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Review

Heavy Metal Pollution in Coastal Environments: Ecological Implications and Management Strategies: A Review

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Abstract: Heavy metals originating from industrial runoff, agricultural practices, urbanization, and natural geological processes persist in coastal sediments due to their low degradation rates and high stability. Their cycling is influenced by sediment dynamics, water circulation, and complex interactions with biological and chemical factors. Heavy metal pollution demonstrates serious risks to coastal biota, including fish, shellfish, algae, and marine mammals through mechanisms such as bioaccumulation and biomagnification. These processes lead to biodiversity loss, habitat degradation, and reduced ecosystem functionality. Current mitigation strategies for pollution control regulations and remediation techniques show promise but face challenges in implementation. Emerging technologies such as nanotechnology and bioremediation offer innovative solutions but require further validation. Knowledge gaps persist in understanding the long-term ecological impacts of heavy metal contamination and optimizing management strategies for diverse coastal ecosystems. Coastal ecosystems are vital for supporting biodiversity and providing essential ecosystem services, but they are increasingly threatened by heavy metal pollution—a pervasive environmental challenge that demands urgent attention. This review investigates the sources, characteristics, pathways, ecological impacts, and management strategies associated with heavy metal contamination in coastal environments. The review synthesizes findings from recent literature, employing a systematic approach to analyze natural and anthropogenic sources, contamination pathways, and the biogeochemical processes governing heavy metal cycling. Future research should focus on addressing these gaps through interdisciplinary approaches, integrating advanced modeling techniques, stakeholder engagement, and sustainable management practices. By prioritizing these efforts, we can safeguard coastal ecosystems and their essential services from the escalating threats of heavy metal pollution.

Keywords: contamination sources; coastal ecosystems; ecological impact; future research; pollution control

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1. Introduction

Coastal environments are among the most dynamic and ecologically significant ecosystems on our planet, serving as crucial habitats for a diverse array of marine species and

providing essential ecosystem services to human communities worldwide [1]. These ecosystems offer critical services to human populations, including coastal protection, fisheries resources, and carbon sequestration, making them indispensable for both biodiversity conservation and human well-being. However, these invaluable coastal ecosystems face increasing threats, particularly the release of heavy metals into both sediments and marine environments [2]. The release of heavy metals into coastal environments has become a growing concern due to their persistence, toxicity, and potential for bioaccumulation in the food chain. Heavy metals, like lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr), are naturally occurring elements that have become pervasive pollutants in coastal areas due to industrialization, urbanization, and agricultural practices [3]. Once deposited into sediments, these metals can persist for extended periods, posing significant risks to ecosystem health and human well-being [4]. The accumulation of heavy metals in coastal wetland sediments presents several ecological challenges. These sediments act as both sinks and sources of contaminants, trapping pollutants in the short term but potentially releasing them back into the water column under changing environmental conditions. What distinguishes this review is its focus on the multi-faceted interactions and biogeochemical transformations of heavy metals in coastal wetland sediments. Unlike traditional reviews that emphasize either the chemistry or the biological impacts of pollution, this article offers a holistic perspective by integrating the chemical, physical, and biological dimensions of metal cycling. The review synthesizes the latest research on the sources and pathways of heavy metal contamination in coastal wetlands, with an emphasis on adsorption processes, sediment–water interactions, and the role of microbial communities in modulating metal bioavailability. It also delves into the mechanisms driving the distribution and accumulation of metals in these environments, shedding light on the factors influencing their mobility and toxicity. Furthermore, this article examines the cascading ecological impacts on wetland organisms, from primary producers to top predators, and highlights the implications for ecosystem services such as water purification, habitat provision, and carbon storage. Understanding the cycling and fate of selected heavy metals in coastal wetland sediments is essential for assessing their ecological impacts and developing effective pollution prevention and remediation strategies [5]. From adsorption onto sediment particles to biogeochemical transformations and bioaccumulation in wetlands [6,7], the pathways and processes governing the behavior of heavy metals in these environments are complex and dynamic [8]. In this review article, we provide an ecological perspective on the cycling and fate of heavy metals in coastal wetland sediments. By synthesizing the current scientific literature, we identify gaps in knowledge and propose areas for future research to improve our understanding of metal dynamics in these critical ecosystems. Additionally, we discuss current strategies for managing sediment pollution and explore innovative approaches for mitigating the effects of heavy metal contamination in coastal wetlands, including the use of bioremediation, phytoremediation, and engineered solutions. Through this comprehensive examination, we aim to contribute to the development of effective, science-based policies and management practices to protect and restore coastal wetland ecosystems facing heavy metal contamination.

2. Sources and Pathways of Heavy Metal Contamination in Coastal Wetland Sediments

Coastal wetland sediments serve as sinks for various pollutants, including heavy metals, which originate from both natural and anthropogenic sources [9]. Understanding the sources and pathways of heavy metal contamination in these sediments is essential for developing targeted management strategies to mitigate their impacts on wetland ecosystems. In the following sections, we will delve into the mechanisms driving the distribution and

accumulation of heavy metals in coastal sediments and examine their ecological impacts on wetland biota.

2.1. Natural Sources

Natural sources of heavy metals in coastal wetland sediments include geological weathering, volcanic activity, and atmospheric deposition. Heavy metals are naturally present in rocks and minerals, and their release into sediments can occur through erosion and weathering processes. Several studies reported that heavy metals such as As, Pb, Cu, Cd, Cr, Sb, Zn, and Ni could be naturally attenuated through precipitation with iron-containing mineral phases, such as goethite, jarosite, and hematite, under specific geochemical conditions [10]. However, the extent of this dilution depends on factors like pH, redox conditions, and the availability of reactive mineral surfaces, which influence the precipitation process and the stability of the resulting metal–mineral complexes In addition, volcanic eruptions release some heavy elements and deposit them on land or in aquatic environments [11]. Geological processes release heavy metals from rocks and minerals, contributing to baseline levels of heavy metals in sediments. Ju et al. [12] demonstrated that the precipitation of minerals like goethite, jarosite, and hematite has been extensively employed to sequester excess dissolved Cd, As, Cu, Zn, and Fe from acidic leach solutions. These natural sources contribute to the baseline levels of heavy metals found in coastal sediments.

2.2. Anthropogenic Sources

Anthropogenic activities play a critical role in contributing to heavy metal contamination in coastal wetland sediments, with diverse sources and mechanisms driving metal release and transport [13]. Industrial discharge, for instance, introduces significant quantities of heavy metals such as Pb, Hg, Cd, and Cr into the environment [5]. These metals often originate from manufacturing processes, petrochemical industries, and waste disposal practices, accumulating in nearby sediments due to direct discharge into aquatic systems. Industrial sites located near coastal wetlands act as persistent point sources of contamination, impacting sediment quality over extended periods. Urban runoff is another major contributor, transporting heavy metals from roads, buildings, and urban infrastructure into coastal wetlands [14]. Heavy metals like Zn, Cu, and Pb, originating from vehicle emissions, tire wear, and building materials, are carried by stormwater into aquatic environments. This non-point source pollution has a cumulative impact on sediment quality, particularly during heavy rainfall events. Agricultural practices also play a substantial role in heavy metal contamination. The use of fertilizers, pesticides, and herbicides often introduces metals such as arsenic, cadmium, and copper into soils, which are subsequently mobilized into coastal waters through surface runoff [15]. For example, phosphate fertilizers frequently contain cadmium as an impurity, contributing to its accumulation in wetland sediments over time. Mining activities further exacerbate heavy metal pollution by releasing metals like As, Pb, and Ni into surrounding waterways. Processes such as ore extraction, smelting, and tailing disposal generate large volumes of metal-laden waste, which can leach into aquatic systems and eventually settle in sediments [16]. Heavy metal contamination of sediments in Boka Kotorska Bay, Montenegro, was classified by Tanaskovski et al. [17] as uncontaminated or contaminated by the calculation of the enrichment factor (EF), metal loading index (MLI), and geoaccumulation index (Igeo) or the use of sediment quality guidelines of US EPA as heavily contaminated with arsenic and chromium and uncontaminated with cadmium and mercury. The results also showed that the surface sediments in Boka Kotorska Bay are enriched with silicon, calcium, astonish, and chromium from natural sources and mercury, lead, and arsenic from anthropogenic sources. The transport

and deposition of these heavy metals depend on hydrological dynamics, such as water flow and sediment transport, amplifying their impact on downstream wetland ecosystems. The sources of heavy metal transport into coastal wetlands, as depicted in Figure 1, include both point sources (natural and anthropogenic), such as industrial outfalls, and diffuse sources like surface runoff and atmospheric deposition. These processes collectively highlight the complexity and scale of anthropogenic contributions to sediment contamination, underscoring the need for targeted mitigation strategies.

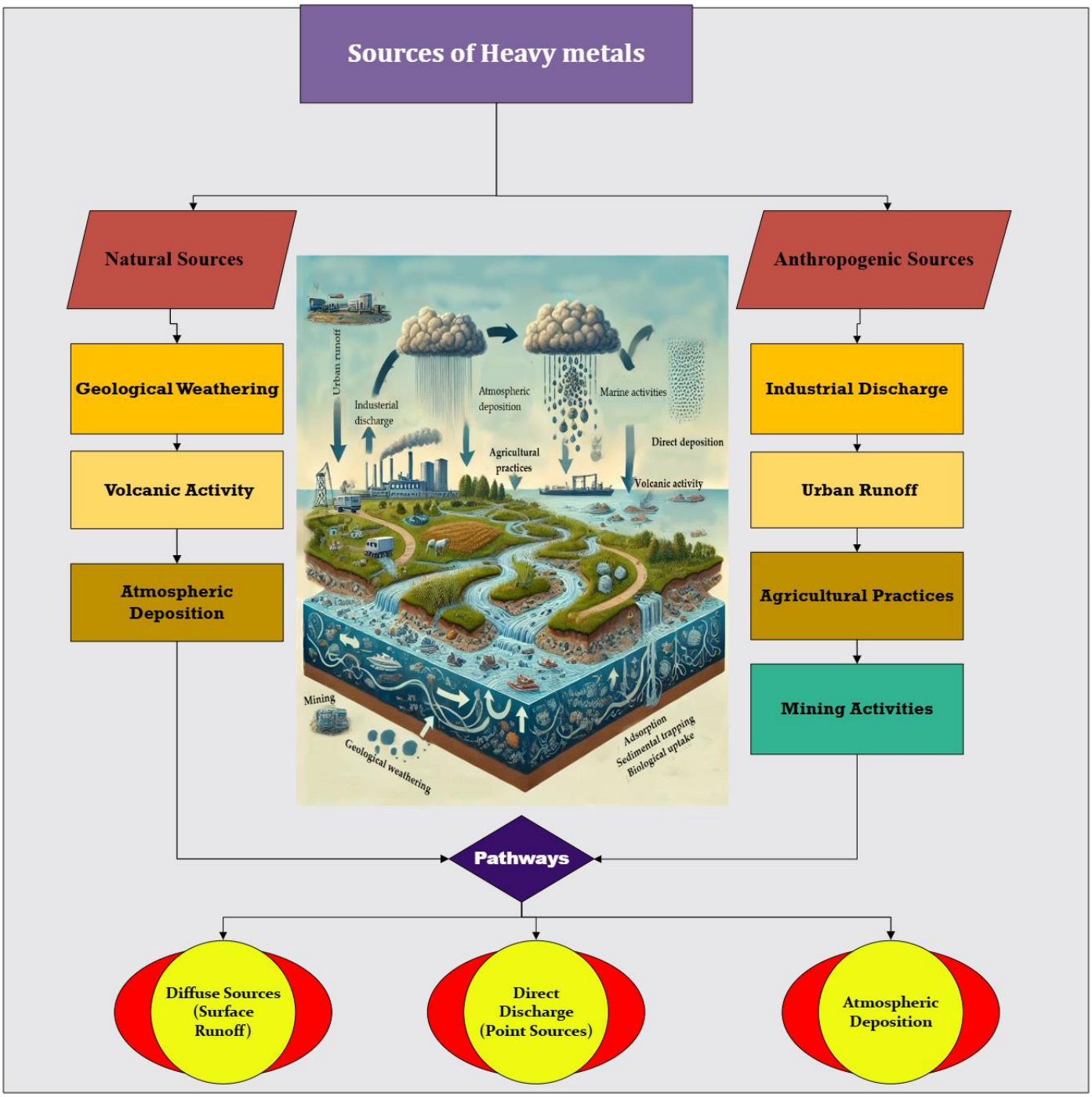

Figure 1. Source and transport pathway of heavy metals in coastal environments.

2.3. Pathways

Once released into the environment, heavy metals can enter coastal wetland sediments through various pathways. These include direct discharge from point sources, such as

industrial outfalls [16] and wastewater treatment plants [18], and diffuse sources, such as surface runoff and atmospheric deposition [19,20]. Suspended particles and dissolved metals can be transported by surface water runoff and deposited in wetland areas, where they accumulate in sediments over time [21]. Additionally, the atmospheric deposition of heavy metals, particularly from industrial emissions and vehicular exhaust, contributes to metal inputs in coastal wetlands [22]. Once deposited, heavy metals can undergo complex biogeochemical transformations, including adsorption onto sediment particles [6], precipitation [23], and dissolution [24], which influence their mobility and bioavailability in wetland sediments. The pathways of heavy metal transport into coastal wetlands are depicted in Figure 1.

Heavy metals exhibit characteristics that contribute to their persistence as pollutants in the environment due to the following factors:

- *Low degradation rates*: Heavy metals cannot be broken down into simpler substances by biological or chemical processes [25]. Unlike organic pollutants, which can be degraded by microorganisms or undergo chemical transformations [26], heavy metals persist in the environment in their elemental form for extended periods.
- *High stability*: Heavy metals are often present in stable chemical forms that resist degradation or transformation [27]. Many heavy metal compounds, such as oxides, sulfides, and complexes with organic matter, have strong chemical bonds that make them resistant to dissolution and decomposition [28].
- *Bioaccumulation:* Heavy metals tend to accumulate in living organisms, a phenomenon known as bioaccumulation [2]. Once introduced into the environment, heavy metals can be taken up by plants and animals and accumulate in their tissues over time [29]. This accumulation may pass through direct exposure to contaminated soil or water and through the assimilation of contaminated food or prey.
- *Bioavailability:* Heavy metals can exist in different chemical forms with varying degrees of bioavailability to organisms [4]. Some forms of heavy metals, such as soluble ions and small particles, are more readily absorbed by organisms and exhibit higher toxicity [30]. Other forms, like complexed or adsorbed metals, may be less bioavailable but can still pose risks if emitted to the surroundings [31].
- *Persistence in sediments*: Heavy metals have a high affinity for binding to sediment particles, particularly those with high surface area and reactive mineral compositions [32]. Once deposited into sediments, heavy metals can remain bound to sediment particles, resisting resuspension and transport in wetland ecosystems [32].
- *Long environmental half-lives*: Heavy metals have long environmental half-lives, meaning they persist in the environment for significant periods before being removed or degraded [33]. Factors like sorption to sediments, slow leaching rates, and limited mobility participated in the prolonged presence of heavy metals in soils, water bodies, and sediments.

3. Distribution and Partitioning

The distribution of heavy metals in coastal ecosystems involves complex interactions between various environmental compartments, including water, sediments, and biota. An overview of how heavy metals are distributed in each of these components is illustrated in the followings:

3.1. Water

Heavy metals can exist in water bodies in both dissolved and particulate forms [34]. Dissolved metals are typically present as free ions or as complexes with inorganic and organic ligands [35]. Particulate-bound metals are associated with suspended particles

in the water column, including mineral particles [36], organic matter [37], and biological debris [38]. These particles can act as transporters for heavy metals, facilitating their transportation and deposition in aquatic environments. These particulate-bound metals are considered bioavailable and can be ingested by aquatic organisms [39].

3.2. Sediments

Sediments serve as sinks for heavy metals in coastal ecosystems, accumulating metals over time through deposition and sedimentation processes [40]. Heavy metals in sediments originate from both natural sources and anthropogenic sources [41,42]. Once deposited into sediments, heavy metals can undergo various biogeochemical processes, including adsorption onto sediment particles [43], complexation with organic matter [44], and precipitation as insoluble compounds [45]. These processes influence the distribution, speciation, and mobility of heavy metals in sediments, affecting their bioavailability and possibly exerting effects on benthic organisms and other biota.

3.3. Biota

Heavy metals could accumulate in biota through processes such as biomagnification and bioaccumulation [46]. Bioaccumulation occurs when organisms absorb metals from their surrounding environment, either through direct uptake from water or sediments or from contaminated food ingestion [47,48]. However, biomagnification appeared when the concentration of metals increases at higher trophic levels in the food chain [49]. Predatory organisms at the top of the food chain, such as fish and birds, may accumulate extensive amounts of heavy metals because of the progressive effect of bioaccumulation along the food chain [50]. The accumulation of heavy metals in biota can have adverse effects on their health and survival, leading to impaired physiological functions, reproductive abnormalities, and population declines [51].

4. Partitioning Processes of Heavy Metals in Coastal Ecosystems

4.1. Adsorption

Adsorption is a key operation that influences the partitioning of heavy metals between water and sediment phases in coastal ecosystems [6]. When heavy metals are released into aquatic environments, they interact with sediment particles through adsorption processes. Sediment particles, particularly those with high surface area and reactive mineral compositions (e.g., clay minerals, iron oxides), provide bound areas for heavy metal ions [52]. Heavy metal ions adsorb onto the surfaces of sediment particles through electrostatic attraction [53], ion exchange [54], and surface complexation reactions [6]. The extent of metal adsorption onto sediment particles relies on different criteria, including the concentration of heavy metal ions in the water column [55], the surface area and mineral composition of sediment particles [56], the occurrence of competing ions [43], and environmental conditions like pH and redox potential [24]. Adsorption onto sediment particles effectively removes heavy metals from the water column, reducing their quantity and bioavailability to aquatic organisms [57]. However, adsorbed metals can potentially desorb back into the water column under certain conditions, leading to metal remobilization and secondary contamination of water bodies [58].

4.2. Desorption

The desorption of heavy metals in coastal ecosystems is influenced by the pH, salinity, redox potential, and competing ions. Acidic conditions enhance the release of metals like Cd, Pb, and Zn due to weaker sediment binding, while high salinity promotes ion exchange, replacing adsorbed metals with Na^+ and Cl^- ions [43,59]. Dissolved organic

matter, including humic substances, facilitates desorption by forming metal complexes, increasing mobility [60]. Redox fluctuations also drive metal release, with reducing conditions dissolving Fe and Mn oxides to release associated metals, while oxidizing states promote precipitation [61]. Anthropogenic inputs further destabilize metal–sediment bonds through chelating agents and acids, enhancing desorption [57]. Understanding these mechanisms is crucial for predicting heavy metal behavior and guiding effective contamination management strategies in coastal ecosystems.

4.3. Sedimentation

Sedimentation plays a crucial role in the partitioning of heavy metals between bottom sediments and suspended particulate matter in coastal ecosystems. Suspended particles, including mineral particles, organic matter, and biological debris, serve as carriers for heavy metals in the water column [62]. Heavy metals associated with suspended particles can undergo sedimentation processes, whereby particles settle out of the water column and accumulate on the sediment bed. Sedimentation rates depend on characteristics like particle size, density, and settling velocity, as well as hydrodynamic conditions such as water flow and turbulence [63]. Over time, deposited heavy metals like Ni, Cr, Fe, and Mn may become incorporated into sediment layers through compaction and burial, reducing their potential for remobilization and exchange with the water column [33]. Sedimentation processes contribute to the long-term storage of heavy metals in coastal sediments, where they can persist for extended periods and serve as potential sources of contamination to benthic organisms and other biota [64].

4.4. Bioaccumulation

Bioaccumulation is the process by which heavy metals accumulate in the tissues of living organisms, including plants, animals, and microorganisms, through uptake from the surrounding environment [47]. Those heavy metals can undergo biomagnification, as previously mentioned, along the aquatic food chain, whereby predators at higher trophic levels, including fish and birds, accumulate higher concentrations of heavy metals than their prey, posing risks to ecosystem health and human consumption [65].

These processes interact dynamically to influence the partitioning and fate of heavy metals in coastal ecosystems. Understanding these processes is essential for assessing the ecological risks associated with metal contamination and developing effective management strategies to mitigate their impacts on coastal ecosystems and human health.

5. Mechanisms and Behaviors of Heavy Metals Biogeochemical Processes

5.1. Adsorption/Desorption

Adsorption and desorption onto sediment particles constitute the primary mechanism for heavy metal retention in coastal wetland sediments. These interactions are significantly affected by the physico-chemical properties of both water and sediments. Characteristics like water pH, salinity, sediment mineralogy, surface area, and cation exchange capacity (CEC) play pivotal roles, as mentioned by Miranda et al. [56]. Minerals possessing high surface area and reactivity, such as clay minerals and iron oxides, exhibit greater adsorption capacity for heavy metals, as reported by Otunola and Ololade [66].

5.2. Complexation

Complexation with organic matter and sulfides can increase the retention of heavy metals in coastal wetland sediments [67]. Organic matter, derived from decaying plant and animal debris, contains functional groups that can form complexes with heavy metal ions, reducing their bioavailability and mobility [68]. Organic functional groups, like

carboxylic and hydroxyl groups in humic substances, play a vital role in binding heavy metals onto mineral-humic complexes [69]. For instance, a study by Nie and Bi [70] reported that Cd adsorption onto hematite–humic acid composites decreased at pH (4) due to the presence of carboxylic groups and highlighted its role in electrostatic binding. However, the complexation capacity of heavy metal increases with the existence of humic substances, enhancing the retention of (hydro)oxide minerals [71]. These interactions alter surface potential and affinity, influencing heavy metal immobilization and transportation in environments like low-pH mine drainages and tropical soils. On the other side, sulfides, as complexation agents derived in anoxic conditions through the sulfate reduction with sulfate-reducing bacteria (SRB), unveil an intricate interplay between biogeochemical processes, sediment characteristics, and metal speciation with heavy metals in coastal wetlands [72]. Sulfides promote the precipitation of metal sulfides, which are highly insoluble and tend to form stable complexes with heavy metals present in the environment, such as As-S [73], Cd-S [74], Mn-S [75], Mo-S [76], and Ni-S [77]. These sulfide-rich sediments often exhibit high levels of organic matter, which serves as a source of carbon and energy for SRB, thereby enhancing sulfate reduction and sulfide production [78].

5.3. Redox Reactions

Redox reactions, driven by microbial activity and sediment biogeochemistry, can influence the speciation and mobility of heavy metals in coastal wetland sediments. Under reducing conditions, certain heavy metals, such as iron and manganese, undergo transformations that affect their solubility and sorption behavior [79]. For example, under anaerobic conditions, iron oxides may be reduced, releasing adsorbed metals into the pore water [80]. Conversely, under oxidizing conditions, heavy metals may be immobilized through precipitation or sorption onto newly formed iron and manganese oxides [81,82].

5.4. Microbial Transformations

Microbial activity in coastal wetland sediments can catalyze transformations of heavy metals through processes such as methylation, demethylation, and reduction. The methylation of metals, like mercury (Hg), by SRB can produce methylmercury, a highly toxic and bio-accumulative form of mercury [83]. While recent studies reveal several kinds of methylators, Gilmour et al. [84] reported that sulfate-reducing and Fe-reducing bacteria demonstrate magnificent methylation rates and typically dominate methylation in their presence, likely due to their abundance in sediment environments. Demethylation processes can also occur, converting methylmercury back to inorganic mercury [85]. The two ways of demethylation that have been reported, which adjust the degradation of methyl components in coastal sediments, are the biotic and abiotic pathways. The biotic pathway occurs due to the activity of Hg-resistant bacteria in environments [86], while the abiotic pathway occurs due to the photochemical process and the absence of sulfide compounds, as reported by Skyllberg et al. [87]. Furthermore, microbial reduction in heavy metal ions can influence their speciation and mobility in sediments, affecting their availability to biota [88,89].

These biogeochemical processes collectively govern the mechanisms and behavior of heavy metals in coastal wetland sediments, influencing their retention, transformation, and availability to resident biota, as shown in Table 1. Understanding these mechanisms is essential for assessing the ecological risks associated with metal contamination and developing effective management strategies to mitigate their impacts on wetland ecosystems.

Table 1. Different mechanisms and behaviors of heavy metal biogeochemical processes.

Key Mechanism(s)	Heavy Metal(s)	Methodology	Environment	Findings and Heavy Metal Behavior	Reference
Adsorption/ Desorption	Lead (Pb), Cadmium (Cd)	Batch experiments with soil columns	Contaminated soils	Strong adsorption of Cd than Pb due to the presence of a competing metal, with desorption increasing in acidic conditions.	[90]
Desorption	Zinc (Zn)	Laboratory desorption experiments	Different contaminated soils	pH < 5.4 triggered Zn release, increasing its mobility in the soil–water system.	[91]
Complexation	Copper (Cu)	Speciation analysis, humic acid titration	Incubation study	40% of Cu bounded to humic acid complexes in non-labile form.	[92]
Complexation	Lead (Pb)	Geochemical modeling, isotherm experiments	Sulfide and ferrous minerals	Pb complexation in sulfide minerals favored at low pH, while Ferrous complexation favored at high pH.	[93]
Redox Reactions	Arsenic (As)	Wet chemistry experiments, bioreactor experiments	Floodplain soils	Mobility of arsenic decreased by 45% during redux conditions bond to changes in OM, mineralogy, and microbial activity	[94]
Redox Reactions	Chromium (Cr)	Sequential extractions, Spectroscopic studies	Wetland contaminated sediments	Cr(III) precipitated in Cr(III)-hydroxides (Fe/Mn-oxides) or trapped in the soil minerals, therefore very tightly bound to the sediment.	[95]
Microbial Transformations	Zinc (Zn), Lead (Pb)	Microbial culture, batch experiments	Tailing-contaminated sand	Sulfate-reducing bacteria removed Zn (II) at 0–40 mg/L; and very strong effects to remove Pb(II) from the solution.	[96]
Microbial Transformations	Mercury (Hg)	Methylation studies, microbial assays	Anaerobic wetland conditions	Molybdate inhibited Hg methylation, exploring the role of SRB.	[97]
Mineral Migration	Lead (Pb), Zinc (Zn), Arsenic (As)	Sequential extraction, simulated physiological media	Mine tailings, agricultural fields	Zn labile fractions increased in oxide-rich tailings, and Pb and As residuals increased in oxic/sulfide-rich tailings.	[98]

Table 1. *Cont.*

Key Mechanism(s)	Heavy Metal(s)	Methodology	Environment	Findings and Heavy Metal Behavior	Reference
Mineral Precipitation	Copper (Cu)	Batch experiment, microbial reactor	Wastewater	Cu precipitated at concentrations (>400 mgL^{-1}).	[99]
Chelation	Copper (Cu)	Sequential extraction, Kinetic modeling	Wetland sediments	At higher pH, chelation by dissolved organic matter occurred, transforming non-residual binding Cu to Cu-SOM complexes.	[100]
Chelation	Zinc (Zn)	Sorption studies, dissolved organic matter analysis	Topsoil samples	Humic and fulvic acids increased Zn mobility by chelation, particularly under alkaditions.	[101]
Bioturbation	Multi-heavy metals	In situ sediment sampling, benthic organism study	Coastal sediments	Bioturbation increased Mn, Co, Ni, and Zn.	[102]
Bioturbation	Cadmium (Cd), Cupper (Cu), and Lead (Pb)	Short-term laboratory experiment	Estuarine sediments	Pb and Cu were precipitated with Fe oxyhydroxides, while 50% of Cd remained dissolved.	[103]
Sorption to Oxides	Arsenic (As)	Thermodynamic modeling, batch adsorption	Oxic/anoxic sediments	As sorbed strongly to Fe oxides in oxic conditions after transformation to lepidocrocite, goethite, or magnetite.	[104]
Sorption to Oxides	Lead (Pb)	Field sampling, laboratory adsorption experiments	Contaminated liquates	Mn(III) complexes could be directly oxidized by PbO_2 to produce Mn oxides.	[105]
Phytoremediation	Lead (Pb), Cadmium (Cd)	Hydroponic experiment, plant tissue analysis	Contaminated soils	Hyperaccumulator plants effectively extracted Pb and Cd from soils, reducing metal concentrations.	[106]
Phytoremediation	Arsenic (As)	Field study, plant tissue analysis	Contaminated soils	*Phragmites australis* absorbed As especially in roots, reducing its concentration in soil.	[107]
Humification	Copper (Cu), Zinc (Zn)	Humic acid analysis, chemical speciation studies	Organic rich soils	Metals like Cu and Zn became less bioavailable as they were bound to humic substances during humification.	[108]
Humification	Cadmium (Cd)	Pot experiment, organic matter analysis	Artificial contaminated soils	Humic acid reduced Se- and Cd-induced growth stimulation and Se and Cd uptake in rice seedlings.	[109]
Sediment Trapping	Cadmium (Cd), Zinc (Zn), Lead (Pb)	Sediment core analysis, geochemical fractionation	Estuarine environments	Fine-grained sediments effectively trapped Cd, Zn and Pb, limiting their remobilization into the water column.	[110]

6. Ecological Impacts

Heavy metal contamination in coastal wetland sediments can have profound ecological consequences for both sediment-dwelling organisms and higher trophic levels within the wetland ecosystem. These impacts include the following:

6.1. Direct Toxicity to Benthic Organisms

Benthic organisms, such as bivalves, polychaetes, and amphipods, are especially vulnerable to heavy metal contamination because of their close association with sedimentary habitats [111]. Exposure to elevated concentrations of heavy metals in sediments can result in chronic and severe toxicity to these organisms, affecting their growth, survival, and reproductive success [112]. Some heavy metals, particularly cadmium and mercury, are known to their direct toxic effects on benthic organisms even at low concentrations, leading to impaired physiological functions and increased mortality [113].

6.2. Bioaccumulation and Biomagnification

Heavy metals that accumulate in coastal wetland sediments can be taken up by sediment-dwelling organisms and subsequently biomagnified along the food chain [114]. Benthic organisms, such as filter-feeding bivalves and deposit-feeding polychaetas, can accumulate high concentrations of heavy metals (i.e., Cd, Cr, Pb, Zn, Cu and Ni) in their tissues through direct uptake from sediment pore water or the ingestion of contaminated sediments [115,116]. These heavy metals can then be carried to higher trophic levels, including fish, birds, and mammals, through the predation and consumption of contaminated prey [117]. The biomagnification and bioaccumulation of heavy metals, particularly mercury, can result in the elevation of heavy metal concentrations in upper trophic level predators, posing risks to ecosystem health and human consumption.

6.3. Alteration of Community Structure and Function

Chronic exposure to heavy metal contamination can alter the community structure and function of coastal wetland ecosystems. Some species of benthic organisms may exhibit tolerance or resistance to heavy metal exposure, leading to shifts in species composition and dominance within benthic communities [118]. Additionally, heavy metals can disrupt ecosystem processes such as nutrient cycling, sediment bioturbation, and organic matter decomposition, which are essential for maintaining wetland productivity and ecosystem stability [119]. Changes in community structure and function can have cascading effects throughout the wetland food web, ultimately impacting ecosystem services such as nutrient cycling, water filtration, and habitat provision [120,121].

6.4. Impacts on Water Birds and Fish Populations

Coastal wetlands are vital habitats for a wide range of avian and fish species, many of which rely on wetland sediments for foraging, nesting, and breeding [122]. Heavy metal contamination in sediments can directly affect these species through the ingestion of contaminated prey or indirect exposure through trophic transfer [123]. Birds that feed on benthic organisms or fish from heavy metal-contaminated wetlands may experience reduced reproductive success, impaired development, and increased mortality due to metal toxicity [124,125]. Similarly, fish populations may suffer from reduced growth rates, altered behavior, and reproductive impairments as a result of heavy metal exposure, leading to population declines and the loss of biodiversity in affected wetland ecosystems [126].

6.5. Implications for Human Health

Heavy metal contamination in coastal wetland sediments can also pose risks to human health through the consumption of contaminated seafood or direct contact with contaminated sediments [127]. Fish and shellfish harvested from metal-contaminated wetlands may accumulate high concentrations of heavy metals in their tissues, posing risks to human consumers and particularly affecting vulnerable populations such as subsistence fishers and coastal communities, which are reliant on seafood for nutrition and livelihoods [128,129].

7. Management Strategies

These ecological impacts highlight the importance of addressing heavy metal contamination in coastal wetland sediments to protect ecosystem health, biodiversity, and human well-being. Effective management strategies that target pollution prevention, remediation, and restoration are essential for mitigating the adverse effects of metal contamination and preserving the ecological integrity of wetland ecosystems. The effective management of heavy metal contamination in coastal wetland sediments requires a comprehensive approach that encompasses pollution prevention, remediation, and restoration efforts. The key strategies include the following.

7.1. Pollution Control Regulations

Effective pollution control regulations are vital for reducing the heavy metals in coastal wetlands, but their success depends on comprehensive design, implementation, and enforcement. Regulatory frameworks typically include setting permissible limits for industrial discharges, establishing stringent wastewater treatment standards, and restricting the use of heavy metal-containing substances in industrial and agricultural practices [130]. However, the absolute existence of these regulations does not guarantee compliance. Weak enforcement mechanisms, lack of regular inspections, and insufficient penalties often undermine their effectiveness, leading to continued pollution. Real-time remote monitoring technologies offer a transformative approach to regulatory enforcement. By enabling continuous tracking of water quality and pollutant levels, these systems can detect violations promptly and reduce the reliance on infrequent manual inspections [131]. For instance, sensors deployed in industrial outfalls or urban runoff channels can monitor key heavy metal concentrations and transmit data to regulatory authorities in real time, allowing for immediate intervention when limits are exceeded. Furthermore, integrating community involvement and stakeholder engagement into the regulatory process can enhance compliance. Public reporting platforms and citizen science initiatives empower local communities to report suspected violations, increasing accountability. However, to address systemic issues, regulations must also consider socioeconomic factors, such as providing financial incentives or technical support for industries and farms to adopt cleaner technologies. The broader challenge lies in harmonizing international and local regulatory frameworks to address transboundary pollution effectively. This is particularly critical for coastal wetlands receiving pollutants from upstream sources or shared watersheds. Strengthening legal frameworks and fostering international cooperation can significantly improve the enforcement of pollution control measures, ensuring the long-term protection of coastal ecosystems.

7.2. Best Management Practices (BMPs)

BMPs, also known as low-impact development practices (LIDs), address hydrology and water quality concerns in both agricultural and urban settings [132]. Implementing BMPs for urban and agricultural land use can help mitigate runoff and erosion, thereby reducing the transport of sediment-bound pollutants, including heavy metals, into wet-

lands. Agricultural BMPs encompass a range of strategies such as contour farming, crop rotation, nutrient management, cover crops, no-tillage, grassed waterways, constructed wetlands, grade stabilization structures, vegetated buffer strips, and blind(tile) inlets [133], In urban areas, common practices include bioretention systems, porous pavements, permeable patios, rain barrels/cisterns, green roofs, wet ponds, and dry ponds, which are aimed at treating stormwater runoff quantity and quality [134]. Constructed wetlands and ponds are large-scale practices typically implemented at drainage outlets to manage stormwater runoff, while smaller-scale practices like buffer strips, bioretention systems, and green roofs are distributed throughout the site at pollution sources [135,136]. These BMPs encompass a variety of measures, including vegetative buffers, erosion control structures, stormwater management practices, and soil conservation techniques [137]. By minimizing the influx of sediment-bound pollutants into wetland ecosystems, BMPs play a crucial role in safeguarding sediment quality and reducing the risks of metal contamination of wetland biota [137,138].

7.2.1. Remediation Techniques

Remediation techniques aim to mitigate existing contamination and restore sediment quality in impacted wetland areas [139]. Common remediation techniques for heavy metal-contaminated sediments include the following:

- *Sediment Dredging:* Engineering solutions, such as dredging, sediment stabilization, and in situ treatment technologies, are commonly employed to remediate heavy metal contamination in coastal areas [140]. Dredging involves the mechanical removal of contaminated sediments from water bodies, followed by disposal or treatment [141]. Sediment stabilization techniques, such as solidification and stabilization, aim to immobilize contaminants in situ by adding amendments such as cement or lime to sediments [142]. In situ treatment technologies, such as chemical oxidation/reduction and microbial remediation, utilize chemical or biological agents to transform or degrade contaminants in sediments [143]. Engineering solutions offer flexibility and scalability for addressing heavy metal contamination in coastal environments, but their effectiveness depends on site-specific conditions and the nature of the contaminants.
- *Capping:* Sediment capping involves placing a layer of clean sediment or engineered materials over contaminated sediments to isolate and contain the contaminants [144]. Capping can effectively reduce the exposure of benthic organisms to heavy metals and prevent the resuspension and redistribution of contaminated sediments. Engineered caps may include materials such as activated carbon [145], clay minerals [66], and Zeolite [146], which enhance contaminant immobilization and minimize heavy metal leaching into the water column. Sediment capping has been successfully applied in coastal areas to remediate contaminated sediments and restore habitat quality [147]. However, challenges such as long-term stability, cap integrity, and potential ecological impacts must be carefully considered when implementing sediment capping projects in coastal environments [144].

7.2.2. Phytoremediation

Phytoremediation has emerged as a promising strategy for remediating heavy metal contamination in coastal areas, utilizing plants to extract, stabilize, or degrade heavy metals in contaminated soils and sediments [148]. Through mechanisms such as phytoextraction, rhizo-filtration, and phytostabilization, plants have the capability to accumulate heavy metals in their tissues without disturbing the topsoil, making it an eco-friendly method [149,150]. In coastal environments, wetland plants like salt marsh grasses and mangroves have been investigated for their potential to remediate heavy metal-contaminated

sediments [151]. These plants absorb heavy metals such as Cu, Zn, As, Pb, Fe, Cd, Hg, and Co from sediment pore water, accumulating them in their roots, shoots, and leaves, thereby reducing metal concentrations in the sediment and water column [152]. Phytoremediation offers several advantages, including low cost, minimal environmental impact, and potential co-benefits like habitat restoration and carbon sequestration [153,154]. Establishing plants in contaminated soil yields ecological and economic benefits through phytostabilization; phytoextraction of precious metals like Hg, Ag, and Ni; sustainable land management; and soil utility and fertility improvement [155]. Plant-based strategies in phytoremediation encompass phytostabilization, phytodegradation, phytovolatilization, phytofiltration, and phytoextraction [156].

7.2.3. Monitoring and Adaptive Management

The regular monitoring of sediment quality, contaminant levels, and ecological indicators is essential for assessing the effectiveness of management strategies and identifying emerging threats. Monitoring programs should include spatial and temporal assessments of heavy metal concentrations in sediments, pore water, and biota, as well as ecological surveys to evaluate changes in wetland habitat quality and biodiversity [157]. Adaptive management approaches, which integrate monitoring data with management decision-making processes, allow for ongoing refinement and adjustment of management strategies based on new information and changing environmental conditions [158]. Sediment quality indicator research was carried out to determine the dangers of heavy metals in the sediments of Nador Lake (Morocco) [159]. The study confirmed that heavy metal contamination is critical for assessing the health of coastal ecosystems and developing monitoring programs that are compliant with the Mediterranean Action Plan—Barcelona Convention System. It also aids in identifying pollution sources, routes, and hotspots, allowing policymakers to execute targeted pollution prevention and control measures in accordance with Convention procedures. Furthermore, such studies contribute to better knowledge of environmental risks and susceptibility in coastal areas, while also informing decision-making processes for land use planning, industrial operations, and waste management within the framework of integrated coastal zone management.

7.2.4. Stakeholder Engagement and Education

Engaging stakeholders, including government agencies, industry representatives, local communities, and conservation organizations, is critical for fostering collaboration and shared responsibility in managing heavy metal contamination in coastal wetlands. Public education and outreach initiatives can raise awareness about the importance of wetland conservation, the risks of heavy metal pollution, and the benefits of adopting sustainable land use practices. Building partnerships and fostering community involvement can help mobilize support for conservation efforts and ensure the long-term protection of wetland ecosystems [160].

These management strategies, as shown in Figure 2, provide a framework for addressing heavy metal contamination in coastal wetland sediments and safeguarding the health and integrity of these valuable ecosystems. By integrating pollution prevention, remediation, monitoring, and stakeholder engagement efforts, it is possible to mitigate the adverse effects of metal contamination and promote the sustainable management of coastal wetlands.

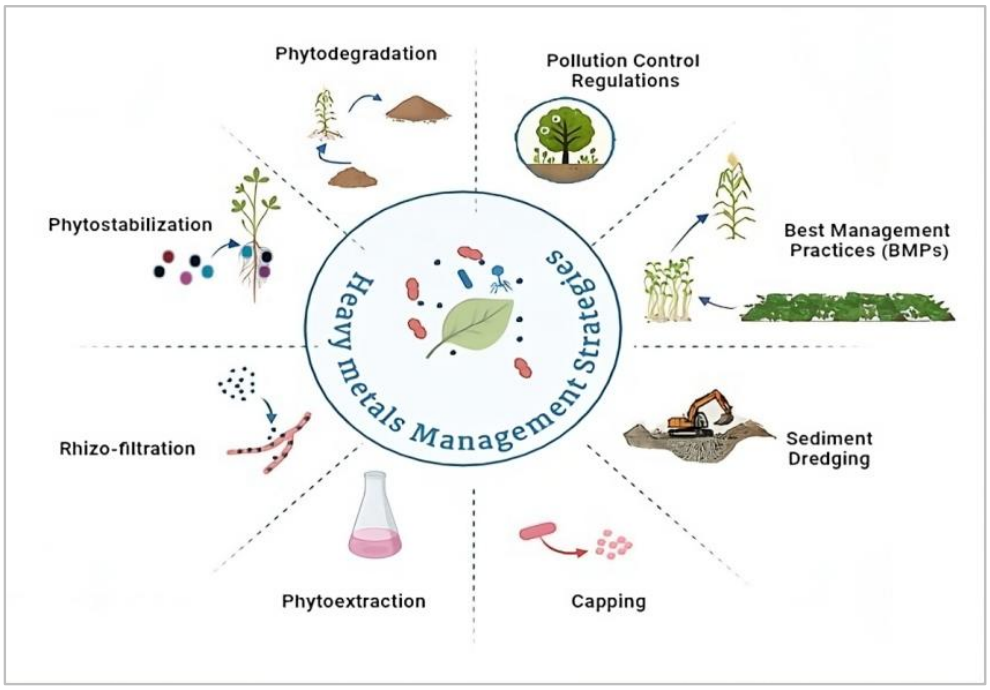

Figure 2. Different heavy metals management strategies.

8. Challenges and Limitations of Remediation Efforts:

Remediating heavy metal contamination in coastal areas presents numerous challenges and limitations that can hinder the effectiveness of remediation efforts. These challenges arise from the complex interactions between contaminants, environmental matrices, and ecological processes and technical, logistical, and financial constraints. Several key challenges and limitations include the following:

- *Persistence and long-term stability*: Heavy metals are known for their persistence and long-term stability in the environment, posing challenges for remediation efforts [161]. Their binding to sediment particles and subsequent incorporation into stable mineral phases reduce their bioavailability but also increase their resistance to natural attenuation [162]. Even after remediation activities, residual contamination may remain in sediments and water bodies, leading to potential risks of recontamination and ecological impacts over time [163]. This persistence necessitates long-term monitoring and maintenance to ensure the sustainability of remediation efforts [164].
- *Limited remediation technologies*: Phytoremediation, sediment capping, and in situ treatment offer potential benefits, but their feasibility and efficiency depend on site-specific conditions, contaminant characteristics, and project goals [140]. However, the available remediation technologies for addressing heavy metal contamination in coastal areas are often limited in their effectiveness and applicability [165]. Phytoremediation, for instance, requires extensive time and space to achieve measurable results, and its effectiveness is reduced in saline or waterlogged soils typical of coastal environments [166]. Similarly, in situ treatments using chemical amendments may face challenges related to uneven distribution and unpredictable interactions with natural sediment matrices [167]. The limited scalability and adaptability of these technologies highlight the need for advancing integrated and hybrid approaches tailored to local conditions.
- *Site complexity and heterogeneity*: Coastal environments are distinguished by high levels of complexity and heterogeneity, which can complicate remediation efforts [168]. It exhibits high spatial and temporal variability due to dynamic processes such as tidal action, sediment transport, and organic matter deposition [169]. Factors such as

hydrodynamic processes, sediment dynamics, and biological interactions can influence the distribution and fate of contaminants [170], making it challenging to achieve uniform remediation outcomes across different sites. These factors create heterogeneous contaminant distributions, complicating remediation efforts [171]. For example, hydrodynamic forces may redistribute contaminants following dredging or capping activities, while sediment heterogeneity can lead to uneven treatment outcomes [172]. Addressing these complexities requires a detailed understanding of site-specific processes and advanced modeling tools to predict contaminant behavior accurately.

- *Ecological impacts and trade-offs:* Remediation activities may have unintended ecological impacts and trade-offs that should be carefully considered [173]. For example, dredging and sediment capping projects may disturb benthic habitats and disrupt ecosystem functions [174], while chemical treatments may introduce additional risks to non-target organisms and sediment quality [175]. These trade-offs highlight the importance of adopting ecologically sensitive approaches and conducting comprehensive risk assessments before implementing remediation strategies [164].
- *Cost and resources:* Remediating heavy metal contamination in coastal areas can be costly and resource-intensive, requiring significant investments of time, labor, and financial resources [176,177]. The high costs associated with remediation activities may limit the feasibility of large-scale projects and impede efforts to address contamination in economically disadvantaged communities. Techniques such as sediment dredging and ex situ treatment often require substantial investments in specialized equipment, labor, and long-term maintenance [178]. The high costs can be prohibitive for economically disadvantaged regions, where limited financial resources constrain the scope and ambition of remediation projects [179]. Exploring cost-effective alternatives, such as the use of locally sourced amendments or community-driven phytoremediation initiatives, can help address these disparities [180].
- *Regulatory and stakeholder concerns*: Regulatory requirements and stakeholder concerns can present barriers to implementing remediation projects in coastal areas [179]. Permitting processes, compliance with environmental regulations, and stakeholder engagement activities may add complexity and delays to remediation efforts, affecting project timelines and outcomes [181]. Additionally, opposition from local communities or interest groups may arise due to perceived risks or inadequate communication, further complicating efforts [182]. Transparent engagement with stakeholders and proactive conflict resolution strategies are essential for overcoming these barriers and ensuring the success of remediation initiatives.

9. Future Directions and Research Needs

Identifying gaps in current knowledge and areas for future research is crucial for advancing our understanding of heavy metal contamination in coastal areas and improving remediation strategies. Based on our suggestions, these are some key gaps and research needs in this field, which are presented in Figure 3.

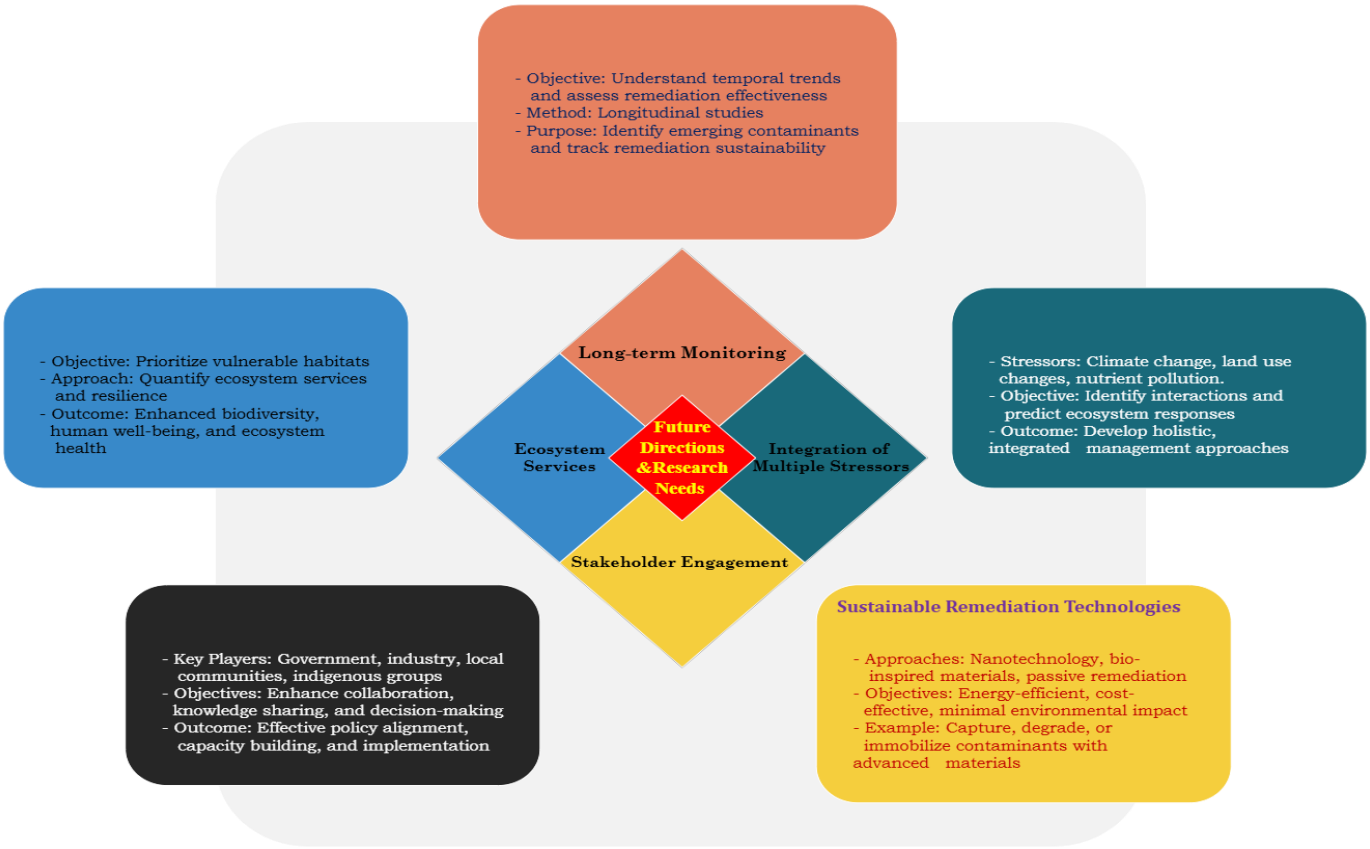

Figure 3. Future directions and research need for heavy metal remediation strategies in coastal areas.

9.1. Long-Term Monitoring and Assessment

The need for long-term monitoring and assessment of heavy metal contamination in coastal environments cannot be overstated, as it plays a critical role in evaluating the sustainability of remediation efforts and ensuring environmental safety. While scientific research often relies on discrete, short-term studies, governmental agencies and environmental organizations conduct continuous monitoring programs supplemented by random inspections when necessary [183–185]. These systematic efforts are essential for understanding temporal trends, identifying emerging contaminants, and assessing the effectiveness of implemented strategies. Long-term monitoring initiatives, supported by regulatory frameworks and advanced technologies, provide a foundation for evaluating the cycling, fate, and transport of heavy metals in dynamic coastal ecosystems [186]. Such programs not only track contamination levels but also assess the impacts of environmental changes, including climatic variations and anthropogenic activities, on heavy metal distribution. Random inspections conducted alongside routine monitoring further enhance the detection of unexpected pollution events, ensuring rapid response and mitigation. Longitudinal studies, which involve extended observation of variables without direct intervention, are invaluable for gaining a deeper understanding of heavy metal dynamics in coastal systems. These studies offer insights into the long-term stability of contaminants, the interplay between natural processes and remediation efforts, and the cumulative ecological impacts of heavy metal contamination. Moreover, they help to evaluate the sustainability of remediation strategies by examining their effectiveness over extended periods, thereby supporting adaptive management approaches. Integrating continuous monitoring with targeted research facilitates a comprehensive understanding of coastal ecosystems, informing policy decisions and management practices. By combining the efforts of scientists, regulatory

agencies, and other stakeholders, long-term monitoring and assessment programs ensure the protection and sustainability of coastal environments for future generations.

9.2. Integration of Multiple Stressors

In planning future research attempts, it is essential to prioritize the integration of multiple stressors, including climate change, land use changes, and nutrient pollution, into assessments of heavy metal contamination in coastal areas [187–189]. Understanding the interactions between heavy metals and other environmental stressors is essential for predicting ecosystem responses, identifying vulnerable areas [190], and developing integrated management approaches that address multiple stressors simultaneously. By integrating multiple stressors into research frameworks, scientists can gain a more comprehensive understanding of the complex dynamics shaping coastal environments. This holistic approach enables the development of integrated management strategies that effectively address the cumulative impacts of various stressors, thereby enhancing ecosystem resilience and sustainability. Moreover, such integrated approaches facilitate the identification of synergies and trade-offs among different stressors, offering valuable insights for informed decision-making and adaptive management practices in coastal regions.

9.3. Mechanistic Understanding of Remediation Processes

To enhance the effectiveness and applicability of remediation processes such as phytoremediation, sediment capping, and in situ treatments in coastal environments, there is a critical need for a mechanistic understanding of these processes [139,177,191]. Research efforts should prioritize elucidating the underlying mechanisms governing contaminant uptake, transformation, and immobilization by remediation agents, as well as their interactions with environmental matrices. A comprehensive mechanistic understanding of remediation processes is essential for optimizing their performance and ensuring their long-term sustainability. By unraveling the intricate pathways through which remediation agents interact with contaminants and environmental components, scientists can identify key factors influencing remediation efficiency and tailor strategies accordingly. This deeper understanding enables the development of more targeted and efficient remediation approaches that minimize unintended consequences and maximize environmental benefits. According to Malyan et al. [192], a comprehensive review includes the complicated set of mechanisms and processes connected such as in a constructed wetland system (CWS), various kinds of CWS, the importance of different CWS component parts (i.e., macrophytes, substrate, microbes), and the impact of many factors (i.e., water flow regime, hydraulic retention time, hydraulic loading rate) affecting removal mechanisms and treatment efficiency for different CWS types.

9.4. Assessment of Ecological Risks and Ecosystem Services

Heavy metals are one of the most dedicated pollutants in coastal environments, and they have received widespread interest due to their natural toxicity, persistence, and bioaccumulation characteristics, becoming a significant threat to the ecological health, aquatic diversity, and ecological quality status of coastal marine ecosystems [193]. Future research should prioritize the assessment of ecological risks associated with heavy metal contamination in coastal areas and evaluate the potential impacts on ecosystem services [194,195]. Beyond simply identifying contamination sources and mechanisms, a comprehensive evaluation should address how heavy metals interact with various biophysical components to disrupt ecological processes and services. For instance, heavy metal toxicity can alter primary productivity, nutrient cycling, and food web dynamics, leading to cascading effects on biodiversity and ecosystem stability [196]. These disruptions compromise critical services such as carbon sequestration, water purification, and coastal protection, which

are vital for maintaining ecological and human well-being [197]. Assessing such risks requires integrating environmental data with ecological modeling to predict long-term impacts and identify thresholds beyond which ecosystems may lose their resilience. Integrated risk assessments can help identify vulnerable habitats, prioritize remediation efforts, and quantify the benefits of remediation in terms of ecosystem resilience, biodiversity conservation, and human well-being. By quantifying the ecological and economic trade-offs of remediation efforts, researchers can better prioritize actions that maximize ecosystem resilience and biodiversity conservation while supporting sustainable development goals [198]. Moreover, advanced methodologies like life cycle analysis, ecosystem valuation, and participatory stakeholder approaches can enhance the assessment of ecological risks and ecosystem services. These tools provide a multidimensional perspective that captures the interconnectedness of environmental, economic, and social factors, enabling more informed decision-making [199].

9.5. Development of Sustainable Remediation Technologies

The advancement of sustainable remediation technologies is imperative to mitigate environmental impacts, minimize energy consumption, and reduce costs, all while maximizing efficiency and effectiveness [200,201]. Research efforts are necessary to focus on the design and optimization of innovative remediation approaches, tailored to coastal areas, where heavy metal contamination poses significant challenges. Researchers should prioritize the exploration of novel remediation strategies, including nanotechnology-based treatments, bio-inspired materials, and passive remediation techniques, which offer promising avenues for sustainable remediation [154,202–205]. Nanotechnology holds immense potential for targeted and efficient remediation by leveraging the unique properties of nanoparticles to capture, immobilize, or degrade contaminants with minimal environmental impact. Bio-inspired materials, inspired by natural processes and organisms, offer sustainable solutions that mimic biological systems to remediate heavy metal pollution effectively. Additionally, passive remediation techniques harness natural processes such as plant uptake, microbial degradation, and chemical precipitation to achieve remediation goals without the need for active intervention.

9.6. Stakeholder Engagement and Knowledge Exchange

Effective stakeholder engagement and knowledge exchange are essential for bridging the gap between research, policy, and practice in managing heavy metal contamination in coastal areas [206]. Future research should prioritize collaborative approaches that involve stakeholders, including government agencies, industry partners, local communities, and indigenous peoples, in decision-making processes, capacity building, and knowledge co-production initiatives [207].

10. Conclusions

This review highlights the complex dynamics of heavy metal contamination in coastal ecosystems, emphasizing its multifaceted risks to biodiversity, ecosystem functionality, and human health. Through an in-depth analysis of sources, pathways, and mechanisms, it is evident that the persistence of heavy metals in sediment and water matrices poses significant challenges for remediation and risk mitigation. The interplay of physical, chemical, and biological processes, such as adsorption, desorption, and redox transformations, governs the distribution and mobility of heavy metals, necessitating tailored and site-specific approaches to remediation. Current remediation methods, including phytoremediation, sediment capping, and in situ treatments, demonstrate varying degrees of effectiveness but are often limited by ecological trade-offs, site heterogeneity, and technical constraints. While

emerging technologies, such as nanomaterials and biochar amendments, offer promising avenues for enhancing remediation efficiency, their long-term stability and environmental safety require further investigation. To address these challenges, advancing mechanistic understanding and integrating interdisciplinary research are paramount. Developing predictive models that incorporate heavy metal behavior, ecosystem services, and socio-economic factors can improve decision-making and prioritize interventions. Additionally, the effectiveness of pollution control regulations and real-time monitoring technologies must be reinforced through stakeholder collaboration and stronger enforcement mechanisms. Ultimately, safeguarding coastal ecosystems from heavy metal contamination demands a holistic and adaptive management framework. By leveraging scientific insights and fostering collaboration among policymakers, researchers, and local communities, we can achieve sustainable solutions that balance ecological conservation with societal needs. Future efforts must focus on bridging knowledge gaps, refining remediation technologies, and enhancing our capacity to mitigate the long-term impacts of heavy metal contamination on these critical ecosystems.

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