphere according to measurements by the IAGOS-CARIBIC observatory: 2014–2016. *Atmos Chem. Phys.* 18, 12329–12343. doi: 10.5194/acp-18-12329-2018

Sonawane, J. M., Rai, A. K., Sharma, M., Tripathi, M., and Prasad, R. (2022). Microbial biofilms: Recent advances and progress in environmental bioremediation. *Sci. Total Environ.* 824, 153843. doi: 10.1016/j.scitotenv.2022.153843

Starnawski, P., Bataillon, T., Ettema, T. J., Jochum, L. M., Schreiber, L., Chen, X., et al. (2017). Microbial community assembly and evolution in subseafloor sediment. *Proc. Natl. Acad. Sci. U.S.A.* 114, 2940–2945. doi: 10.1073/pnas.1614190114

Summer, K., Reichelt-Brushett, A., and Howe, P. (2019). Toxicity of manganese to various life stages of selected marine Cnidarian species. *Ecotoxicol Environ. Saf.* 167, 83–94. doi: 10.1016/j.ecoenv.2018.09.116

Taslima, K., Al-Emran, M., Rahman, M. S., Hasan, J., Ferdous, Z., Rohani, M. F., et al. (2022). Impacts of heavy metals on early development, growth and reproduction of fish - A review. *Toxicol. Rep.* 9, 858–868. doi: 10.1016/j.toxrep.2022.04.013

Tongununui, P., Kuriya, Y., Murata, M., Sawada, H., Araki, M., Nomura, M., et al. (2021). Mangrove crab intestine and habitat sediment microbiomes cooperatively work on carbon and nitrogen cycling. *PloS One* 16, e0261654. doi: 10.1371/journal.pone.0261654

Tripathy, P. K., Mohapatra, M., Pattnaik, R., Tarafdar, L., Panda, S., and Rastogi, G. (2022). "Macrophyte diversity and distribution in brackish coastal lagoons: A field survey from Chilika, Odisha," in *Coastal Ecosystems* (Springer), 325–358. doi: 10.1007/978-3-030-84255-0_14

Tshithukhe, G., Motitsoe, S. N., and Hill, M. P. (2021). Heavy metals assimilation by native and non-native aquatic macrophyte species: A case study of a river in the Eastern Cape province of South Africa. *Plants (Basel)* 10, 2676. doi: 10.3390/plants10122676

Ustaoğlu, F., Taş, B., Tepe, Y., and Topaldemir, H. (2021). Comprehensive assessment of water quality and associated health risk by using physicochemical quality indices and multivariate analysis in Terme River, Turkey. *Environ. Sci. pollut. Res.* 28, 62736–62754. doi: 10.1007/s11356-021-15135-3

Varol, M., Ustaoğlu, F., and Tokatl, C. (2021). Ecological risks and controlling factors of trace elements in sediments of dam lakes in the Black Sea Region (Turkey). *Environ. Res.* 205, 112478. doi: 10.1016/j.envres.2021.112478

Vital, S. A., Cardoso, C., Avio, C., Pittura, L., Regoli, F., and Bebianno, M. J. (2021). Do microplastic contaminated seafood consumption pose a potential risk to human health? *Mar. pollut. Bull.* 171.

Wang, C., Zou, Y., Yu, L., and Lv, Y. (2020). Potential source contributions and risk assessment of PAHs in sediments from the tail-reaches of the Yellow River Estuary, China: PCA model, PMF model, and mean ERM quotient analysis. *Environ. Sci. pollut. Res.* 27, 9780–9789. doi: 10.1007/s11356-019-07530-8

Webb, P. (2019). "Chapter 12: *ocean sediments*," in *Introduction to Oceanography* (Roger Williams University: Rebus Community), 273–297.

Wojtkowska, M., and Bogacki, J. (2022). Assessment of trace metals contamination, species distribution and mobility in river sediments using EDTA extraction. *Int. J. Environ. Res. Public Health* 19, 6978. doi: 10.3390/ijerph19126978

Wu, H., Xu, C., Wang, J., Xiang, Y., Ren, M., Qie, H., et al. (2021). Health risk assessment based on source identification of heavy metals: A case study of Beiyun River, China. *Ecotoxicol Environ. Saf* 213, 112046. doi: 10.1016/j.ecoenv.2021.112046

Xia, G., Ji, X., Xu, Z., and Ji, X. (2022). Transparent cellulose-based bio-hybrid films with enhanced anti-ultraviolet, antioxidant and antibacterial performance. *Carbohydr Polym* 298, 120118. doi: 10.1016/j.carbpol.2022.120118

Yang, S., Sun, K., Liu, J., Wei, N., and Zhao, X. (2022). Comparison of pollution levels, biomagnification capacity, and risk assessments of heavy metals in nearshore and offshore regions of the south China sea. *Int. J. Environ. Res. Public Health* 19, 12248. doi: 10.3390/ijerph191912248

Yap, C. K., and Al-Mutairi, K. A. (2022). Ecological-health risk assessments of heavy metals (Cu, Pb, and Zn) in aquatic sediments from the ASEAN-5 emerging developing countries: A review and synthesis. *Biology* 11, 7.

Zhang, S., Chen, B., Du, J., Wang, T., Shi, H., and Wang, F. (2022). Distribution, assessment, and source of heavy metals in sediments of the Qinjiang River, China. *Int. J. Environ. Res. Public Health* 19, 9140. doi: 10.3390/ijerph19159140

Zhang, X., Yang, M., Yang, H., Pian, R., Wang, J., and Wu, A. M. (2024). The uptake, transfer, and detoxification of cadmium in plants and its exogenous effects. *Cells* 13, 907. doi: 10.3390/cells13110907

Zhao, Z., Oury, B. M., Xia, L., Qin, Z., Pan, X., Qian, J., et al. (2023). The ecological response and distribution characteristics of microorganisms and polycyclic aromatic hydrocarbons in a retired coal gas plant post-thermal remediation site. *Sci. Total Environ.* 857, 159314. doi: 10.1016/j.scitotenv.2022.159314

Zilius, M., Bonaglia, S., Broman, E., Chiozzini, V. G., Samuiloviene, A., Nascimento, F. J. A., et al. (2020). N2 fixation dominates nitrogen cycling in a mangrove fiddler crab holobiont. *Sci. Rep.* 10, 13966. doi: 10.1038/s41598-020-70834-0