REVIEW ON; THE HEAVY METAL FILTRATION EFFICIENCY OF MANGROVE ROOT SYSTEMS

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Abstract

Mangrove forests are unique coastal ecosystems that play an important role in reducing pollution, especially from heavy metals. These pollutants, including lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn), often enter coastal waters from industries, aquaculture, and urban development. Mangrove roots act as major sinks for Pb, Cd, Cu, and Zn, with metals concentrated in roots rather than aerial parts, reducing ecological risks. Avicennia marina effectively immobilizes Zn and Cu, Rhizosphere microdata accumulates higher Cu and Zn, while Kandelia candel shows strong Cd and Pb retention. Sediment properties such as grain size, organic matter, and redox potential regulate metal availability, and ecological studies confirm mangroves also act as bio indicators of contamination severity. Heavy metal retention in mangroves happens through several processes such as trapping sediments, changes in soil chemistry around roots, and natural barriers in roots that block metals from moving upward. Laboratory studies explain how metals are stored at the cellular level, while field studies show that factors like salinity, water flow, and seasonal changes affect how metals behave in real ecosystems. Studies from around the world, including Sri Lanka, show that the ability of mangroves to filter metals depends on soil chemistry, tidal flows, and human activities. Protecting and restoring mangrove ecosystems is therefore vital for sustainable coastal management, bioremediation, and long-term environmental safety.This document is a template for Microsoft Word for the submission of a full four-page paper to ICPIES conference. This electronic document is a "live" template. The various components of your paper [title, text, heads, etc.] are already defined on the style sheet, as illustrated by the portions given in this document. Keywords: Mangroves, Heavy metals, Bioaccumulation, Filtration efficiency, Coastal pollution

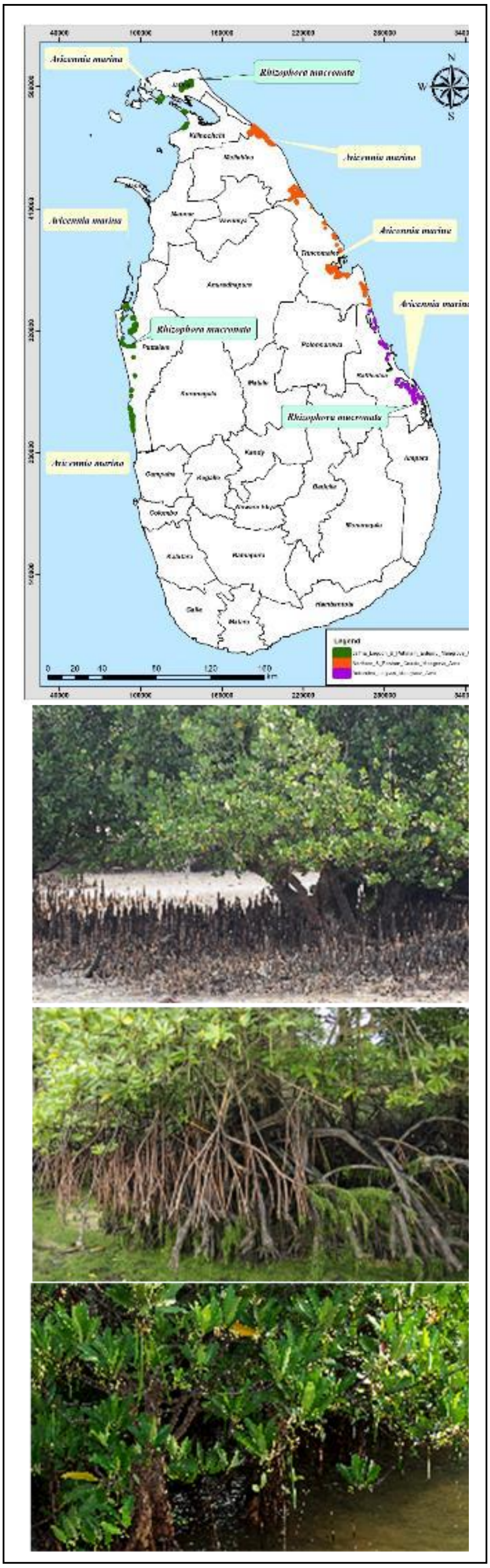
I. Introduction

Coastal environments worldwide are increasingly affected by heavy metals (HMs) contamination due to accelerated urbanization, industrialization, mining runoff, aquaculture, sewage discharge, and atmospheric deposition[1], [2].Once released into estuarine systems, heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu) tend to bind with suspended particulates. These particulates are eventually deposited into fine-grained sediments, where they accumulate and persist over long timescales due to their non-degradable nature [1].In these dynamic and often anoxic environments, trace metals interact with organic matter, sulfides, and iron/manganese oxides, creating vertical and lateral gradients in metal concentration across sediment layers [2], [3]. This spatial variability is particularly significant in mangroves near urban and industrial areas, such as those in Hong Kong, Vietnam, and the Persian Gulf[4].

Mangrove ecosystems are coastal forests made up of salt-tolerant trees that are important parts of tropical and subtropical shorelines[5].These forests are located at the interface of land and sea, which deliver essential ecosystem services, including shoreline stabilization, sediment trapping through their complex root systems.Mangroves intertidal forests dominated by halophytic tree species serve as natural bio filters in these contaminated estuarine environments, offering a biologically active interface for sediment water metal interactions. Their unique root structures, such as pneumatophores, cable roots, and lenticels are enhance sediment deposition, aeration, and metal complexation [5]. Numerous studies have emphasized that mangrove roots can accumulate high concentrations of metals such as Cu, Pb, Zn, and Cd, particularly in species like Avicennia marina, Rhizophora apiculata, and Kandelia candel [6], [7].

Figure 1-Geographic Distribution of Mangroves Species across Sri Lanka

In Sri Lanka's Batticaloa Lagoon, Avicennia marina demonstrated limited lead (Pb) accumulation in root tissues under dry-season and high-salinity conditions [8]. Similarly, studies in Jaffna Lagoon and Puttalam estuaries showed that sediment properties especially grain size and organic matter are strongly influenced Pb and Zn retention, while root tissues of Avicennia marina and Rhizophora mucronata acted as sinks for metals under different hydrological regimes [9]. These findings not only highlight the filtration efficiency of Sri Lankan mangroves but also emphasize their ability for integration into region-specific bioremediation strategies.



Metal accumulation primarily concentrated in the root cortex and endodermis, aided by anatomical barriers and biochemical processes such as lignification and phytochelatin production, These process effectively prevent upward translocation of metals and thereby reducing ecological risk to herbivores and decomposers[7], [10]. Review studies have emphasized that mangrove species differ significantly in their metal uptake capacities, with variations linked to both species-specific physiology and sediment geochemistry [5], [11]. Meta-analyses further reveal that accumulation is often higher in fine sediments with high organic content and low redox potential, conditions typically found in mature mangrove stands[1]. Several regional assessments highlight that while mangrove roots act as effective sinks for metals, long-term stability and potential remobilization of these contaminants under changing environmental conditions remain poorly understood[4], [12].

Accordingly, this research aims to evaluate the role of mangrove root systems as natural filters for heavy metals removal in coastal environments, to assess heavy metal bioaccumulation in different mangrove species as indicators of environmental health, and explore the potential of incorporating of mangrove ecosystems into region specific bioremediation strategies for improved heavy metal removal in water treatment applications. Procedure for Paper Submission

Methods and materials

A systematic review approach was employed to assess existing research on the heavy metal filtration efficiency of mangrove root systems in coastal environments. An initial search across academic databases, including as Google Scholar, Science Direct, and lens.org, total of 171 peer-reviewed articles were identified. Following a rigorous process screening process to remove duplication and exclude studies lacking methodological robustness, 34 articles were selected for in-depth analysis based on predefined inclusion and exclusion criteria. The reviewed literature was then categorized into six major themes:(1) Heavy Metal Accumulation and Bioaccumulation in Mangrove Ecosystem, (2) Ecological Overview of Heavy Metal Accumulation in Mangrove Root Systems, (3) Heavy Metal Filtration Capacity in Mangrove Root Systems, (4)Research Methodologies and Case Studies, (5)Impact of Heavy Metals on Mangrove Physiology,(6)Future Perspectives and Recommendations. These studies provided insights into mangroves species with metal uptake, sediment characteristics, and root morphological factors influencing bioaccumulation.

1. *Heavy Metal Accumulation and Bioaccumulation in Mangrove Ecosystem*

Heavy metal accumulation in mangrove ecosystems is driven by the interaction between mangrove species physiological features and sediment characteristics. Mangrove roots serve as the primary sites of metal storage, effectively immobilizing contaminants and reducing their upward transfer into stems and leaves [11], [13].

1.1Mangroves Species with Sediment Interactions in Heavy Metal Accumulation

Mangrove ecosystems are identified as critical accumulators for heavy metals, with species such as Avicennia marina, Rhizophora mucronata, and Kandelia candel widely reported as efficient bioaccumulators. According to [11] and [13] heavy metals including Pb, Cd, Zn, Cu, and Fe are predominantly stored in root tissues, limiting their translocation to aerial parts and thereby reducing ecological risk through the food web. The geographic distribution of these mangrove species across key coastal lagoons in Sri Lanka, along with the associated heavy metal types, is illustrated in Figure 1.

Avicennia marina is one of the most widely distributed mangrove species. It is particularly effective at immobilizing metals in its roots. Studies show that A. marina roots accumulate high concentrations of Zn, Cu, Pb, Cd, Ni, and Cr, largely due to the strong binding affinity of root cell walls and the barrier function of the Casparian strip [11]. These features allow A. marina to serve as a reliable bio indicator of sediment contamination, especially in lagoons and estuaries with high pollution pressure.

Rhizophora species, exhibit distinct accumulation patterns. Research in Tamil Nadu, India, demonstrated that Rhizophora mucronata and related species retained significantly higher amounts of Cu and Zn compared to A. marina, even under similar sediment conditions [14]. This suggests that species physiological features such as differences in root permeability, exudation of chelating compounds, and selective ion uptake play an important role in determining bioaccumulation levels.

Kandelia candel, though less studied compared to Avicennia and Rhizophora, has been shown to effectively accumulate Cd, Pb, and Zn in root tissues, with limited transfer to leaves. The structural adaptations in its roots, including thickened outer root layers, may enhance tolerance under heavy metal stress [13].

1.2 Sediment Characteristics and Heavy Metal Profiles

The interaction between mangrove physiology and sediment characteristics strongly influences accumulation efficiency. Sediment properties such as pH, organic matter, and redox potential influence metal solubility and bioavailability. In Hong Kong's Mai Po Marshes, for example, copper and zinc levels in sediments were closely reflected in root concentrations [14], [15].However, differences among species can sometimes more important than sediment effects. Rhizophora species consistently show higher Cu and Zn accumulation than Avicennia marina [16]. These patterns show that both sediment conditions and species features like root barriers, phytochelatin production, and metal storage are important for controlling bioaccumulation in mangrove ecosystems.

Research looking at many sites show that mangrove sediments usually contain a lot of Fe, followed by Cr, Ni, Mn, and Zn [17]. However, how much of these metals plants take up differs by species.Fe often stays in the roots because it forms oxides in oxygen-poor soils, while Mn and Zn move more easily into leaves. These differences show that mangroves act as natural filters that control heavy metal movement in coastal areas.

[17] found that sediment metal concentrations followed the order Fe > Cr > Ni > Mn > Zn. Metal accumulation, assessed using bio concentration and translocation factors, varied with metal type, mangrove species, and plant tissue. Overall, most metals were strongly sequestered in roots, minimizing upward transport, whereas Mn showed comparatively higher accumulation in leaves. This root-dominated accumulation pattern is a consistent feature of mangrove bio filtration capacity across regions.

1.3 Human and Environmental Influences on Heavy Metal Bioaccumulation

Human activities also strongly influence on heavy metal accumulation in mangrove ecosystems.[1] Emphasized that In New Caledonia, Fe and Ni from natural erosion were less available to mangroves, whereas Cu and Zn were more available due to organic sediments and human inputs. Similarly, [18] in the Cochin Estuary, India, documented significantly higher Pb and Cd concentrations in mangrove roots located near industrial zones compared to less disturbed sites. These findings highlighted the spatial variability in accumulation due to human activity.

Bioaccumulation also changes with seasons and water movement. [2] observed that fluctuation in salinity and tides can affect sediment chemistry, which in turn changes metal availability and root uptake[8] reported similar findings in Batticaloa Lagoon, Sri Lanka, where seasonal shifts in salinity altered Pb bioavailability to A. marina These changes over time show why bioaccumulation studies should include sampling in different seasons to avoid misleading results. The spatial distribution of study sites across Sri Lanka, along with the dominant heavy metals identified at each lagoon, is presented in Table 2.

Mangrove roots act as effective bio filters in different regions, with metal accumulation influenced by plant traits, sediment, and environmental conditions. A. marina is often a reliable accumulator, though adaptations differ among species and contamination levels. These results highlight the role of mangrove roots in reducing metal movement in coastal areas and the need for standard methods to compare studies across sites.

Table 1- Study sites and dominant heavy metals reported at each lagoon

Location	Species Studied	Dominant Heavy Metals Studied	Contamination Level	Study Reference
Batticaloa Lagoon	Avicennia marina	Pb	Moderate	Kularatne (2014)
Negombo Lagoon	Avicennia marina, Rhizophora apiculata	Cd, Pb, Zn	High	Silva et al. (2013)
Puttalam Lagoon	Rhizophora mucronata	Cu, Pb, Zn	Moderate	Wijeyaratne & Attygalle (2014)
Rekawa Lagoon	Avicennia marina	Pb, Cd	Moderate	Jayasiri et al. (2017)
Kalametiya Lagoon	Mixed mangrove species	Cu, Zn, Pb	High	Perera et al. (2023)

2. Ecological Overview of Heavy Metal Accumulation in Mangrove Root Systems

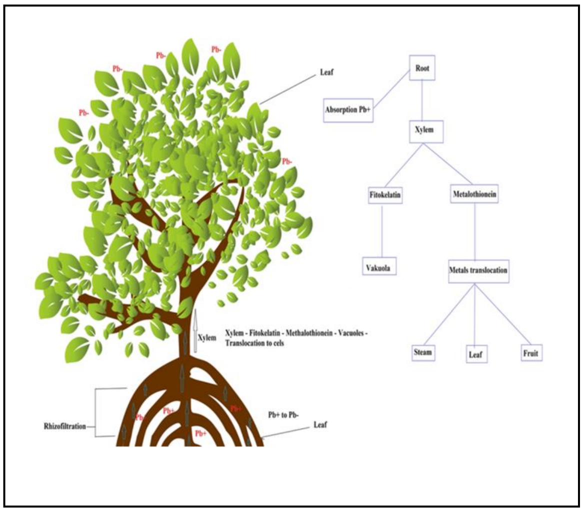
Mangrove ecosystems, located at the interface of land and sea, play a critical role in filtering, immobilizing, and redistributing contaminants introduced from rivers, industrial discharges, aquaculture effluents, and atmospheric deposition[5]. Mangrove root systems are unique among coastal vegetation, and their structural and physiological features make them highly efficient sinks for heavy metals. In most mangrove species, contaminants are retained in sediments and roots rather than being translocated to aerial tissues[1], [11] .

2.1 Heavy Metal Filtration Mechanisms and Processes in Mangrove Root Systems

The heavy metal filtration process in mangrove root systems operates through multiple mechanisms. First, sediment trapping and adsorption occur when fine-grained sediments rich in organic matter accumulate around dense root mats, providing abundant binding sites for metals such as Cd, Pb, and Cu [12], [19]. Second, rhizosphere interactions alter pH and redox potential, enhancing metal immobilization through precipitation and complexation with sulfides, oxides, and organic ligands[5], [20]. Third, root uptake and sequestration play a critical role, as endodermal barriers and cell wall binding restrict upward metal transport, leading to preferential storage in root tissues[21].Collectively, these processes act as a natural filtration system, reducing the bioavailability of metals in surrounding coastal waters and limiting their entry into marine food webs.

To better illustrate these mechanisms, Figure 2 presents a simplified schematic of how heavy metals are absorbed, immobilized, and sequestered within mangrove root tissues, with limited upward transport to stems and leaves.

Figure 2- Simplified schematic of heavy metal accumulation in mangrove roots and aerial parts, showing pathways of absorption, translocation, and sequestration within root and shoot tissues (adapted from Wilda et al., 2021).



From an ecological perspective, mangroves act both as biogeochemical barriers and bio indicators of contamination. They protect adjacent ecosystems such as seagrass beds and coral reefs by trapping metals, but shifts in sediment chemistry or hydrodynamic conditions can remobilize stored contaminants *[1]*. Thus, while mangroves provide essential ecosystem services in metal retention, the long-term ecological implications depend on the balance between accumulation, sequestration, and potential remobilization.

2.2 Heavy Metal Contamination and Ecological Assessment

Heavy metal contamination in mangroves stresses individual plants and also affects sediment quality, animals, and overall ecosystem function. Ecological studies usually assess sediment chemistry and use pollution indices to measure contamination levels, sources, and risks [18], [21].

[21] Reported Avicennia marina habitats along the Red Sea coast of Saudi Arabia, documenting elevated concentrations of Cd, Pb, and Cu in surface sediments near industrial and urban discharge points. Using the geoaccumulation index (Igeo) and contamination factor (CF), they found moderate to high contamination, mainly from human activities like desalination plants and shipyards. Risk indices indicated possible threats to benthic biodiversity and the long-term survival of mangroves.

In contrast, [18] investigated the Cochin Estuary in India and found markedly higher metal loads, particularly near industrial complexes and port areas. Their enrichment factor (EF) analysis revealed extreme enrichment for Pb and Zn, directly linked to manufacturing and shipping activities. Unlike the Red Sea, where contamination was localized, the Cochin Estuary showed widespread sediment pollution, pointing to broad human impact across the system.

Sri Lankan studies further highlight regional variability in contamination sources and severity. [22] Analyzed sediments from estuaries in the country's northern and western coasts, detecting the highest Zn, Pb, and Cu concentrations near urbanized and aquaculture-intensive areas. Multivariate statistical techniques identified both natural geological sources and anthropogenic inputs, suggesting that while human activities dominate contamination near settlements, background levels are influenced by catchment geology.

[1] Provided a different case in New Caledonia showed that sediment type and redox conditions strongly influenced metal movement and ecological risk. In this case, Fe and Ni, derived mainly from natural erosion, were present in high concentrations but exhibited low bioavailability due to stable mineral associations in reduced sediment layers. Conversely, Cu and Zn, often bound to organic matter, were more mobile and posed higher ecological risks, particularly under conditions of sediment disturbance or oxidation.

[23] Study in northern China showed that sediment size, water movement, and human activity together control metal distribution. Fine sediments in low-energy areas had higher metal levels, while strong tidal flow in high-energy areas limited accumulation. This shows that sediment dynamics are as important as pollution sources in shaping contamination patterns.

Comparative analysis of these studies reveals both consistencies and divergences in ecological risk assessment outcomes. For example, while [21] and [18] both used Igeo and EF indices, differences in sediment texture, hydrology, and urban-industrial proximity explain the variation in contamination severity. Similarly, [22] and [1] highlight that even in areas with high total metal content, actual ecological risk depends heavily on metal speciation and bioavailability, not just concentration.

From a management perspective, ecological risk assessment in mangrove ecosystems should integrate both chemical and physical sediment characteristics. Sites with high metal contamination but low mobility may require less immediate intervention, whereas areas with highly bioavailable metals and that can likely enter the food web pose great ecological risks. Additionally, restoration and conservation strategies should consider sediment hydrodynamics to prevent the remobilization of buried contaminants.

Mangroves act both as sinks for heavy metals and as indicators of coastal pollution. They can trap and hold metals, protecting nearby marine areas, but changes in sediment chemistry from human or natural causes may release these metals back into the environment. This shows the importance of ongoing monitoring and flexible management in metal-affected mangrove systems.

3. Heavy Metal Filtration Capacity in Mangrove Root Systems.

Mangrove root systems are highly effective in filtering and holding heavy metals from coastal sediments. This action significantly reduces the transfer of contaminants to aerial tissues and nearby ecosystems, thereby protecting the broader environment [24]. The filtration efficiency of mangrove roots can be quantitatively assessed by comparing the concentrations of heavy metals in the sediments, roots, and leaves is presented in table 2.

In this study, sediment samples and three mangrove species (Excoecaria agallocha, Avicennia officinalis, and Sonneratia apetala) were collected from the world's largest mangrove forest along the Northern Bay of Bengal Coast to evaluate metal concentrations, contamination levels, and the phytoremediation potential of these plants. Table 1 shows the results they obtained from the above said methods. The contamination factor (CF) values for the studied metals were in the descending order of Cu > Sr > Zn > Fe > Mn [25].

Table 2- Heavy metal concentrations in sediments, roots, and leaves of selected mangrove species, showing the filtration role of mangrove roots (adapted from Hossain et al., 2022).

Metal Type	**Heavy Metal concentration in Sediments (mg/kg)**	**Heavy Metal Concentration of in Mangrove Roots**	**Heavy Metal Concentration of in Mangrove Leaf Part**
Fe	22,760–27,470	737.37 ± 153.06	598.75 ± 410.65
Mn	80.37–116.37	151.13 ± 34.26	297.27 ± 148.11
Sr	167.92–221.44	20.98 ± 6.97	21.40 ± 8.71
Cu	72.41–95.89	16.12 ± 4.34	14.25 ± 2.51
Zn	51.28–71.20	11.3 ± 2.39	12.56 ± 2.13

The results show that sediments had the highest amounts of heavy metals, but only a small part of this was taken up by mangrove roots, and even less moved to the leaves. Manganese (Mn) behaved differently, as its level was higher in leaves than in roots, which means it can move more easily to the upper parts of the plant. Copper (Cu) and zinc (Zn) were mostly stored in the roots, with very little reaching the leaves. Strontium (Sr) showed very low amounts in both roots and leaves compared to sediments, meaning the plants did not take it up much.

In studies of Australian mangroves,[6] found that roots of Avicennia marina concentrated Cu, Pb, and Zn strongly relative to sediments, with limited transfer to aerial parts. Concentrations in root tissues were consistently higher than in leaves, reflecting a detoxification strategy based on sequestration within root cortical tissues.

[26] reported that, compared to typical mangrove ecosystems worldwide, the mangroves in Hainan Island exhibited low to medium levels of metal accumulation. This was attributed mainly to ongoing human activities and land exploitation in the region. In their study, they examined seven metals such as Cu, Pb, Zn, Cd, Cr, Hg, and As were found that the average concentrations in surface sediments as 14.8, 24.1, 57.9, 0.17, 29.6, 0.08, and 9.7 μg g^{-1}, whereas those in mangrove tissues were 2.8, 1.4, 8.7, 0.03, 1.1, 0.03, and 0.2 gg−1,respectively.

In Sri Lanka,[8] investigated Pb dynamics in Avicennia marina at Batticaloa Lagoon and found that Pb levels in both sediments (<0.25 mg/kg) and plant tissues (<0.5 mg/kg) were below detection limits, indicating that under highly saline and dry conditions, A. marina was not effective in sequestering Pb, despite elevated Pb concentrations in lagoon water.

According to [10] identified heavy metal retention in mangrove sediments is not solely dependent on organic matter levels, but also on root-driven redox conditions and species-specific traits. Avicennia marina, through its oxygenating root system, can enhance metal mobility and bioavailability, whereas Rhizophora stands tend to stabilize metals more effectively. This underscores the dual role of mangrove roots in both immobilizing and, under certain conditions, mobilizing heavy metals within sediments.

Together, these studies demonstrate that mangrove root systems act as critical filters, capable of retaining substantial amounts of heavy metals, but with filtration efficiency strongly influenced by metal type, species-specific traits, and local environmental conditions.

4. Research Methodologies and Case Studies

Research into the heavy metal filtration efficiency of mangrove root systems has employed a diverse range of methodologies, from controlled laboratory experiments to long-term field monitoring. Each approach contributes unique insights into the bioaccumulation processes, environmental influences, and potential for mangrove-based remediation, but also presents specific limitations in terms of ecological realism, scalability, or mechanistic understanding.

Sediment and plant tissues (roots, stems, leaves) are collected either from field sites or experimental setups. Samples are washed, oven-dried, and ground before analysis. In field studies, sediment is usually taken from the upper 0–20 cm using corers or grab samplers, while controlled experiments expose seedlings to defined metal solutions for tracking uptake [25], [26].

4.1 Analytical Techniques

A variety of analytical tools have been employed to detect and quantify heavy metals in mangrove ecosystems. Atomic Absorption Spectroscopy (AAS) remains one of the most widely used methods due to its reliability and accessibility, while more sensitive variations such as Graphite Furnace AAS allow detection of trace-level elements. Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) are increasingly favored for multi-elemental analysis with higher precision and lower detection limits[25].

In addition, scanning electron microscopy coupled with energy-dispersive X-ray (SEM-EDX) microanalysis has been used to localize metals at the cellular level, providing insights into tissue-level sequestration mechanisms[27]. Sequential extraction procedures have also been employed to partition metals into bioavailable, reducible, and residual fractions, thus linking metal speciation with ecological risk[10].

4.2 Case Studies

Different case studies show how these methods are used in mangrove research around the world. In the Sundarbans of Bangladesh, standardized sampling combined with ICP-OES testing showed how different species take up metals, proving their potential for phytoremediation[25]. In Xiamen Lagoon, China, AAS-based analyses demonstrated effective metal uptake by Kandelia obovata, while sequential extraction helped explain sediment metal interactions[26].

In New Caledonia, fractionation techniques revealed how Cu, Zn, and Pb are linked with organic matter and Fe/Mn oxides, showing how sediment chemistry controls metal mobility [10]. At a finer scale, In Australia, SEM-EDX mapping of Avicennia marina roots showed metals concentrated in the root surface and special leaf hairs, pointing to both blocking and excretion pathways (MacFarlane & Burchett, 2000c). Collectively, these studies demonstrate how methodological diversity enables a deeper understanding of metal dynamics across sediments, roots, and aerial tissues.

Field studies also explain how natural conditions affect metal uptake. For example, Avicennia marina along the Red Sea coast showed links between metal stress and adaptive responses when physiological and biochemical measures were combined [28]. In Sri Lanka, [8] investigated seasonal Pb variations in Batticaloa Lagoon, highlighting how salinity and hydrology shape accumulation patterns.

Controlled laboratory studies provide mechanistic understanding under defined conditions. [29] exposed A. marina seedlings to Cu, Pb, and Zn, using SEM-X ray microanalysis to track cellular distribution and barriers to metal transport. These experiments revealed how root structures selectively immobilize or block metals, clarifying processes not easily observed in the field.

The table 3 lists different experimental methods scientists have used to study heavy metals in mangroves. These include collecting sediments and plant parts, measuring metals with instruments like AAS and ICP, mapping metals inside tissues with SEM-EDX, and using sequential extraction to see how metals are bound in sediments.

Table 3- Summary of common methodologies used in mangrove heavy metal research, their applications, and key cited studies

Method	Application	Cited Studies
Sediment & root sampling	Sediment cores at varying depths; separation of root, stem, and leaf tissues for analysis	Harbison (1986); Marchand et al. (2011)
Atomic Absorption Spectroscopy (AAS)	Quantification of single metals in plant and sediment samples	Tam & Wong (1997)
ICP-OES / ICP-MS	Multi-element detection in sediments and mangrove tissues	Qiu et al. (2011)
SEM-EDX (Scanning Electron Microscopy with Energy Dispersive X-ray)	Elemental mapping and localization of metals within root and leaf tissues	MacFarlane & Burchett (2000)

Controlled laboratory studies provide mechanistic understanding under defined conditions. MacFarlane & Burchett, (2000) exposed A. marina seedlings to Cu, Pb, and Zn, using SEM-X ray microanalysis to track cellular distribution and barriers to metal transport. These experiments revealed how root structures selectively immobilize or block metals, clarifying processes not easily observed in the field.

5. Impact of Heavy Metals on Mangrove Physiology

Mangroves in metal-rich environments show both sensitivity and strong adaptive capacity. Exposure to Cu, Cd, Pb, Zn, and Ni may reduce chlorophyll and sugar levels initially (El-Moselhy et al., 2014), but species like Avicennia marina counteract this by producing antioxidant enzymes and protective metabolites, which help sustain photosynthesis. Similarly, Ferreira et al., (2016) found that A. marina retained iron in roots, limiting its transfer to leaves, while R. mucronata and Bruguiera gymnorrhiza showed higher leaf metal accumulation but still activated protective responses.

Heavy metals affect mangroves in many ways. For example, El-Moselhy et al., 2014) studied Avicennia marina along Egypt's Red Sea coast. They found that when metals like Cu, Cd, Pb, Zn, and Ni were high, the trees had less chlorophyll and sugars, which weakened photosynthesis. To protect themselves, the plants increased antioxidants such as catalase and compounds like phenols and proline. These defenses helped them reduce damage from metal stress.

[30] tested A. marina, Rhizophora mucronata, and Bruguiera gymnorrhiza under iron (Fe) stress. A. marina stored more Fe in its roots, stopping the metal from reaching the leaves. This allowed it to keep healthier leaves and continue photosynthesis. In contrast, R. mucronata and B. gymnorrhiza moved more Fe into their leaves, which caused yellowing and leaf death. This shows that species differ in how well their roots block metals, and this difference affects how much stress they suffer.

6. Future Perspectives and Recommendations

Mangrove root systems play a vital role in controlling heavy metal pollution, but there is still room to improve how we study and apply this knowledge in Sri Lanka. Based on the current findings, three main recommendations stand out.

Mangroves can be integrated into constructed wetlands and wastewater treatment systems. Species such as Avicennia marina and Rhizophora mucronata, which are common in Sri Lanka, are already known to trap metals effectively in their roots. Using these species in small-scale treatment setups for aquaculture ponds, industrial effluents, or municipal wastewater could provide a low-cost and eco-friendly way to reduce heavy metal contamination [24], [25].

Long-term monitoring of mangrove ecosystems should be developed. Seasonal changes in salinity, tidal flow, and climate factors strongly influence how metals move between sediments and roots [2], [8]. In Sri Lanka's lagoons, where salinity shifts between dry and wet seasons, monitoring programs could help predict when and where metal accumulation is highest, improving local management strategies.

Mangrove restoration should be promoted as a nature-based solution. Restoring degraded mangrove habitats can provide two key benefits, enhancing biodiversity and reducing heavy metal risks for nearby coastal communities. Healthy mangrove forests not only trap pollutants but also protect fisheries and aquaculture zones, which are crucial for Sri Lanka's economy [5], [18].

Mangrove root systems can help reduce heavy metal pollution in Sri Lanka. This can be done by using species like Avicennia marina and Rhizophora mucronata in wastewater treatment, setting up long-term monitoring programs to track seasonal changes in metal accumulation, and restoring mangrove forests to improve biodiversity, support fisheries, and protect coastal communities from contamination.

Conclusion

Mangrove roots are highly effective natural filters that reduce heavy metal pollution in coastal areas. Their special structures allow them to trap and store metals like Pb, Cd, Cu, and Zn in sediments and roots, hereby limiting their transfer into aerial parts and reducing ecological risks to associated food chain. Evidence across global and regional studies, including those from Sri Lanka, demonstrates that species differences, sediment properties, and hydrological conditions all decide the amount of metal absorption and storage.

The reviewed studies highlight three key points. Mangrove roots store heavy metals mainly in the roots, which helps protect leaves and nearby marine life. Contamination levels differ across regions depending on human activities, soil chemistry, and tides, with higher risks when metals are more mobile and available. New research methods have improved our understanding of how metals are trapped, but more work is still needed to connect lab results with real ecosystem conditions.

From an applied perspective, mangroves hold great potential for bioremediation, especially in tropical countries like Sri Lanka where urbanization, aquaculture, and industrialization increase coastal pollution. Beyond their role in wastewater treatment, mangrove systems can be used in constructed wetlands, shoreline protection, and integrated coastal zone management. They can also serve as natural bio indicators for monitoring pollution, provide carbon storage benefits, and support sustainable fisheries by improving water quality. Long-term monitoring of metal dynamics, restoration of degraded mangrove forests, and the use of advanced mapping and modeling tools can further enhance their application. However, the long-term stability of stored metals and the risk of their release under changing environmental conditions remain important challenges that need further research.

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