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Mangroves in Phytoremediation: Strategies, mechanisms and future perspectives for ecosystem restoration- A Review Article

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Abstract

Mangroves are unique coastal ecosystems characterized by salt-tolerant trees and other plant species thriving in intertidal zones. These ecosystems are immensely valuable, offering a multitude of ecological, economic, and social benefits. Functionally, mangroves act as natural barriers against coastal erosion, storm surges, and the impacts of climate change, thus safeguarding adjacent shorelines and human settlements. In addition, they play a critical role in carbon sequestration, contributing significantly to climate regulation by capturing and storing atmospheric carbon dioxide. Mangroves also support a rich biodiversity, serving as crucial habitats for numerous species, including fish, birds, and invertebrates. Furthermore, they provide essential resources for local communities, including timber, fuel, and fisheries, thus sustaining livelihoods and cultural practices. Despite their importance, these vital ecosystems face immense threats from anthropogenic activities. Urbanization, agricultural expansion, pollution, and unsustainable resource extraction have led to the degradation and contamination of mangrove habitats. Heavy metals from industrial runoff, hydrocarbons from maritime activities, and various other contaminants undermine the health of these ecosystems, leading to reduced biodiversity, impaired ecological functions, and diminished benefits for human communities. In response to these challenges, phytoremediation has emerged as an innovative plant-based technology that offers a viable avenue for restoring contaminated mangrove habitats. Phytoremediation utilizes the natural abilities of certain plant species to remove, stabilize, or detoxify pollutants from the environment. This review explores the current state of research on phytoremediation in mangrove ecosystems, the mechanisms involved, and its effectiveness as a restoration tool.

Keywords: Contaminants, Heavy metals, Mangroves, Phytoremediation, Restoration

1. Introduction

Mangroves are vital coastal ecosystems found in tropical and subtropical regions, characterized by their unique assemblage of salt-tolerant trees and other plant species. These ecosystems are typically located in intertidal zones, where the land meets the sea, creating a complex interplay of environmental factors, including salinity, hydrology, and sedimentation patterns. Mangroves serve multiple ecological, social, and economic functions [1]. Mangrove forests play a critical role in coastal protection. They act as natural barriers against tidal surges, storms, and erosion, thereby safeguarding coastal communities from the impacts of climate change and extreme weather events [2]. Additionally, mangroves are significant carbon sinks, sequestering large amounts of carbon dioxide from the atmosphere and storing it in their biomass and the underlying soil. This carbon sequestration capacity is particularly crucial in the context of global climate change, as it helps mitigate the greenhouse effect [3]. It has been estimated that mangroves store up to four times more carbon per unit area than tropical rainforests, highlighting their role in combating climate change [4]. They provide resources such as wood, honey, and traditional medicines while supporting fisheries, which are vital for the livelihoods of millions of coastal inhabitants worldwide [5]. In many regions, mangroves also contribute to ecotourism, attracting visitors for bird watching, biodiversity, and scenic beauty [6]. Despite their importance, mangroves face significant threats from anthropogenic activities. Urbanization, coastal development, aquaculture, and pollution have led to widespread mangrove deforestation and degradation [7]. According to the Global Forest Resources Assessment, mangrove forests are among the most endangered ecosystems, with an estimated annual loss of around 1-2% of their total area globally [8].

In light of increasing contamination from industrial, agricultural, and urban runoff, mangrove ecosystems are often exposed to heavy metals, hydrocarbons, and other pollutants. Phytoremediation defined as the use of plants to absorb, accumulate, and detoxify pollutants from the environment has emerged as a promising strategy for restoring contaminated mangrove habitats [9].

Phytoremediation employs natural processes, thereby offering a cost-effective, environmentally friendly alternative to conventional remediation methods, which can be expensive and disruptive to the ecosystem. Given their unique physiological adaptations, including salt tolerance and the ability to thrive in anaerobic soils, mangrove species exhibit considerable potential for phytoremediation. Various approaches within phytoremediation such as phytoaccumulation, phytostabilization, and phytodegradation can significantly mitigate the effects of contaminants and restore ecological balance. Additionally, employing native mangrove species for these purposes promotes local biodiversity and the resilience of these ecosystems, making phytoremediation a valuable tool in mangrove restoration efforts [10].

In this review, we will explore the mechanisms of phytoremediation in mangrove ecosystems, assess the effectiveness of various mangrove species in pollutant remediation, and discuss the challenges and future directions in this field. Understanding these dynamics is crucial for developing integrated conservation strategies that not only restore contaminated ecosystems but also enhance the sustainability of mangrove forests globally.

2. Mechanisms of Phytoremediation in Mangroves

Phytoremediation is a versatile and environmentally friendly approach that utilizes plants to remediate contaminated environmental sites. In mangrove ecosystems, various phytoremediation strategies can be deployed to effectively address different types of pollution, including heavy metals, organic pollutants, and excess nutrients. Several key mechanisms facilitate the phytoremediation process, enabling mangrove species to tolerate, accumulate, and degrade pollutants.

Phytoaccumulation: This involves the uptake and accumulation of contaminants in the plant tissues, particularly in roots, stems, and leaves. Mangrove species have unique strategies to absorb heavy metals and other pollutants from the sediment and water. The roots of mangrove trees act as a barrier, filtering out toxic substances from the surrounding environment. Once absorbed, contaminants are transported through the vascular system to other plant tissues. Some species, such as *Avicennia marina* and *Rhizophora mangle*, possess specialized mechanisms to sequester heavy metals in vacuoles, thereby minimizing their toxicity [11]. Studies have shown that these species can accumulate significant amounts of metals like lead (Pb), cadmium (Cd), and mercury (Hg) without exhibiting detrimental effects on growth. Research indicates that *Bruguiera gymnorhiza* can effectively accumulate cadmium from contaminated sediments, demonstrating its potential as a bioindicator of pollution levels and its role in bioremediation [12].

Phytostabilization: This is a mechanism where plants immobilize contaminants in the soil, preventing their movement into the water table and subsequent bioavailability. This is particularly important in mangrove ecosystems where heavy metal contamination poses risks to both ecological health and human safety.

Mangrove trees build extensive root systems that help stabilize soil particles while also promoting the formation of stable metal complexes in the rhizosphere. The increased microbial biomass can lead to the bio-absorption of metals, reducing their toxicity. *Avicennia* species can effectively immobilize heavy metals like zinc (Zn) and copper (Cu) in sediments, thus preventing leaching into groundwater and nearby aquatic environments [13]. This mechanism is vital for the long-term stability of contaminated mangrove habitats.

Phytodegradation: This refers to the breakdown of organic pollutants, such as hydrocarbons and pesticides, through plant metabolism or microbial activity associated with the plants. This process is particularly relevant in areas affected by oil spills or chemical leaks. Mangroves can metabolize contaminants through various biochemical pathways, leading to their degradation into less harmful compounds. Some mangrove species produce specific enzymes (e.g., peroxidases, laccases) that facilitate the degradation of complex organic molecules. *Rhizophora apiculata* has been shown to degrade hydrocarbons, significantly reducing concentrations of contaminants following oil spills [14]. Furthermore, mangrove-associated microorganisms can enhance the degradation process, highlighting the importance of plant-microbe interactions in phytodegradation.

Rhizodegradation: This involves the degradation of contaminants in the soil surrounding the plant roots, influenced by root exudates that stimulate microbial activity. The roots of mangrove trees exude a variety of organic compounds, such as sugars, amino acids, and phenolics, which serve as substrates for microorganisms. This interaction results in enhanced microbial populations in the rhizosphere, which in turn can degrade organic pollutants [15]. The rhizosphere environment created by the roots can also alter the chemical dynamics of pollutants, making them more available for microbial degradation. The root exudates of species like *Aegiceras corniculatum* can stimulate the breakdown of organic contaminants in the rhizosphere, effectively reducing pollutant concentrations in mangrove sediments [10]. This mechanism underscores the significance of promoting healthy and diverse microbial communities in mangrove ecosystems for efficient rhizodegradation.

Phytovolatilization: Phytovolatilization: This is a less common but significant mechanism whereby plants uptake contaminants and release them as volatile compounds through transpiration. This mechanism is especially notable in certain plant species that have adapted to effectively metabolize and transpire these pollutants [16]. Among these, some mangrove species stand out due to their ecological role and the unique environments they inhabit. Mangroves, which thrive in saline coastal intertidal zones, have special adaptations that enable them to absorb both water and various pollutants from the sediment and surrounding water bodies. Certain studies have shown that mangrove species can take up VOCs such as toluene, benzene, and other organic solvents, which may be present in contaminated soils and coastal waters. Once inside the plant, these compounds can be transformed through metabolic processes, ultimately being released into the atmosphere as less harmful species or as the original VOCs [17]. The mechanism of phytovolatilization not only plays a crucial role in reducing pollutant concentrations in contaminated environments but also aids in improving air quality. By releasing VOCs into the atmosphere, and in some cases transforming them into less harmful substances, these plants contribute to the detoxification of their surroundings [18].

3. Species Selection for Phytoremediation in Mangrove Ecosystems

The selection of appropriate plant species is crucial for the success of phytoremediation strategies, particularly in the unique and often challenging environments of mangrove ecosystems. Mangroves, characterized by their salt-tolerance, complex root systems, and adaptability to anaerobic conditions, offer a diverse range of species that exhibit varying abilities to absorb, accumulate, and detoxify pollutants. When selecting species for phytoremediation, several key factors should be considered, including the specific pollutants being remediated, the ecological characteristics of the site, and the functional traits of the mangrove species.

Types of Contaminants

Phytoremediation can target a range of contaminants, including heavy metals, organic pollutants, and excess nutrients. Each contaminant type may require specific plant characteristics for effective removal:

Heavy Metals: Species that exhibit phytoaccumulation abilities are essential for cleaning up heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As). *Avicennia marina* is known for its high tolerance to saline and contaminated environments, this species can accumulate various heavy metals in its tissues [11] and *Bruguiera gymnorhiza* demonstrates significant uptake capacities for cadmium and zinc, making it suitable for polluted sites [12].

Organic Pollutants: For breaking down hydrocarbons and other organic contaminants, species capable of phytodegradation are preferred: *Rhizophora* spp can secrete enzymes that degrade hydrocarbons, making them effective in oil-contaminated ecosystems [19].

Nutrient Overload: To manage excess nutrients, especially nitrogen and phosphorus from agricultural runoff, fast-growing species that enhance nitrification and denitrification processes are desirable: *Kandelia obovata* species can contribute to nutrient cycling and improve water quality through its root interactions with microorganisms [20].

Ecological Adaptations

Choosing species that are well-adapted to local environmental conditions, such as salinity, temperature, and hydrology, is vital for ensuring successful phytoremediation:

Mangrove species exhibit varying degrees of salt tolerance. For example: *Avicennia* and *Salicornia* species are particularly salt-tolerant, thriving in highly saline, waterlogged conditions, which makes them suitable options for areas with high salinity levels [21]. The structure and functional characteristics of roots can greatly influence a species' capability for pollutant uptake: *Rhizophora* species possess extensive aerial roots that stabilize soil and increase surface area for uptake, enhancing their phytoremediation potential [22].

Growth Habits and Carbon Sequestration

Another crucial consideration for species selection in phytoremediation is the growth rate and biomass production, which directly relates to the plant's ability to sequester carbon. Species like *Sonneratia* and *Avicennia* are characterized by rapid growth, which allows for faster accumulation of biomass and more extensive root systems. Such species improve the speed of phytoremediation processes and contribute to carbon sequestration, enhancing the overall ecological benefits of the intervention [3].

High litter fall from mangrove trees can contribute to soil organic matter, improving soil structure and fostering a rich microbial community essential for degradation processes: *Bruguiera* and *Kandelia* species are known for their significant litter production, adding organic material that supports microbial activity necessary for pollutant degradation [23].

Biodiversity and Specificity

Promoting species diversity in phytoremediation efforts can lead to more resilient ecosystems that are better equipped to handle environmental stress. A diverse assemblage of mangrove species can create a synergistic effect that enhances the overall capacity for pollutant removal. Species diversity can improve ecosystem stability and enhance biogeochemical cycles [24]. Different mangrove species may host various beneficial microbes (mycorrhizae and endophytes) that can further enhance pollutant degradation and uptake. For instance, certain *Avicennia* species can form symbiotic relationships with specific fungi that aid in heavy metal uptake [25].

Local Knowledge and Traditional Practices

Incorporating local knowledge and traditional ecological practices can aid in the selection of species that are not only effective in phytoremediation but also culturally acceptable. Collaborating with local communities can provide insights into species that have historical significance in aiding ecosystem health. This practice fosters community involvement and ensures the conservation of traditional ecological knowledge [26]. Employing native mangrove species preserves genetic diversity and enhances ecosystem resilience to climate change and environmental stressors [6].

4. Challenges and Future Perspectives in Phytoremediation of Mangrove Ecosystems

Phytoremediation presents a promising solution for the restoration of contaminated environments, particularly in sensitive ecosystems such as mangroves. Despite its potential, the application of phytoremediation in mangroves faces several challenges that must be addressed to enhance effectiveness and sustainability. Moreover, future perspectives can guide the development of innovative strategies to optimize the use of mangrove species in the cleanup of pollutants.

Mangrove ecosystems are inherently saline and often waterlogged, which can pose significant stress for plant growth and development. High salinity levels can inhibit the physiological processes necessary for effective pollutant uptake and accumulation [21]. Climate change has resulted in increasing temperatures and varying precipitation patterns, which may further stress mangrove species, potentially affecting their growth and phytoremediation capabilities [27]. Mangrove ecosystems can be contaminated with a wide range of pollutants, including heavy metals, organic compounds, and nutrients from anthropogenic sources. The chemical diversity and interactions between these pollutants can complicate the phytoremediation process. For example, certain pollutants may interfere with the uptake and detoxification processes of others, reducing overall effectiveness

[28]. High concentrations of contaminants can be toxic not just to plants but also to associated microbial communities critical for enhancing phytoremediation processes. Toxic effects can impair the efficiency of bioremediation achieved through rhizodegradation and synergistic plant-microbe interactions [22].

The physical and chemical properties of contaminated soils can hinder root development and pollutant bioavailability. For example, hydrophobic organic compounds may sorb strongly to organic matter or bind with soil particles, making them less accessible to plant uptake [29]. Suboptimal nutrient conditions in contaminated sites may adversely affect plant health and physiological processes vital for phytoremediation. This can lead to stunted growth and reduced capacity for contaminant uptake and degradation. While some mangrove species have been studied for their phytoremediation capabilities, comprehensive knowledge on the phytoremediation potential of less common species remains limited. More research is needed to understand the mechanisms and capacities of different mangrove species relative to specific pollutants [30]. Much of the existing research is based on greenhouse or laboratory studies, which may not accurately represent the complexities of field conditions [12]. Field studies are necessary to evaluate the real-world effectiveness of mangrove phytoremediation.

Awareness and understanding of phytoremediation and its benefits among local communities may be limited. Community engagement is critical for successful implementation, yet achieving this can be challenging due to cultural beliefs or lack of education on environmental issues [26]. There may be insufficient policies to support phytoremediation efforts and integration into broader environmental management practices.

Establishing clear regulatory frameworks can facilitate the adoption of phytoremediation technologies and support funding for research and implementation. Integrating phytoremediation with other remediation strategies, such as bioremediation or chemical methods, could enhance the overall effectiveness of contaminant removal. For instance, combining phytoremediation with microbial inoculation can leverage the strengths of both plants and microbes for improved pollutant degradation [31]. Mangroves can be combined with constructed wetlands to improve water treatment capabilities in contaminated coastal areas. This hybrid approach can optimize nutrient removal while providing habitat for diverse flora and fauna. Advances in genetic engineering can help develop mangrove species with enhanced traits for phytoremediation, such as increased metal uptake capacity or improved tolerance to salinity and toxicity [25]. This approach may allow the selection or creation of species specifically tailored to thrive in contaminated mangrove ecosystems. The use of biochar or nanomaterial amendments in mangrove soils can enhance pollutant sorption, improve nutrient conditions, and stimulate microbial activity, thus boosting phytoremediation potential [32].

Ongoing research into such materials may yield novel solutions for remediation challenges. Emphasizing species diversity in phytoremediation efforts can enhance resilience and stability in mangrove ecosystems. Incorporating native species with complementary phytoremediation capabilities can maximize pollutant removal while supporting ecological functions [4]. Phytoremediation in mangroves not only addresses contamination but also contributes to the restoration of vital ecosystem services, such as carbon sequestration, habitat provision, and coastal protection [23].

Engaging local communities in phytoremediation efforts can foster stewardship of mangrove ecosystems. Community-led initiatives can enhance awareness of the importance of mangroves and promote sustainable practices [33]. Developing educational programs and workshops can help raise awareness and provide essential knowledge on the benefits of phytoremediation and its application in mangrove ecosystems, encouraging active participation from local stakeholders. Advocating for policies that support the integration of phytoremediation into coastal management strategies can provide the necessary regulatory backing to promote the adoption of such technologies [26]. Securing funding for research into mangrove phytoremediation can drive innovation, focusing on the development of effective, practical approaches to environmental restoration in contaminated mangrove areas.

5. Conclusion

Phytoremediation of mangroves presents a promising and sustainable approach to restoring contaminated coastal ecosystems. By using the natural capabilities of mangrove species, it is possible to mitigate pollution, enhance biodiversity, and improve ecosystem services. Continued research and field trials are essential to advancing this technology and ensuring the health of these critical habitats for future generations. Phytoremediation of mangroves stands as a promising and sustainable strategy for the restoration of contaminated coastal ecosystems, addressing some of the most significant environmental challenges faced today. By harnessing the inherent capabilities of mangrove species, which include their unique adaptations to saline environments and their extensive root systems, we can effectively mitigate pollution from heavy metals, hydrocarbons, and other harmful contaminants. This natural remediation approach not only aids in the detoxification of polluted sediments and waters but also plays a crucial role in enhancing biodiversity within these habitats. Moreover, the successful application of phytoremediation promotes community engagement, as local populations can participate actively in restoration efforts. However, to fully realize the potential of phytoremediation in mangrove rehabilitation, ongoing research and comprehensive field trials are essential. Such studies will help identify the most effective plant species for specific contaminants and optimize methodologies for restoration. This sustainable approach not only aims to restore ecological balance but also enhances the socio-economic benefits that these critical habitats provide to coastal communities worldwide.

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