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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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An Insight into the Ecological Risks and Mitigation of Heavy Metal Pollution in Aquatic Sediments and Marine Ecosystems

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Simple Summary

The review summarizes the effects of heavy metals on ecology of sediments and deals with the use of phytoremediation as a measure for mitigation of heavy metals from contaminated sediments. In this regard, it highlights on the impacts of urbanization and industrialization on accumulation of heavy metals in the aquatic sediments, the ill-effects that are being caused to the aquatic lives and also the humans. Finally, the review concludes with a note on the use of eco-friendly and environmentally sustainable phytoremediation techniques, logistics and their advancements in heavy metal remediation from sediments.

Abstract

The aquatic ecosystems are important ecological and socio economic zones all over the world. However, a massive deterioration in the functionality of the aquatic zones has been observed globally in recent times due to an enormous rise of environmental pollution with ever increasing human population, urbanization, land reformation and industrialization. In spite of that, there is a dearth of an ample study for assessment of aquatic and sediment pollution and their effects on biogeochemical cycling, food chains and overall livelihoods of species including humans. Thus, there is an immediate necessity for digging into the status of aquatic sediment pollution, evaluation of the associated ecological risks and estimation of the probable pollution sources. Therefore, this review enlightens on the composition, concentrations, sources and spatial patterns of 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 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 thereby be useful to monitor and manage the vast aquatic ecosystem and develop strategies for remediation in near future.

Keywords: aquatic ecosystem; bioremediation; ecological risks; heavy metals; phytoremediation; pollution; sediments

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1. Introduction

Sediments are the vital components of any aquatic system. The sediments are supplemented with solids and ions through an array of physicochemical processes that serve as the main source for biogeochemical cycling and nutrient turn-ups [1]. However, one of the negative impacts of rapid urbanization is the development of stress on the aquatic sediments resulting in deterioration of the quality of water, eutrophication, excess flooding, and heavy metal (HM) pollution [2,3].

The major problem with the HMs is their inefficient elimination through natural decomposition processes due to their long half-lives, non-biodegradability and lesser self-purification ability [4]. Hence, they attach, settle and accumulate within the sediments of the water bodies by binding to the

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particulate matters. Due to the low solubility of HMs in water, the 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 the adjacent rivers and carried downstream along the course of the river [5]. The freshwater salts get deposited in the bottom sediments after sinking and do not affect the 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 fresh water 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 the aquatic bodies [6,7]. The microorganisms also contribute to the HMs by subsiding mercury (Hg) during certain biochemical activities and thereby decrease the quality of water [8].

The natural biogeochemical cycling of heavy metals is highly perturbed by the anthropogenic activities [2]. The anthropogenic activities that mostly contribute to the marine environment pollution through infiltration of HMs into the 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 incarnation, 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, tyres, minerals (phosphates), aquaculture activities, agricultural practices (inorganic pesticides and chemical fertilizers) and natural fields [9–11]. The improperly managed electronic waste (e-waste) has been recognized as a recent potential source of threat to humans and 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 [12].

However, the dynamicity of the accumulating HMs in the sediments are controlled by numerous physical, chemical, hydrological and hydraulic issues such as the presence of floodplains, lakes, reservoirs, hydraulic structures that disrupt the natural river-flow. The climatic changes, flow-competence of the water, land-use structures, pollution types, sources, size of the particles, features of river basin including pH, salinity, content of organic carbon and calcium carbonate, landscape diversity and the geological structures also contribute to the HMs deposition and pollution in the sediments [4]. The HMs become the secondary source of pollution for the water when they are being released from the sediments with the changes in the surrounding environment [pH and Eh] [13].

The characterization of HMs is important for the assessment of HMs load within water [14]. There is a high concern about the pollution of HMs in aquatic sediments particularly for developing countries, and it demands for scrutinizing the present status, to develop probable remedial strategies [15]. However, the spatial distribution and their overlapping characteristics, make the qualitative and quantitative identification of HMs very challenging. These have resulted in variability of data and lack of comprehensiveness in determination of risks associated with HMs in surface sediments [11]. 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 [16–19].

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, the modes of transfer through food chains, thereby affecting human health and (3) 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 matters, 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 through riverflow, dust in winds, glaciers or chemical precipitation [20]. The soft sediments of marine origin provide valuable contributions to global ecosystem functioning through mineralization of organic compounds, cycling of carbon and nitrogen and thereby affect the dynamics of marine ecology [21]. In recent era, community-based ecology studies through metagenomics-transcriptomics and very recent metabolomics provide a holistic knowledge on the ecosystem functioning in the sediments beyond the biogeochemical cycling. This mediates the detailed understanding of the interplay of the biogeochemical exchanges, biochemical intermediates synthesized during energy transformation and biosynthesis metabolism in the marine sediments, even beyond the static sequence-based identification of microbiome [21].

One such integrated study from Australia revealed the variations in metabolic criticality involving amino acid metabolism, glycosylation and phospholipids synthesis from among the species of salt marshes [21]. The role of pH and acid volatile sulphide (AVS) in the sediments are critical in determining the biogeochemical cycling of methane, nitrogen and sulphur among the sediment microbiome. Similar metegenomic studies from Antarctic marine sediments have explored the drive of the biogeochemical cycles with respect to nitrogen metabolism under severe climate changes [22]. This study has identified cluster of genes involved in nitrification, along with sulphur oxidation and carbon utilization. The organotrophy coupled with carbon fixation through Calvin and tricarboxylic acid cycles are found to be dominant metabolic pathways in marine sediments. The benthic communities are well-equipped for utilization of organic matter from the bottom of the sediments. This nitrogen-sulphur biogeochemical cycling helps in thriving of microorganisms as well as higher trophic levels and flux of essential nutrients in bentho-pelagic communities in Polar Regions. The availability of sulphur in marine sediments drives the process of dissimilatory sulfate reduction (DSR) by the anaerobic microbes on the surface marine sediments producing thiosulfate and elemental sulphur. The sulfate reduction on other hand is common in deep anoxic sediment [23]. The lower organic carbon content in marine sediments of Western Antarctica as compared to Antarctica Peninsula steers the higher activities of lithotrophic microorganisms in the region [22]. 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 Pacific and Atlantic Ocean [24].

The sediment depths also influence nutrient processing, thereby determining the vertical stratification of the microbial distribution with the presence of sulfide and nitrogen utilizing microbes on the surface sediments while sulfate-reducing and anaerobic-methane-oxidizers in the middle and deep layer sediments [25]. The fungal density in the water column is inversely proportional to the depth. These fungi within water columns contribute to the marine carbon cycle through processing of organic carbon from the phytoplanktons [24].

The availability of energy for cellular functioning is inversely proportional to the age and depth of the sediments. Hence the cellular metabolic rates decrease within few meters of the sediment surface. However, an active turnover biomass is observed within few hundred meters below the sea-bed. This survival of microbes under energy-deficit deep marine biospheres is attributed to the evolutionary selection of species from the surface areas [26]. In comparison to polar sediments, the deep trenches called hadal zones, 6000 m below sea, where there is a vertical transport of photosynthetic organic compounds, also plays an important role in marine ecology. Diverse heterotrophic lineages of microbial communities with high rates of respiration have been reported from Mussau and Mariana trenches [27]. High abundance of n-alkanes have been identified from deep trenches which might have attributed to the presence of a hydrocarbon-degrading microorganisms as potentially active keystone species [27,28]. Therefore alkane degradation is an important pathway for turnover of carbon in the sediments of deep marine trenches. During this carbon assimilation, the methylated amines (MA), precursors of methane, produced by methanogenesis, contribute to the greenhouse effects through the release of carbon-active gases and are ubiquitously present in marine sediments [29]. The methylotropic 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 the phytoplanktons produce them, into the meso- and bathy-pelagic communities in the form of marine snow [24]. This phenomenon helps in the partitioning of CO2 between atmosphere and marine sediments and thereby the sequestered carbon is removed from the surface sediments to deep oceanic floors. However, the variation in the magnitude and the depth of mineralization depends on the nearby food webs. Eg. The flux of POC is increased by the large phytoplankton cells where as feeding of zooplanktons influence 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 [30].

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 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 establishment of fungal association with diatoms, macroalgae, seagrass and corals where the symbioses gives rise to defense against environmental stresses in marine habitats. Genomics studies have revealed the abundant expression of fungal genes associated with the hydrolysis of lipids, proteins and carbohydrates as well as synthesis of antimicrobial compounds in organic carbon rich sediments from Canterbury and Peru coastal basins [24].

The viruses are the other important components that contribute to the marine sediment ecosystem by modification of the composition of microbial community and biogeochemical cycles of the marine sediments. The dead zones with low/no oxygen at the seafloor sediments are formed due to oxygen depletion by the microbial decomposition of the decaying and sinking cynaobacterial blooms below the euphatic zones.

The marine sediments are reworked upon by the aquatic organisms through a mechanism called bioturbation which is believed to be one of the primary drivers for biodiversity, particularly in aquatic ecosystem. This bioturbation provides numerous ecosystem services like provision of shelters for organisms, alteration of nutrients, sediment differentiation, production of soil and affecting the species evolution [31]. Shrimps, particularly ghost and mud shrimps, walrushes, polychaetes, salmons and benthic fauna are dominant bioturbators that modify pore-water, influence cycling of nutrients and process organic matter deposition in aquatic system. This process ultimately affects the microorganism population of the oceanic beds by modulating the physicochemical properties of the sediments [32]. The 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 [33]. The 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 the feces. This then serves as a productive resource in marine and coastal ecosystems [34,35]. Therefore, the diversity and abundance of sesarmid mangrove crabs determine the properties of the sediments through addition of organic matter. The fiddler crabs, on other hand, impact on the carbon and nitrogen cycling in the carbon-rich and nitrogen-poor mangrove sediments through the symbiotic associations with the sediment bacteria and their own burrowing actions [36,37].

3. Accumulation of HMs in Sediments and Their Effects on Marine Ecosystem

Though the marine habitats are one of the principal regulators of ecosystem functioning yet they are the most anthropogenically despoiled ecosystems globally [38]. The HMs, defined as the 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 wide-spread non-point sources within the marine sediments [10]. Both free and combined forms of HMs with carbonate, sulfide, oxy-hydroxide are distributed in aquatic ecosystems [39]. The accumulation of HMs occurs in the marine biofilms and organic matter by a number of mechanism including precipitation, sedimentation, adsorption and desorption potentially affecting the survival marine lives [40]. The air-deposition of HMs is also one of the significant mechanisms for their infiltration into the marine sediments from terrestrial run-offs 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 [41].

Due to the property of bio-magnification of HMs in aquatic ecosystems and coral reefs, the marine habitats are one of the most suitable regions to assess the degree of HMs pollution in the marine ecosystems [42]. The feeding on HMs-contaminated coral reefs by the zooplanktons, fish, crabs, oysters, mussels, sea cucumbers and shellfish leads the entry of the HMs into the aquatic food chain [43–45].

A vast literature exists on the determination of biomagnifications of HMs in sediments and marine ecosystems all over the world [46,47]. These have proved that the concentration of HMs increases with size and age in large marine organisms, and in higher trophic levels, through bioaccumulation and biomagnifications processes, indicating that the large organisms with long life-span and predators on the higher trophic levels of marine ecological pyramids are significantly affected by the HMs [48]. The adsorption of HMs within sediments and mobility through water columns play an important role in bioaccumulation of HMs within aquatic species along with the rate of metabolism and excretion of the HMs within the aquatic organisms [10]. The bioturbation that distributes the HMs within the 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 give HMs an entry into the food chain, ultimately affecting the human health. As per the literature, a total of 10 million people are affected globally due to HMs contamination [49].

The HMs are absorbed into fish gills, amphipod cuticles and other sensitive organs of aquatic creatures [10]. 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 long-run due to reduced and abnormal growth, locomotor abilities and behavioral patterns, making them more vulnerable to predation [50].

The oral ingestion, inhalation, and dermal exposure are the three principle entry-routes of HMs in humans. Within the human body, they generate reactive oxygen species (ROS) and get deposited in various organs causing chronic and carcinogenic effects [4]. Additionally, if the 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 biomagnifications [10]. Therefore, there is a need to increase awareness about the toxic effects and the ecological risks involved in HMs pollution among the people living in coastal areas and engaged in coastal activities [51].

In developing countries, as in Association of Southeast Asian Nations (ASEAN-5) consisting of Indonesia, Malaysia, Philippines, Thailand and Vietnam, studies have elucidated on the ecological risks of HMs from the marine sediments, questioning the investigation of the corresponding health risks and developing remediation strategies [11]. Review of studies for over 20 years from 1981-2021, have reported cupper (Cu), Pb and zinc (Zn) as considerable to high potential ecological risks in ASEAN-5 countries [11]. The studies have highlighted the presence of HMs including Cd, chromium (Cr), Pb, Zn, Cu, arsenic (As) at different aquatic trophic levels including seagrass ecosystem, crustaceans, mollusks, aquatic plants, fishes, bivalves, microalgae and planktons and have also reported biomagnification of the same with trophic magnification factor greater than 1 [10]. Studies from Naples Bay showed that the marine nematodes that constitute 90% of total benthic fauna bioaccumulate As, Cr, manganese (Mn), Zn and Nickel (Ni) from the sediments that slowly increases among the deposit feeders, microalgal grazers, followed by predators of microbes and small metazoans respectively and thereby contribute to the biomagnifications of the HMs from the

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sediments to higher trophic levels [48]. The variation of the biomagnification of HMs in different coastal areas has been explained and attributed to multiple factors including the diversity in geographical locations, food web complexities and position of the species within the trophic levels, the cellular composition of the species, physiological requirements of the HMs among the species, their feeding habits and detoxification mechanisms [52]. The salinity of the sediments is one of the determining factors for HMs bioaccumulation in marine ecosystems. Bioaccumulation of Hg and As has been found to be more concentrated among benthic than pelagic population and also to vary between epipelagic and mesopelagic population [53].

The organisms living close to the sediments (bottom-feeding fish and sediment-dwelling invertebrates) with higher rates of metabolism and short life spans and at lower trophic levels have low biomagnifications of HMs [10]. However, Boldrocchi et al. showed that the gastropods from lower trophic levels and shorter food chains in marine ecosystems have the highest bioaccumulation rates of Cd and Ni [54]. In marine ecosystems, planktons are the entry points for the bioaccumulation of HMs which gradually pass on through the aquatic food webs by the species feeding on them. In the planktons, though the HMs are essential for photosynthesis, high concentration of the same bind to metallotheins and perturb the equilibrium of the living cells. The microorganisms including oligonitrophilic bacteria and actinomycetes are also negatively impacted by the HMs [46].

The external factors associated with the coastal sediments including pH, sunlight received, dissolved organic matter, nutrient contents and salinity also determine the ultimate rate of bioaccumulation of the HMs. A study with zooplanktons from the Baltic Sea showed that the bioaccumulation of Zn and Pb within the algae decreased due to the variations in the bioavailability of the metals, the scavenging and biosorption abilities of the zooplankton, concentration of organic matter and hydrochemical characteristics of the sediments [55]. The low solubility, complex-forming abilities and occurrence in low concentrations make Pb less potential for biomagnification in marine sediments [56]. 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 tropical marine seagrass ecosystem of China [46]. The Cu, though essential for life, changes the enzyme actions, interfere with regulation of ions, upsets the acid-base balance and cause endocrinal disorders in marine species [57]. The 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 [50]. The hexavalent Cr is highly harmful as compared to the other forms of Cr as it is potent to be carcinogenic by causing mutations in proteins within the living species [58]. The Cd that lacks the biomagnifying qualities is very bio-permanent and stays in organisms for many years after absorption [59]. On the other hand, As bioaccumulates in fish, crustaceans and algae, but does not spread along the food chain [59]. 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, high concentration of Fe that may arise from burning of fuels at the marine zones increases the absorption and storage of carbon in the aquatic zones and ultimately affects the carbon cycling and global climate [60]. The Fe in distant sea also boosts the release of organic carbon and dimethyl sulphide from marine organisms that influences the radiative forcing in the atmosphere [61]. The conversion of soluble Mn^{+} to insoluble Mn^{+} also impacts to ecotoxicology of marine sediments due to high solubility, bioavailability and delayed rate of transition [61].

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 [52]. The rate of biomagnification in marine ecosystem is highest for Hg where it is found to bio-magnify from low particulate organic matter (POM) trophic level to higher fish [62]. Of these again, methylmercury (MeHg), produced from mercuric sulphide by 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 [63]. The toxicity increases due to it's high water-solubility and high power of retention in fatty membranes. Though research is lacking on the oxidation states of Hg among the aquatic species, but total Hg biomagnifications has been recorded from small zooplanktons to macroplanktons and to fishes in marine ecosystems, particularly enhanced under warm temperatures [10]. Though inorganic Hg lacks biomagnifying property, but being volatile can potentially travel around the biospheres and remain active over a year [64]. The metal Hg emerges from various inevitable natural geological sources, but 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, 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 [65].

The metal Hg has an antagonistic effect on Se, as reported from a survey on Atlantic blue marlin, *Makaira nigricans* from North Atlantic Ocean, where high rising concentration of Se and low accumulation of Hg has been reported between the period of 1975-2021 [66]. However, like Hg, Se has also been recorded to produce biomagnifications from low to high trophic levels in tropical marine aquatic systems, mesoplanktons and crustacean species in South Atlantic food web, zooplankton to perch in temperate lakes and invertebrates–zooplanktons–fish [67]. However, contrastingly, the Se has also been found to be diminishing among pelagic, benthopelagic and benthic organisms; zooplankton to predatory finfish and to bottlenose dolphins and fish–zooplankton–gastropods–bivalves in marine ecosystems [68]. The contrasting phenomena for distribution of Se in aquatic ecosystems can be due to the availability of various oxidative states of the Se (like selenate and selenite) in different concentrations. In marine ecosystem, arsenobetain is another common As and has been found to show biomagnification at tertiary consumer of predatory fish and sharks [10]. Silver (Ag) has also emerged as a biocide originating from anthropogenic sources of smelting, coal combustion, photographic films that can bioconcentrate in fishes, gastropods, crustaceans, algae and phytoplanktons [69].

The bioaccumulation of toxic HMs in consumable marine species has harmful effects on the entire food chain, with humans in particular, where the HMs have proved to be carcinogenic [70]. Therefore, the assessment of risk of consumption of marine products is important following the guidelines of tolerance levels laid down by the Food and Agriculture Organization [FAO] and World Health Organization [WHO] [71]. Estimated daily intakes (EDI) needs to be calculated by taking into consideration the concentration of the HMs present in the marine items and the daily intake rate of that item.

4. Management of HMs in Sediments by Phytoremediation

The traditional methods used previously for HMs removal from sediments including sediment wash, immobilization and stabilization of pollutants exert negative impacts on sediments and it's microbial diversity [72]. Therefore, the bioremediation techniques are highly recommendable for mitigation of the HMs-induced pollution in marine environments due to their affordability, high efficacy, realistic nature, reliability, ecological and environmental sustainability [73–76].

However, it is to be borne in mind that the complete removal of HMs from sediments is not possible but only the transformation of oxidation states can be done (Bhat et al., 2022). The metal-resistant bacterial species such as *Pseudomonas sp*., *Microbacterium sp*., *Alcanivorax borkumensis*, *Bacillus sp*., *Dechloromonas aromatic*, *Acinetobacter sp*., *Corynebacterium sp*. and *Ralstonia sp*. and the fungi like *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 few of the promising agents that have already been used for HMs bioremediation as they are capable of altering the HMs concentration in marine sediments as well as can assist the plants to adjust to profuse concentration of HMs [77–82]. Use of bacterial bio-block for removal of HMs from waste water and thereby inhibiting the passage of HMs from waste water treatment plants into the aquatic sediments is a wellestablished technique for HMs removal [83]. The tea-waste bio-block used as an assist material for the recruitment of bacterial biofilm, notably *E. coli*, *Arthrobacter* and *Bacillus sp.* to build a batch technique for concurrent biosorption as well as bioaccumulation of Cr [84]. Halophilic actinomycetes: *Nocardiopsis halophila* and *Nocardiopsis rosea* were used as biosorbents for the removal of Cr and Zn in wastewater [85]. The bio-blocks of fungi like *Penicillium fellutanum* and *Aspergillus sp.* were found to efficiently biosorp Hg, Ni and Zn [86].

The green technology involving phytoremediation has been a productive mechanism to manage the environmental pollution issues by uptake of HMs from the water, followed by translocation, bioaccumulation and degradation of the same within the plant body [87]. A total of 400 plant species have been identified as effective for phytoremediation till date and have been harnessed for effective HMs pollution from aquatic sediments and other environments [12]. Since plant genotype plays an important role in phytoremediation abilities, the biodiversity among plant species that regulates the metabolic processes, resistance and mobilization of HMs plays an important role in determination of potent candidates for phytoremediation in aquatic sediments and a total of five classes (*Salviniaceae*, *Araceae*, *Cyperaceae*, *Haloragaceae* and *Poaceae*) of aquatic plants have been found to be involved in HMs phyto-extraction [88]. The 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 proved to be proficient in phytoremediation from water and sediments by different mechanisms of extraction, stabilization, volatilization, stabilization and transformation of HMs including As, Cd, Cr, Pb and Hg [89–99]. Eid et al., experimentally proved that of these hydrophytes *Phragmites australis* is capable of concentrating the highest amount of Ni and Cd while *Echinochloa stagnina* could accumulate the highest amount of Pb from HMs wetland sediments [100]. *Phragmites australis* was also found to bioaccumulate and translocate Co, Mo, Pb, Cr, Cu, Fe, Mn, Zn, and Hg in the contaminated estuarine sediments of Spain [101]. The mangrove species *Excoecaria agallocha*, *Avicennia marina*, *Avicennia officinalis*, *Sonneratia apetala* have been also found to be hyper-accumualtors of HMs in sediments [102].

The ornamental plants and genetically modified plants including Arabidopsis thaliana, Brassica juncea, Calendula officinalis, Chlorophytum comosum, Melastoma malabathricum, Mirabilis jalapa, and Polypogonmons peliensis [12]. Though the large-scale application of traditional phytoremediation techniques is unrealistic, the emerging trends of genetically modifying the organisms to ensure long-lasting effective means for remediation [8].Intercropping of Vallisneria natans and Hydrilla verticillata with Myriophyllum spicatum were found to be effective in removal of Cu and Pb from aquatic sediments decreasing the RI < 150 [103]. The phytoremediation includes numerous methods like accumulation of HMs in the form of phytocelatin-metal complexes and transferring them into the aerial parts of the plants from roots (phytoextraction), break down of metal complexes into simple forms using secondary metabolites or transport proteins on the root-surfaces (phytostabilization), conversion of contaminants to volatile substances and release them through aerial parts (phytovolatilization) and metabolized to less-toxic compounds and degraded within plant organs (phytodegradation). In addition, the aquatic plants can efficiently remove the HMs from water through rhizofiltration in which they assimilate the HMs through roots and make the water contaminant-free [8]. The Cd, Pb and Cr which are accumulated in the roots are efficiently removed by this process. The tobacco, spinach and sunflower plants proved to be highly proficient in rhizofiltration [104]. Makarova et al. demonstrated the phytoextraction of Cd, Cu and Ni by Trifolium repens where the plant growth regulators and iron chelate and potassium salt of K2HEDP were essential for the phytoextraction of Cd [105]. 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 field irrigated with wastewater. However, variation in concentration of accumulated HMs in macrophyte Vossia cuspidate was observed with respect to both seasons and plant tissues, with higher concentrations being deposited in roots [106]. Therefore, it showed that the plant genotype, phytohormones, root architecture, rhizosphere activities, root-exudation, redox potentials, organic ligands, metal chelates, edaphic factors (pH, temperature, moisture, vapour 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. For 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 help in changing the soil properties and aid to better remediation. Eg. Thlaspi caerulescens showed the highest Cd and Zn accumulation at low acidic pH of 6.5 to 7.0 [107]. Low pH, high moisture and organic content of the soil increase the mobilization of HMs by chelate formation and increased cation exchange capacity. The agricultural amendments like application of manure, peat and compost in the sediments as well as genetic modification of the plants and other crop management processes enhance the rate of bioaccumulation of HMs by plants in sediments [8].

5. Current Challenges

Phytoremediation opens up a number of ways to overcome HMs pollution problems from soil. But the gaps in knowledge prevail with respect to aquatic systems and sediments due to lack of research in this field. Therefore, more researches are needed to explore diverse plant species for their effective bioremediation possibilities and to design realistic, replicable and feasible phytoremediation techniques. Also, for best facilitation of phytoremediation, the various factors that influence the process directly or indirectly need to be evaluated including the HMs type, 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. The challenges associated with 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 has proved to be an effective technique to reutilize the adsorbed products [108].

6. Conclusions

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

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