Chapter 10
Phytoremediation in Wetlands

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Abstract This chapter explores the role of phytoremediation in wetlands, focusing on the use of wetland plants to absorb, detoxify, and mitigate contaminants present in water. Wetlands serve as natural filtration systems, and the integration of phytoremediation techniques enhances their ability to treat various pollutants, including heavy metals, organic compounds, and nutrients. The chapter begins by providing an overview of wetland ecosystems, emphasizing their ecological importance and their function as buffers against environmental degradation. It then delves into the principles of phytoremediation, highlighting the mechanisms by which plants in wetland environments absorb and metabolize contaminants. The various types of phytoremediation; phytoextraction, phytodegradation, phytostabilization, phytovolatilization, and rhizofiltration are discussed in detail, with a focus on their applications in wetland management. Case studies of constructed wetlands designed for industrial and agricultural wastewater treatment are presented, demonstrating the effectiveness of phytoremediation in real-world scenarios. The chapter also examines factors influencing the efficiency of phytoremediation, such as plant species selection, environmental conditions, and plant-microbe interactions. Future perspectives and opportunities in the field are explored, including innovations in biotechnology, the integration of phytoremediation with other treatment methods, and policy considerations. Overall, this chapter underscores the potential of wetland phytoremediation as a sustainable and cost-effective approach to environmental remediation, contributing to the preservation and restoration of wetland ecosystems.

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10.1 Introduction

Wetlands are among the most productive ecosystems in the world, playing a crucial role in maintaining ecological balance and supporting biodiversity. These ecosystems are characterized by the presence of water, either permanently or seasonally, which creates conditions that support the growth of hydrophytic vegetation (Mitsch and Gosselink 2015). Wetlands can be found on every continent and encompass a wide variety of habitats, from mangrove swamps and peat bogs to floodplains and marshes. They act as natural buffers, mitigating the impacts of floods, controlling water quality, and sequestering carbon, which helps combat climate change (Gell et al. 2023). Despite their ecological importance, wetlands are increasingly under threat from human activities, leading to the degradation and loss of these vital ecosystems (Davidson 2014).

Wetlands are among the most vital ecosystems on Earth, providing essential services such as water purification, flood control, carbon sequestration, and biodiversity support. Despite covering only about 6% of the Earth's surface, wetlands are estimated to host nearly 40% of global biodiversity, making them crucial for maintaining ecological balance and supporting human livelihoods (Mitsch and Gosselink 2015). However, these ecosystems are increasingly under threat due to various anthropogenic activities, leading to the degradation of water quality and loss of biodiversity. Industrial discharges, agricultural runoff, and urban development have introduced a wide range of contaminants, including heavy metals, nutrients, and organic pollutants, into wetland environments, thereby necessitating effective remediation strategies (Mitsch and Gosselink 2015).

Wetlands are typically defined as areas where water covers the soil or is present at or near the surface for varying periods, leading to conditions that favor water-tolerant vegetation (Cowardin 1979). This definition includes a wide range of environments, from coastal estuaries and tidal marshes to inland lakes, rivers, and peatlands. Wetlands are highly dynamic systems, with their hydrology and vegetation changing over time due to natural processes such as flooding, sedimentation, and succession (Mitsch and Gosselink 2015).

Wetlands can be classified into several types based on their hydrology, vegetation, and location. The primary types of wetlands include marshes, swamps, bogs, and fens, each with distinct characteristics and ecological functions.

Marshes are wetlands dominated by herbaceous plants, such as grasses, sedges, and reeds. They are typically found in areas with shallow, standing water and are divided into two main types: freshwater marshes and saltwater marshes (Tiner

2002). Freshwater marshes occur along rivers, lakes, and floodplains, while saltwater marshes are found along coastlines, particularly in estuaries where freshwater meets saltwater (Mitsch and Gosselink 2015). Marshes play a critical role in water purification by trapping sediments and filtering pollutants, as well as providing habitat for a wide range of wildlife, including birds, amphibians, and fish (Tiner 2002).

Swamps are wetlands characterized by the presence of woody vegetation, such as trees and shrubs. They can be further divided into two categories: forested swamps and shrub swamps. Forested swamps are dominated by trees, while shrub swamps are dominated by shrubs (Keddy 2010). Swamps are typically found in areas with slow-moving or stagnant water, such as river floodplains, lake edges, and coastal regions (Mitsch and Gosselink 2015). Swamps are important for flood control, as they can absorb excess water during storms and release it slowly over time, reducing the risk of downstream flooding (Keddy 2010).

Bogs are wetlands that receive water primarily from precipitation, resulting in low nutrient levels and acidic conditions. They are characterized by the accumulation of peat, a type of organic soil formed from the slow decomposition of plant material, particularly mosses (Rydin et al. 2013). Bogs are typically found in cool, temperate regions and are home to unique plant species, such as sphagnum moss, cranberries, and carnivorous plants (Mitsch and Gosselink 2015). Bogs play a vital role in carbon sequestration, as the slow decomposition of plant material in these environments leads to the accumulation of large amounts of carbon in the form of peat (Rydin et al. 2013).

Fens are wetlands that receive water from both precipitation and groundwater, resulting in higher nutrient levels compared to bogs. They are characterized by the presence of peat and are typically found in areas with a mix of grasses, sedges, and woody vegetation (Amon et al. 2002). Fens are important for maintaining water quality, as they can filter and store nutrients, preventing them from entering nearby water bodies (Mitsch and Gosselink 2015). Fens also provide critical habitat for a variety of plant and animal species, including rare and endangered species (Amon et al. 2002).

10.1.1 Importance of Wetlands in the Global Ecosystem

Wetlands are often referred to as the “kidneys of the landscape” because of their ability to filter and cleanse water, removing pollutants and sediments from surface and groundwater (Mitsch and Gosselink 2015). They play a critical role in maintaining water quality by trapping and transforming pollutants, such as nitrogen, phosphorus, and heavy metals, through processes like sedimentation, adsorption, and microbial degradation (Verhoeven et al. 2006). Wetlands also act as buffers between land and water, absorbing excess nutrients and preventing them from reaching rivers, lakes, and oceans, where they can cause harmful algal blooms and other forms of pollution (Mitsch and Gosselink 2015).

In addition to their role in water purification, wetlands are essential for flood control. By storing excess water during periods of heavy rainfall and slowly releasing it over time, wetlands reduce the risk of flooding downstream and help to maintain stable water levels in rivers and lakes (Bullock and Acreman 2003). This function is particularly important in urban areas, where the loss of wetlands has led to increased flood risks and costly damage to infrastructure (Mitsch and Gosselink 2015).

Wetlands also play a crucial role in climate regulation by acting as carbon sinks. Peatlands, in particular, store large amounts of carbon in the form of peat, which accumulates over thousands of years (Parish et al. 2008). By sequestering carbon, wetlands help to mitigate climate change by reducing the amount of carbon dioxide in the atmosphere (Joosten et al. 2012). However, when wetlands are drained or degraded, the stored carbon is released back into the atmosphere, contributing to global warming (Parish et al. 2008).

Biodiversity is another key aspect of wetland ecosystems. Wetlands provide habitat for a wide variety of species, including many that are rare or endangered (Davidson 2014). They support diverse communities of plants, animals, and microorganisms, and are particularly important for migratory birds, which rely on wetlands for breeding, feeding, and resting during their long journeys (Kingsford et al. 2017). Wetlands also provide critical habitat for fish and amphibians, many of which are important for commercial and recreational fishing (Mitsch and Gosselink 2015).

In addition to their ecological functions, wetlands provide numerous cultural, recreational, and economic benefits. Many wetlands are important sites for tourism and recreation, offering opportunities for birdwatching, fishing, and hiking. Wetlands also provide valuable resources, such as fish, timber, and medicinal plants, which support the livelihoods of millions of people around the world (Barbier et al. 1997).

Despite their importance, wetlands are increasingly threatened by human activities, which have led to significant loss and degradation of these ecosystems. Understanding the environmental threats to wetlands is essential for developing effective conservation strategies and ensuring the continued provision of the ecological services they provide (Davidson 2014).

10.1.2 Environmental Threats to Wetland Ecosystems

Wetlands are among the most threatened ecosystems globally, with an estimated 64% of the world's wetlands having been lost since 1900 (Davidson 2014). The primary drivers of wetland loss and degradation include land conversion, pollution, water diversion, and climate change.

10.1.2.1 Land Conversion

One of the most significant threats to wetlands is land conversion for agriculture, urban development, and infrastructure projects. Wetlands are often drained or filled in to create space for farming, housing, roads, and industrial facilities (Mitsch and Gosselink 2015). This process not only destroys the wetland habitat but also disrupts the hydrological processes that sustain wetland ecosystems (Davidson 2014). For example, the conversion of wetlands for agriculture has led to the loss of important floodplains and the degradation of water quality in many regions.

10.1.2.2 Pollution

Pollution from agricultural runoff, industrial discharges, and urban stormwater is another major threat to wetlands. Nutrient pollution, in particular, can lead to eutrophication, a process in which excess nutrients, such as nitrogen and phosphorus, stimulate the growth of algae and other aquatic plants, depleting oxygen levels in the water and leading to the death of fish and other aquatic organisms (Verhoeven et al. 2006; Adewumi et al. 2023). Heavy metals, pesticides, and other toxic chemicals can also accumulate in wetland sediments and plants, posing risks to wildlife and human health (Mitsch and Gosselink 2015).

10.1.2.3 Water Diversion

Water diversion for irrigation, hydropower, and urban water supply has significantly altered the hydrology of many wetland ecosystems, leading to changes in water levels, flow patterns, and water quality (Kingsford 2000). Dams and levees, for example, can block the natural flow of water to wetlands, reducing their ability to recharge and maintain healthy water levels (Mitsch and Gosselink 2015). In some cases, water diversion has led to the complete drying up of wetlands, resulting in the loss of critical habitat for wildlife and the degradation of ecosystem services (Kingsford 2000).

10.1.2.4 Climate Change

Climate change is expected to have profound impacts on wetland ecosystems, altering temperature and precipitation patterns, sea levels, and the frequency and intensity of extreme weather events (Erwin 2009). Rising sea levels, for example, threaten coastal wetlands, such as salt marshes and mangroves, which may be inundated by seawater or eroded by increased storm surges (Erwin 2009). Changes in temperature and precipitation patterns can also affect the hydrology of inland wetlands, leading to shifts in vegetation and wildlife communities (Erwin 2009).

10.1.2.5 Invasive Species

Invasive species pose a significant threat to wetland ecosystems by outcompeting native species, altering habitat structure, and disrupting ecological processes (Zedler and Kercher 2004). For example, invasive plants, such as Phragmites and water hyacinth, can rapidly colonize wetlands, displacing native vegetation and reducing biodiversity (Zedler and Kercher 2004). Invasive animals, such as non-native fish and amphibians, can also have negative impacts on wetland ecosystems by preying on native species and altering food webs (Zedler and Kercher 2004).

The cumulative effects of these threats have led to significant declines in wetland extent and quality, with many wetlands now degraded or lost entirely (Davidson 2014). Addressing these threats requires coordinated efforts at local, national, and international levels, including the implementation of policies and practices that promote wetland conservation, restoration, and sustainable management.

10.2 Phytoremediation

One promising approach to addressing water contamination in wetlands is phytoremediation, a green technology that utilizes plants to absorb, detoxify, or stabilize contaminants from the environment (Salt et al. 1998). Phytoremediation is gaining popularity due to its cost-effectiveness, environmental sustainability, and ability to enhance ecosystem services (Ogundele and Anaun 2022). Wetland plants, in particular, are uniquely suited for phytoremediation because of their adaptive traits, such as tolerance to waterlogged conditions, efficient nutrient uptake, and symbiotic relationships with microbial communities that enhance contaminant degradation (Wang and Que 2013; Aransiola et al. 2024).

Phytoremediation in wetlands involves several mechanisms by which plants remove or neutralize contaminants. These include phytoextraction, where plants absorb contaminants into their tissues; phytodegradation, in which plants metabolize pollutants into less toxic forms; phytostabilization, where contaminants are immobilized in the soil or sediments by plant roots; and phytovolatilization, where volatile contaminants are released into the atmosphere through transpiration (Ali et al. 2013). Wetland plants such as cattails (*Typha spp.*), common reed (*Phragmites australis*), and bulrushes (*Schoenoplectus spp.*) have been widely studied for their phytoremediation potential (Sarwar et al. 2017).

Phytoremediation is an innovative and environmentally friendly approach that utilizes plants to remove, detoxify, or stabilize environmental pollutants from soil, water, and air. Derived from the Greek word “phyto” (meaning plant) and the Latin word “remedium” (meaning to restore balance), phytoremediation represents a natural process through which plants, in association with their symbiotic microorganisms, mitigate contamination in the environment (Salt et al. 1998). This technique has gained considerable attention over recent decades as a cost-effective and sustainable alternative to conventional remediation methods, which are often expensive, invasive, and disruptive to the ecosystem (Pulford and Watson 2003).

Phytoremediation exploits the unique abilities of certain plants, known as hyperaccumulators, to tolerate and accumulate high concentrations of pollutants in their tissues. These plants, either naturally occurring or genetically modified, can absorb contaminants such as heavy metals, pesticides, petroleum hydrocarbons, and radionuclides, reducing their bioavailability in the environment (Pilon-Smits 2005). The effectiveness of phytoremediation depends on several factors, including the type of pollutant, the characteristics of the contaminated site, and the plant species used. Understanding the principles underlying this process is essential for optimizing its application and maximizing its benefits (Ali et al. 2013).

The principles of phytoremediation are grounded in plant physiology, soil science, and environmental chemistry. At the core of this process is the plant's ability to interact with contaminants through various mechanisms, including uptake, accumulation, degradation, and stabilization. These mechanisms are supported by the plant's root system, which plays a crucial role in accessing and transforming pollutants in the soil and water (Macek et al. 2000). Additionally, the rhizosphere, the area surrounding the plant roots, is a hotspot of microbial activity, where beneficial microorganisms enhance phytoremediation by breaking down contaminants and facilitating their uptake by plants (Sarwar et al. 2017).

One of the primary advantages of phytoremediation is its ability to remediate large areas of contaminated land with minimal disturbance to the environment. Unlike traditional methods that often involve the excavation and disposal of contaminated soil, phytoremediation works in situ, meaning that the remediation occurs directly at the site of contamination (Macek et al. 2000). This reduces the risk of secondary contamination and helps preserve the integrity of the ecosystem. Moreover, phytoremediation can improve soil health and promote biodiversity by enhancing soil structure, increasing organic matter content, and providing habitat for wildlife (Pulford and Watson 2003).

Phytoremediation is also a visually appealing remediation strategy, as it transforms contaminated sites into green spaces that can be used for recreational purposes, wildlife habitat restoration, or even agricultural production after successful remediation (Salt et al. 1998; Aransiola et al. 2013). Additionally, the plants used in phytoremediation can provide economic benefits, such as the production of biomass for bioenergy or the recovery of valuable metals through a process known as phytomining (Ghosh and Singh 2005). However, the success of phytoremediation depends on the careful selection of plant species and the appropriate management of the site to ensure that the contaminants are effectively removed or neutralized (Pilon-Smits 2005).

Phytoremediation can be categorized into several types, each targeting specific pollutants and environmental matrices. The selection of the appropriate phytoremediation strategy depends on the nature of the contamination and the desired outcome of the remediation process (Ali et al. 2013). Table 10.1 contains potential of some species of plant for phytoremediation.

Table 10.1 Potential of some species of plant for phytoremediation

S/n	Plant species	Pollutant	Remediation results	References
1	*Brassica juncea*	Heavy metals (Lead, Cadmium)	Significant reduction of lead and cadmium in contaminated soil.	Salt et al. (1995)
2	*Phragmites australis*	Nutrients (Nitrogen, Phosphorus)	Reduced nutrient levels in wastewater	Vymazal (2007)
3	*Helianthus annuus*	Arsenic	Accumulation and reduction of arsenic in contaminated soil	Tangahu et al. (2011)
4	*Salix viminalis*	Heavy metals (Cadmium, Zinc)	Successful accumulation of cadmium and zinc from contaminated soil.	Keller et al. (2003)
5	*Lemna minor*	Organic pollutants (PCBs)	Degradation of PCBs in contaminated water	Reinhold et al. (2010)
6	*Spartina alterniflora*	Hydrocarbons	Degradation and reduction of hydrocarbons in wetland soils	Lin and Mendelssohn (1998)
7	*Arundo donax*	Heavy metals (Cadmium, Lead)	Significant uptake and reduction of cadmium and lead from soils	Pilu et al. (2012)

10.2.1 Phytoextraction

Phytoextraction is a specialized form of phytoremediation, a green technology that uses plants to clean up contaminated environments. This process involves the uptake of contaminants, particularly heavy metals, from the soil and their accumulation in the above-ground parts of plants, which are then harvested and disposed of or recycled (Ali et al. 2013). Over the past few decades, phytoextraction has emerged as a promising, cost-effective, and environmentally friendly method for remediating contaminated soils, particularly those polluted by heavy metals from industrial activities, mining, and agricultural practices (Salt et al. 1998). The process not only reduces the bioavailability of harmful substances in the environment but also offers the potential for recovering valuable metals through phytomining (Ghosh and Singh 2005; Aransiola et al. 2019).

Phytoextraction is based on the ability of plants to absorb contaminants from the soil through their root systems and translocate them to the aerial parts of the plant, such as stems, leaves, and shoots. This process is influenced by several key mechanisms, including root uptake, translocation, and accumulation of contaminants in the plant tissues (Rascio and Navari-Izzo 2011; Aransiola et al. 2024). The uptake of contaminants by plant roots is the first step in phytoextraction. This process occurs through active or passive transport mechanisms, depending on the nature of the contaminant and the plant species. Active uptake involves the use of energy to transport ions across cell membranes, while passive uptake relies on diffusion and osmosis (Verbruggen et al. 2009). The efficiency of root uptake is influenced by factors such as soil pH, contaminant concentration, and the presence of chelating agents, which can increase the solubility and mobility of contaminants in the soil (Evangelou et al. 2007).

After contaminants are absorbed by the roots, they are translocated to the above-ground parts of the plant via the plant's vascular system, primarily through the xylem (Kramer 2010). Translocation depends on the plant's ability to move contaminants efficiently from the roots to the shoots. The efficiency of this process is influenced by the plant's physiological characteristics, such as transpiration rate and the presence of specific transport proteins that facilitate the movement of contaminants (Verbruggen et al. 2009). Once contaminants reach the aerial parts of the plant, they are stored in vacuoles or bound to cell wall components in the leaves, stems, and shoots (Kramer 2010). The ability of a plant to accumulate high levels of contaminants without suffering toxicity is a critical factor in the success of phytoextraction. Hyperaccumulator plants, which have developed unique physiological and biochemical mechanisms to tolerate and store large amounts of contaminants, are often used in phytoextraction (Baker et al. 2020).

Several factors influence the efficiency of phytoextraction, including plant species, soil properties, and the characteristics of the contaminant. The selection of appropriate plant species is one of the most important factors in phytoextraction. Hyperaccumulator plants, which can tolerate and accumulate high levels of contaminants, are often preferred for this purpose. Examples of hyperaccumulators include *Brassica juncea* (Indian mustard), *Thlaspi caerulescens* (Alpine pennycress), and *Pteris vittata* (Chinese brake fern) (Baker et al. 2020). These plants have developed unique adaptations, such as enhanced root uptake, efficient translocation, and the ability to sequester contaminants in vacuoles, which make them ideal for phytoextraction (Verbruggen et al. 2009).

Soil properties, such as pH, texture, organic matter content, and nutrient levels, play a significant role in the phytoextraction process. Soil pH, for example, affects the solubility and mobility of contaminants, with acidic soils generally increasing the availability of heavy metals for plant uptake (Evangelou et al. 2007). Soil texture influences the ease with which roots can penetrate the soil and access contaminants, while organic matter content affects the binding and mobility of contaminants in the soil (Ali et al. 2013). The nature of the contaminant itself also affects the efficiency of phytoextraction. Heavy metals, for instance, differ in their bioavailability and mobility in the soil, which influences their uptake by plants. Metals such as cadmium (Cd) and zinc (Zn) are more readily absorbed by plants compared to lead (Pb) and chromium (Cr), which tend to be more strongly bound to soil particles (Rascio and Navari-Izzo 2011). The chemical form of the contaminant, as well as its concentration in the soil, also plays a crucial role in determining its phytoextraction potential (Verbruggen et al. 2009).

To improve the efficiency of phytoextraction, soil amendments can be used to increase the bioavailability of contaminants and enhance their uptake by plants. Chelating agents, for example, are compounds that bind to metal ions, increasing their solubility and mobility in the soil (Evangelou et al. 2007). Common chelating agents used in phytoextraction include ethylenediaminetetraacetic acid (EDTA) and ethylenediaminedisuccinic acid (EDDS) (Ali et al. 2013). While chelating agents can significantly enhance metal uptake, their use must be carefully managed to prevent leaching and contamination of groundwater. Other soil amendments, such as organic matter and fertilizers, can also improve the effectiveness of phytoextraction. Organic matter can enhance soil structure, increase microbial activity, and improve nutrient availability, all of which can promote plant growth and contaminant uptake (Ghosh and Singh 2005). Fertilizers, particularly those containing nitrogen, phosphorus, and potassium, can support plant growth and increase biomass production, leading to higher contaminant removal (Pulford and Watson 2003).

Phytomining is a specialized form of phytoextraction that involves the use of plants to recover economically valuable metals from contaminated soils. This process is particularly relevant for metals such as nickel (Ni), cobalt (Co), and gold (Au), which can be accumulated in high concentrations by hyperaccumulator plants (Baker et al. 2020). After harvesting, the plant biomass is processed to extract the metals, which can then be sold for profit. Phytomining offers a unique opportunity to combine environmental remediation with resource recovery, making it an attractive option for contaminated sites where valuable metals are present (Ghosh and Singh 2005).

Phytoextraction offers several advantages over traditional remediation methods. One of the primary benefits is its cost-effectiveness. Compared to physical and chemical remediation techniques, which often require significant investment in equipment, labor, and disposal, phytoextraction is relatively inexpensive and can be implemented with minimal disruption to the environment (Ali et al. 2013). Another advantage of phytoextraction is its environmental sustainability. Unlike traditional methods that may involve the excavation and disposal of contaminated soil, phytoextraction works in situ, meaning that the contaminants are removed directly from the soil without disturbing the site. This reduces the risk of secondary contamination and helps preserve the integrity of the ecosystem (Salt et al. 1998).

Phytoextraction also has the potential to improve soil health and promote biodiversity. By increasing organic matter content, enhancing soil structure, and providing habitat for wildlife, phytoextraction can contribute to the restoration of degraded ecosystems (Pulford and Watson 2003). Additionally, the plants used in phytoextraction can provide economic benefits, such as the production of biomass for bioenergy or the recovery of valuable metals through phytomining (Ghosh and Singh 2005).

Despite its potential, phytoextraction has several limitations that can restrict its applicability. One of the main challenges is the time required for effective remediation. Phytoextraction is generally a slow process, and it may take several years or even decades to achieve significant reductions in contaminant levels, especially in highly contaminated sites (Ali et al. 2013). This extended time frame can be a drawback for sites that require immediate remediation. Another limitation is the depth of contamination. Most plants have shallow root systems, which limits the effectiveness of phytoextraction to the upper layers of soil. Contaminants located at greater depths may not be accessible to the plants, reducing the overall effectiveness of the remediation process (Kramer 2010). The potential for contaminant leaching and volatilization is another concern. In some cases, contaminants may be released back into the environment during the phytoextraction process, leading to the redistribution of pollutants rather than their removal. Careful site management and the use of appropriate soil amendments can help mitigate these risks, but they cannot be entirely eliminated (Evangelou et al. 2007). Additionally, the disposal of contaminated plant biomass presents a challenge. After harvesting, the plant material must be safely disposed of or processed to recover the contaminants. This can be a complex and costly process, particularly for plants that have accumulated high levels of toxic metals (Rascio and Navari-Izzo 2011).

10.2.2 Phytodegradation

Phytodegradation is a specialized form of phytoremediation that involves the use of plants to degrade organic contaminants in the environment. Unlike other forms of phytoremediation, which focus on the removal or stabilization of contaminants, phytodegradation specifically targets the breakdown of organic pollutants through biological and chemical processes facilitated by plant systems (Ghosh and Singh 2005). This process leverages the natural metabolic activities of plants and their associated microorganisms to transform harmful substances into less toxic or non-toxic forms, ultimately leading to the remediation of contaminated sites (Moosavi and Seghatoleslami 2013).

Phytodegradation encompasses several key mechanisms through which plants and their associated microorganisms contribute to the degradation of organic contaminants. These mechanisms include the uptake and accumulation of contaminants, the enzymatic breakdown of pollutants, and the transformation of contaminants into less harmful products (Kumar et al. 2019). The initial step in phytodegradation involves the uptake of contaminants by plant roots from the soil or water. This uptake is often facilitated by plant root systems, which can absorb organic pollutants from the surrounding environment (Ghosh and Singh 2005). Once inside the plant, contaminants may be transported to different tissues and accumulate in various cellular compartments, where they can be further metabolized or transformed. One of the central mechanisms of phytodegradation is the enzymatic breakdown of contaminants. Plants produce a range of enzymes, such as peroxidases, laccases, and dioxygenases, that can degrade organic pollutants (Wei et al. 2021). These enzymes are involved in various biochemical reactions that break down complex organic molecules into simpler, less toxic forms. For example, peroxidases can catalyze the oxidation of aromatic hydrocarbons, while laccases can degrade lignin and other phenolic compounds (Kumar et al. 2019).

Plants also support microbial communities in their rhizospheres, which play a crucial role in the degradation of organic contaminants. These microorganisms, including bacteria and fungi, can further metabolize contaminants that are taken up by the plant or present in the soil (Miller and Jastrow 2013). The interactions between plants and microbes create a synergistic effect, enhancing the overall degradation process. After contaminants are taken up by plants and broken down by enzymes, they may undergo further transformation into less toxic forms. For instance, some contaminants can be converted into non-toxic or less toxic metabolites through processes such as hydroxylation, methylation, or conjugation (Wei et al. 2021). These transformed products can be stored in plant tissues or further degraded by soil microorganisms.

Phytodegradation is effective against a wide range of organic contaminants, including pesticides, solvents, petroleum hydrocarbons, and polycyclic aromatic hydrocarbons (PAHs). Understanding the types of contaminants that can be degraded by plants is essential for selecting appropriate species and optimizing remediation strategies (Moosavi and Seghatoleslami 2013). Phytodegradation has been successfully used to remediate soils contaminated with pesticides, such as atrazine, chlorpyrifos, and parathion. Plants can degrade these compounds through enzymatic processes or by promoting microbial activity in the rhizosphere (Wei et al. 2021). For example, Panicum maximum and Brassica juncea have been shown to effectively degrade atrazine in contaminated soils (Ghosh and Singh 2005). Organic solvents, such as trichloroethylene (TCE) and tetrachloroethylene (PCE), are common environmental contaminants resulting from industrial activities. Plants can degrade these solvents through processes such as phytotransformation and microbial degradation. Populus species, for instance, have demonstrated the ability to degrade TCE and PCE in contaminated groundwater (Miller and Jastrow 2013). Petroleum hydrocarbons, including benzene, toluene, ethylbenzene, and xylenes (BTEX), are major pollutants from oil spills and industrial discharges. Phytodegradation can effectively remediate petroleum-contaminated soils by promoting the microbial degradation of these hydrocarbons or by direct plant uptake and metabolism (Moosavi and Seghatoleslami 2013). Canna indica and Helianthus annuus are examples of plants used for this purpose (Ghosh and Singh 2005). Polycyclic Aromatic Hydrocarbons (PAHs) are a group of organic compounds with multiple aromatic rings that are resistant to degradation. Phytodegradation can target PAHs by enhancing microbial activity in the rhizosphere or by direct enzymatic breakdown within plant tissues (Kumar et al. 2019). Plants such as Phragmites australis and Salix species have shown promise in degrading PAHs in contaminated soils (Wei et al. 2021).

Several factors influence the efficiency of phytodegradation, including plant species, environmental conditions, and contaminant characteristics. Optimizing these factors is crucial for achieving successful remediation outcomes (Moosavi and Seghatoleslami 2013). The selection of appropriate plant species is critical for effective phytodegradation. Plants with high metabolic activity and the ability to produce specific enzymes required for contaminant degradation are preferred. Hyperaccumulator plants, which have evolved mechanisms to tolerate and degrade high levels of contaminants, are often used in phytoremediation (Ghosh and Singh 2005). Additionally, plant species with extensive root systems and high biomass production can enhance contaminant uptake and degradation. Environmental conditions, such as soil pH, temperature, and moisture, can significantly impact the efficiency of phytodegradation. Soil pH affects the availability and mobility of contaminants, with acidic or alkaline conditions potentially influencing the activity of plant enzymes and microbial communities (Miller and Jastrow 2013). Temperature and moisture levels also affect plant growth and metabolic activity, which can in turn impact the rate of contaminant degradation (Wei et al. 2021).

The chemical properties of contaminants, such as their solubility, persistence, and toxicity, play a role in their degradation. Contaminants that are highly soluble and easily taken up by plants are generally more amenable to phytodegradation. In contrast, contaminants with low solubility or high persistence may require additional strategies, such as soil amendments or microbial inoculation, to enhance their degradation (Kumar et al. 2019).

To improve the efficiency of phytodegradation, soil amendments and microbial inoculation can be employed. These strategies aim to enhance the bioavailability of contaminants, promote plant growth, and support the activity of degrading microorganisms (Moosavi and Seghatoleslami 2013). Soil amendments, such as organic matter, fertilizers, and chelating agents, can be used to improve phytodegradation outcomes. Organic matter can enhance soil structure, increase microbial activity, and improve nutrient availability, all of which contribute to better plant growth and contaminant degradation (Wei et al. 2021). Fertilizers can support plant growth and increase biomass production, leading to higher rates of contaminant uptake and degradation. Chelating agents can increase the solubility and mobility of contaminants, making them more accessible to plants (Ghosh and Singh 2005).

The introduction of specific microorganisms into the rhizosphere can enhance the degradation of organic contaminants. These microorganisms, including bacteria and fungi, can work in synergy with plants to break down contaminants through their metabolic activities (Miller and Jastrow 2013). Microbial inoculation can be particularly effective for contaminants that are resistant to plant-mediated degradation. For example, the addition of specific bacterial strains capable of degrading chlorinated solvents or PAHs can improve the overall remediation process (Kumar et al. 2019).

10.2.3 Phytostabilization

Phytostabilization is a method of phytoremediation designed to stabilize contaminants in soil and water, preventing their migration and reducing their bioavailability. Unlike other phytoremediation techniques that focus on the removal or degradation of pollutants, phytostabilization aims to immobilize contaminants, thereby mitigating their environmental and health risks (Salt et al. 1998). This process involves the use of plants to reduce the mobility and bioavailability of contaminants, thus preventing their spread into the ecosystem. Phytostabilization operates through several mechanisms that collectively reduce the movement and availability of contaminants.

Plants can uptake contaminants through their root systems. While not all contaminants are translocated to aerial parts, their immobilization in root tissues can reduce their availability to soil and water. This process is particularly relevant for heavy metals and metalloids (McGrath and Zhao 2003). Plants with extensive root systems can trap and retain contaminants in the rhizosphere, thus preventing their further migration. Plants release various organic compounds into the soil through their roots, known as root exudates. These exudates can form complexes with contaminants, particularly heavy metals, thus reducing their solubility and mobility. For example, organic acids and phosphates released by plants can bind with metal ions, effectively immobilizing them (Kumpiene et al. 2008). Phytostabilization can involve the formation of metal-organic complexes within plant tissues. Plants often produce chelating agents such as phytochelatins and metallothioneins that bind metal ions, thereby reducing their availability and toxicity. This mechanism is crucial for stabilizing heavy metals in contaminated soils (Pilon-Smits 2005).

Plant root systems can improve soil structure by increasing soil aggregation and reducing soil erosion. This physical stabilization helps prevent the dispersion of contaminants into surrounding areas. Additionally, the presence of vegetation can reduce surface runoff and erosion, which further limits the movement of contaminants (Pulford and Watson 2003). The rhizosphere is home to various microorganisms that can assist in the stabilization of contaminants. These microbes can interact with plant roots and contribute to the immobilization and transformation of contaminants. For instance, certain bacteria can precipitate metal ions as insoluble compounds, further reducing their mobility (Xu et al. 2021).

Phytostabilization is particularly effective for dealing with contaminants that are persistent and have low mobility, such as heavy metals and metalloids. Key contaminants addressed by phytostabilization includes heavy metals like lead (Pb), cadmium (Cd), zinc (Zn), and arsenic (As) are commonly targeted by phytostabilization efforts. These metals are often present in contaminated soils and can pose significant health risks. Plants used in phytostabilization can immobilize these metals through various mechanisms, including root uptake, complexation with root exudates, and soil amendments (McGrath and Zhao 2003). Metalloids such as arsenic and selenium are also of concern in phytostabilization. Arsenic, for example, can be stabilized in soil through the formation of insoluble arsenic compounds or by reducing its bioavailability through root exudates (Xu et al. 2021). Selenium can be stabilized by forming selenides or selenites in the soil, reducing its mobility and bioavailability. While phytostabilization is less commonly used for organic contaminants compared to metals, it can still play a role in immobilizing certain persistent organic pollutants. For instance, plants can stabilize some organic compounds by enhancing microbial degradation in the rhizosphere or by forming complexes with these compounds (Pilon-Smits 2005).

10.2.4 Phytovolatilization

Phytovolatilization is a specialized phytoremediation technique that involves the use of plants to remove contaminants from the soil or water and subsequently release them into the atmosphere in a less harmful or transformed form (Burken and Ma 2006). This process primarily targets volatile organic compounds (VOCs), such as certain solvents and halogenated compounds, which can be transported through the plant and emitted into the air via transpiration and volatilization processes (Cristaldi et al. 2017). By harnessing the natural metabolic capabilities of plants, phytovolatilization offers an innovative approach to managing and mitigating environmental contaminants.

Phytovolatilization operates through several key mechanisms, including the uptake of contaminants, their transport through the plant, and their release into the atmosphere. The initial stage of phytovolatilization involves the uptake of volatile contaminants by plant roots from contaminated soil or water. This process relies on the plant's ability to absorb contaminants through its root system. The uptake efficiency can be influenced by factors such as root density, plant species, and contaminant concentration (Burken and Ma 2006). Once contaminants are absorbed by the roots, they are transported through the plant's vascular system to the aerial parts. This transport occurs via the xylem and phloem, which move water and nutrients throughout the plant. The efficiency of this transport process depends on plant physiology, including root structure, stem vascularization, and leaf surface area (Cristaldi et al. 2017).

The final stage of phytovolatilization involves the release of contaminants into the atmosphere. This occurs primarily through transpiration, where water vapor and volatile compounds are expelled from the plant's leaves. Volatilization can also occur through direct evaporation from plant surfaces. The rate of emission is influenced by environmental factors such as temperature, humidity, and wind speed (Abdullah et al. 2020). Some contaminants may undergo biochemical transformation within the plant before being volatilized. Plants can metabolize volatile compounds into less harmful forms, which are then emitted. This detoxification process can involve various enzymatic reactions, such as hydroxylation or conjugation, that modify the chemical structure of contaminants (Cristaldi et al. 2017).

Phytovolatilization is particularly effective for certain types of volatile contaminants, including:

Halogenated Compounds: Halogenated VOCs, such as trichloroethylene (TCE), tetrachloroethylene (PCE), and carbon tetrachloride, are commonly targeted by phytovolatilization. These compounds are often used in industrial processes and can be persistent environmental pollutants. Plants such as Populus spp. and Salix spp. have shown the ability to volatilize these halogenated compounds effectively (Abdullah et al. 2020).

Solvents: Organic solvents like benzene, toluene, ethylbenzene, and xylenes (BTEX) are also amenable to phytovolatilization. These compounds are frequently found in petroleum products and industrial waste. Plants capable of volatilizing these solvents can help manage contamination in areas affected by oil spills and industrial activities (Burken and Ma 2006).

Pesticides: Certain pesticides, particularly those with volatile properties, can be targeted by phytovolatilization. For example, herbicides such as atrazine and glyphosate have been studied for their potential volatilization from plant tissues.

The ability of plants to volatilize these pesticides can aid in the management of agricultural residues (Cristaldi et al. 2017).

Aromatic Compounds: Aromatic compounds, such as toluene and naphthalene, are another class of VOCs that can be managed through phytovolatilization. These compounds are commonly found in industrial effluents and can pose environmental and health risks. Plants that can volatilize these aromatic compounds contribute to the reduction of pollution in affected areas (Abdullah et al. 2020).

10.2.5 Rhizofiltration

Rhizofiltration is a phytoremediation technology that utilizes plant roots to absorb, concentrate, and remove contaminants from aqueous environments, such as contaminated groundwater or wastewater (Laghlimi et al. 2015). This technique primarily targets heavy metals, metalloids, and organic pollutants present in water. By leveraging the natural processes of plant root systems, rhizofiltration offers a sustainable and cost-effective approach to managing and mitigating environmental pollution (Salt et al. 1998).

Rhizofiltration operates through several key mechanisms, including the uptake of contaminants, their accumulation in root tissues, and the subsequent removal of contaminants from the water. The initial stage of rhizofiltration involves the absorption of contaminants from the surrounding water by plant roots. This process relies on the plant's root system to interact with the aqueous environment and take up contaminants through mechanisms such as passive diffusion and active transport (Laghlimi et al. 2015). The effectiveness of uptake depends on factors such as root surface area, plant species, and contaminant concentration. Once contaminants are absorbed by the roots, they are concentrated within the root tissues. This accumulation can occur through various mechanisms, including binding to root cell walls, sequestration in vacuoles, or complexation with root exudates (Salt et al. 1998). The ability of plants to accumulate contaminants is influenced by the chemical properties of the contaminants, such as their solubility and reactivity. The final stage of rhizofiltration involves the removal of accumulated contaminants from the root system. This can occur through various methods, including periodic harvesting of plant biomass, treatment of root tissues, or disposal of contaminated plant material (Laghlimi et al. 2015). Effective management of plant biomass is essential to prevent the re-release of contaminants into the environment. In addition to physical accumulation, some plants can detoxify contaminants through biochemical processes. For example, plants may convert toxic substances into less harmful forms through enzymatic reactions or metabolic pathways. This detoxification can further enhance the effectiveness of rhizofiltration by reducing the toxicity of contaminants (Salt et al. 1998).

Rhizofiltration is particularly effective for addressing a range of contaminants, including heavy metals, metalloids, and organic pollutants.

Heavy Metals Heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) are commonly targeted by rhizofiltration. These metals can be toxic to plants, animals, and humans, making their removal from contaminated water a priority (Babaniyi et al. 2023). Plants such as Helianthus annuus (sunflower), Brassica juncea (Indian mustard), and Pteris vittata (Chinese brake fern) have shown effectiveness in removing heavy metals through rhizofiltration (Gavrilescu 2022).

Metalloids Metalloids like arsenic (As) and selenium (Se) are also amenable to rhizofiltration. These elements can pose significant health risks when present in high concentrations in water. Plants can take up and accumulate metalloids, thereby reducing their levels in contaminated water sources (Laghlimi et al. 2015).

Organic Pollutants Organic pollutants, including pesticides and solvents, can be targeted by rhizofiltration. Plants that can uptake and accumulate organic contaminants from water help in managing pollution from agricultural and industrial sources. While less common than heavy metals, the rhizofiltration of organic pollutants is an area of ongoing research (Salt et al. 1998).

10.2.6 Effectiveness of Phytoremediation in Wetland Management

Phytoremediation is an effective strategy for managing contaminants in wetlands due to the specific characteristics of wetland plants and their interactions with the contaminated environment. Wetlands are naturally equipped to handle various pollutants through biological, chemical, and physical processes. The effectiveness of phytoremediation in these ecosystems can be attributed to several factors, including plant adaptability, the natural filtering capacity of wetlands, and the integration of plant processes into the overall remediation strategy (Mitsch and Gosselink 2015).

10.2.6.1 Plant Adaptability

Wetland plants are uniquely adapted to their environments, which often include challenging conditions such as high moisture levels and variable nutrient availability. This adaptability extends to their ability to interact with contaminants in their surroundings. Plants such as Typha spp. (cattails) and Phragmites australis (common reed) have evolved mechanisms to cope with waterlogged soils and can effectively uptake and accumulate pollutants, including heavy metals and organic compounds (Veselá et al. 2021). Their tolerance to extreme conditions makes them suitable candidates for phytoremediation in wetland environments.

10.2.6.2 Natural Filtering Capacity

Wetlands act as natural filters, capturing sediments and pollutants from water before it flows to other ecosystems. This filtering capability is enhanced by the presence of wetland plants, which can further improve water quality through phytoremediation processes. For instance, Schoenoplectus californicus (California bulrush) can remove excess nutrients and heavy metals from water, thus contributing to the overall health of the wetland ecosystem (Ghavzan and Trivedy 2005). The integration of plant-based remediation with natural wetland functions results in a more comprehensive approach to managing contamination.

10.2.6.3 Integration of Plant Processes

Phytoremediation involves various plant processes that work synergistically to address contamination. These processes include the uptake, accumulation, and detoxification of contaminants. Wetland plants can absorb pollutants from the water and soil, concentrate them in their tissues, and either detoxify them or facilitate their removal from the environment. This integration of plant processes into wetland management enhances the overall effectiveness of phytoremediation strategies (Ansari et al. 2014).

10.3 Applications of Wetland Phytoremediation

10.3.1 Treatment of Industrial Wastewater

Industrial wastewater treatment is a critical concern in environmental management, given the potential for various pollutants to degrade ecosystems and harm human health. Traditional wastewater treatment methods, such as chemical precipitation, activated carbon adsorption, and ion exchange, can be expensive and generate secondary waste. In contrast, phytoremediation, particularly in the context of wetlands, offers a sustainable, cost-effective, and ecologically sound alternative for treating industrial wastewater. Wetland phytoremediation harnesses the natural abilities of plants to absorb, accumulate, and detoxify pollutants, making it a valuable tool for industries such as mining, agriculture, and textiles (Vymazal 2011).

10.3.1.1 Treatment of Industrial Wastewater in Mining

Mining activities often result in the production of large volumes of wastewater, contaminated with heavy metals, metalloids, and other toxic substances. These pollutants, if not properly managed, can lead to severe environmental degradation, including soil and water contamination, biodiversity loss, and adverse health impacts on local communities (Sheoran and Sheoran 2006). Wetland phytoremediation offers a promising solution for treating mining wastewater by utilizing the natural capabilities of wetland plants to remove or stabilize contaminants (Thompson et al. 2019).

Heavy metals such as arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg) are common pollutants in mining wastewater. Wetland plants, including Phragmites australis (common reed) and Typha latifolia (broadleaf cattail), have been extensively studied for their ability to uptake and accumulate these metals in their tissues, thereby reducing their concentration in the water (Vymazal 2010). For instance, Phragmites australis has been shown to remove up to 85% of lead and cadmium from contaminated water, making it an effective tool for mitigating heavy metal pollution in mining-affected wetlands (Yang and Shen 2020).

Acid mine drainage (AMD) is a major environmental concern associated with mining activities, particularly in coal and metal mining. AMD occurs when sulfide minerals in exposed rock surfaces oxidize upon contact with water and oxygen, producing sulfuric acid and dissolving heavy metals into the surrounding water. The acidic and metal-laden water can devastate aquatic ecosystems and contaminate drinking water sources (Fitamo and Leta 2010). Wetland phytoremediation, through the use of plants such as Juncus effusus (common rush) and Carex rostrata (beaked sedge), has been employed to neutralize acidity and remove metals from AMD (Sheoran and Sheoran 2006). These plants can raise the pH of the water and precipitate metals as less soluble compounds, reducing their mobility and toxicity.

10.3.1.2 Treatment of Agricultural Wastewater

Agricultural activities contribute significantly to water pollution through the runoff of fertilizers, pesticides, and animal waste into nearby water bodies. These pollutants can cause eutrophication, algal blooms, and contamination of drinking water sources. Wetland phytoremediation offers a natural and sustainable method for treating agricultural wastewater by using plants to absorb and transform pollutants before they reach sensitive aquatic ecosystems.

Excessive nitrogen (N) and phosphorus (P) from fertilizers are primary contributors to nutrient pollution in agricultural wastewater. Wetland plants such as Typha spp. (cattails) and Scirpus spp. (bulrushes) have demonstrated the ability to uptake and assimilate these nutrients into their biomass, thereby reducing nutrient levels in the water (Vymazal 2011). Studies have shown that constructed wetlands planted with these species can remove up to 70–90% of nitrogen and phosphorus from agricultural runoff, significantly improving water quality (Kadlec 2009).

Pesticides used in agriculture can contaminate water bodies through surface runoff, leading to harmful effects on aquatic life and human health. Wetland phytoremediation can degrade and detoxify these pesticides through processes such as phytodegradation and rhizodegradation. Plants like Spartina alterniflora (smooth cordgrass) and Phragmites australis have been found to enhance the microbial breakdown of pesticides in the rhizosphere, reducing their persistence in the environment (Dzantor 2007). The roots of these plants provide a habitat for microbial communities that can degrade pesticide molecules into less toxic forms, further mitigating their environmental impact.

Animal waste from livestock operations is another source of agricultural pollution, particularly through the release of pathogens and nutrients into water bodies. Constructed wetlands planted with species such as Juncus effusus and Scirpus validus (softstem bulrush) have been used to treat wastewater from animal farms by filtering out solids, absorbing nutrients, and reducing pathogen loads (Vymazal 2010). These wetlands can effectively reduce biochemical oxygen demand (BOD), total suspended solids (TSS), and fecal coliform bacteria in agricultural wastewater, contributing to the overall health of downstream ecosystems.

10.3.1.3 Treatment of Textile Industry Wastewater

The textile industry is one of the most water-intensive industries globally, generating large volumes of wastewater contaminated with dyes, chemicals, and heavy metals. The complex composition of textile wastewater, which includes both organic and inorganic pollutants, poses significant challenges for traditional treatment methods. Wetland phytoremediation offers an alternative approach to treating textile wastewater, utilizing the ability of plants to absorb, degrade, and stabilize contaminants.

Dyes are a major pollutant in textile wastewater, often resistant to degradation and toxic to aquatic life. Wetland plants, such as Phragmites australis and Typha latifolia, have been investigated for their ability to remove and degrade dyes from wastewater (Vymazal 2010). The rhizosphere of these plants supports microbial communities that can break down dye molecules, while the plants themselves can absorb and accumulate dyes in their tissues. Studies have shown that constructed wetlands can remove up to 90% of certain textile dyes, depending on the plant species and environmental conditions (Hussein and Scholz 2017).

Textile wastewater often contains heavy metals such as chromium (Cr), zinc (Zn), and copper (Cu), which are used in dyeing and finishing processes. These metals can be toxic to aquatic organisms and pose risks to human health if they enter drinking water supplies. Wetland plants like Scirpus validus and Juncus effusus have been shown to stabilize heavy metals in the soil and sediments of constructed wetlands, reducing their bioavailability and preventing their movement into water bodies (Vymazal 2011). This stabilization process helps mitigate the environmental impact of heavy metals from textile wastewater.

The textile industry uses a wide range of chemicals, including surfactants, solvents, and bleaching agents, which can contaminate wastewater. Wetland phytoremediation can degrade these chemicals through processes such as phytodegradation and rhizodegradation. Plants like Spartina alterniflora and Phragmites australis have been found to facilitate the breakdown of organic chemicals in the rhizosphere, reducing their toxicity and persistence in the environment (Dzantor 2007). The root systems of these plants provide a habitat for microorganisms that can degrade complex chemical compounds into simpler, less harmful substances.

10.3.2 Remediation of Agricultural Runoff

Agricultural runoff, rich in nutrients, pesticides, and herbicides, poses significant threats to water quality and ecosystem health. As agricultural activities expand, the challenges of managing the environmental impacts of runoff have become increasingly pressing. Traditional approaches to mitigate these effects, such as chemical treatments and structural barriers, often come with limitations, including high costs and the risk of secondary pollution. Wetland phytoremediation, which uses plants to absorb, degrade, or stabilize contaminants, presents an effective and sustainable alternative for managing agricultural runoff (Vymazal 2011).

10.3.2.1 Nutrient Removal in Agricultural Runoff

Agricultural runoff is a major source of nutrient pollution, particularly nitrogen (N) and phosphorus (P), which are introduced into the environment through the use of fertilizers. These nutrients, when present in excessive amounts, can lead to eutrophication, a process characterized by excessive plant and algal growth in water bodies, followed by oxygen depletion and the decline of aquatic life (Smith and Schindler 2009). Wetland phytoremediation offers a natural and effective means of removing these nutrients from runoff before they reach sensitive aquatic ecosystems.

Nitrates, a common form of nitrogen in agricultural runoff, pose serious environmental risks. High nitrate levels can lead to eutrophication and pose health risks to humans, such as methemoglobinemia or "blue baby syndrome," particularly in infants (Camargo and Alonso 2006). Wetland plants, such as Typha spp. (cattails) and Phragmites australis (common reed), play a critical role in nitrate removal through processes such as uptake, microbial denitrification, and sedimentation (Vymazal 2007).

Wetland plants absorb nitrates through their roots and incorporate them into their biomass, effectively reducing nitrate concentrations in the water. Additionally, the anaerobic conditions often found in wetlands promote microbial denitrification, a process in which nitrate is converted into nitrogen gas (N_2) and released into the atmosphere, thus permanently removing nitrogen from the water system (Reddy et al. 1999). Studies have shown that constructed wetlands can achieve nitrate removal efficiencies of up to 90%, depending on the plant species, wetland design, and environmental conditions (Vymazal 2011).

Phosphorus, primarily in the form of phosphates, is another key nutrient contributing to eutrophication in water bodies (Ogundele et al. 2023). Unlike nitrogen, phosphorus does not have a gaseous form that can be released into the atmosphere, making its removal more challenging. Wetland phytoremediation addresses this challenge through plant uptake, adsorption to soil particles, and incorporation into sediments (Kadlec 2009). Plants like Scirpus spp. (bulrushes) and Juncus effusus (soft rush) have been found to be effective in removing phosphates from agricultural runoff (Vymazal 2007). These plants absorb phosphates through their root systems and store them in their tissues. Additionally, phosphates can bind to soil particles and organic matter within the wetland, where they are less likely to be released back into the water column. Constructed wetlands have been shown to reduce phosphate concentrations by 60–80%, depending on the specific conditions and management practices (Kadlec 2009).

10.3.2.2 Pesticide and Herbicide Degradation in Agricultural Wetlands

Pesticides and herbicides used in agriculture can contaminate surface and groundwater through runoff, posing risks to aquatic ecosystems and human health (Babaniyi et al. 2024). These chemicals are designed to be toxic to specific organisms, but their persistence in the environment can lead to unintended consequences, including the disruption of non-target species and the contamination of drinking water sources (Arias-Estévez et al. 2008). Wetland phytoremediation offers a promising approach to mitigating these risks by degrading and transforming pesticides and herbicides into less harmful substances.

Phytodegradation refers to the breakdown of organic pollutants, such as pesticides, by plants and associated microbial communities. In wetland environments, this process is facilitated by the unique conditions present in the rhizosphere, the zone of soil surrounding plant roots. The rhizosphere hosts a diverse microbial community that can degrade pesticides into less toxic metabolites (Dzantor 2007). Plants such as Spartina alterniflora (smooth cordgrass) and Phragmites australis have been shown to enhance the degradation of pesticides in wetland systems. These plants exude root exudates that stimulate microbial activity, leading to increased breakdown of pesticide molecules (Gleba et al. 1999). For example, wetlands planted with Phragmites australis have demonstrated significant reductions in concentrations of organophosphate pesticides, such as malathion and chlorpyrifos, with removal efficiencies exceeding 80% in some cases (Dzantor 2007).

Rhizodegradation, a subset of phytodegradation, involves the breakdown of contaminants in the rhizosphere, driven primarily by microbial activity. Wetland plants create favorable conditions for rhizodegradation by releasing organic compounds, such as sugars and amino acids, which serve as energy sources for soil microbes (Amora-Lazcano et al. 2010). These microbes, in turn, break down pesticides and herbicides into less harmful compounds, reducing their persistence in the environment.

The effectiveness of rhizodegradation depends on several factors, including the type of pesticide, the microbial community present, and the specific plant species involved. Wetland plants with extensive root systems, such as Scirpus spp. and Typha spp., provide a larger surface area for microbial colonization, enhancing the degradation process (Dzantor 2007). Moreover, the anaerobic conditions often found in wetland sediments can promote the breakdown of certain pesticides that are resistant to degradation under aerobic conditions (Mitsch et al. 2015).

Herbicides, which are used to control unwanted plant species in agriculture, can also be effectively managed through wetland phytoremediation. Wetland plants can transform herbicides into less toxic forms through metabolic processes, reducing their environmental impact. For instance, studies have shown that plants like Eichhornia crassipes (water hyacinth) can uptake and metabolize herbicides such as atrazine, converting them into less harmful compounds that are either stored in plant tissues or volatilized into the atmosphere (Gleba et al. 1999).

Phytovolatilization, the process by which plants uptake contaminants and release them into the atmosphere as volatile compounds, is another important mechanism in the degradation of certain herbicides. While this process does not remove contaminants from the environment entirely, it can reduce their concentration in water and soil, thereby mitigating their impact on aquatic ecosystems (Amora-Lazcano et al. 2010).

10.3.3 Removal of Heavy Metals from Contaminated Water

Wetland ecosystems are recognized for their potential in treating contaminated water, particularly in the removal of heavy metals. Heavy metals, including lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), and arsenic (As), pose significant environmental and public health risks due to their toxicity, persistence, and tendency to bioaccumulate in the food chain (Alloway 2012). Traditional methods for heavy metal remediation, such as chemical precipitation, ion exchange, and membrane filtration, can be costly and may generate secondary pollutants. Wetland phytoremediation offers a cost-effective and sustainable alternative, leveraging the natural processes of wetland plants to absorb, accumulate, and stabilize heavy metals in contaminated water and sediments (Vymazal 2010).

10.3.3.1 Role of Wetland Plants in Bioaccumulation of Heavy Metals

Wetland plants play a crucial role in the removal of heavy metals from contaminated water through processes such as bioaccumulation, phytostabilization, and phytovolatilization. Bioaccumulation refers to the uptake and accumulation of heavy metals in plant tissues, where they can be sequestered and rendered less bioavailable (Salt et al. 1998). The effectiveness of wetland plants in bioaccumulating heavy metals depends on factors such as plant species, metal type, environmental conditions, and the presence of associated microbial communities.

Lead (Pb) Bioaccumulation Lead is one of the most common heavy metals found in contaminated water bodies, primarily due to industrial activities, mining, and the use of leaded gasoline (Nriagu 1990). Wetland plants such as Typha latifolia (common cattail) and Phragmites australis (common reed) have demonstrated a high capacity for lead uptake and accumulation in their roots and shoots. These plants can bioaccumulate lead from contaminated sediments and water, thereby reducing its concentration in the environment. The mechanism of lead uptake involves the absorption of Pb^{2+} ions by plant roots, where they are often sequestered in the vacuoles or cell walls, minimizing their toxicity to the plant (Sharma and Dubey 2005). In some cases, lead can be translocated to the above-ground parts of the plant, where it can be harvested and removed from the site. Studies have shown that Typha latifolia can accumulate lead concentrations up to 1000 mg/kg in its roots, making it an effective species for phytoremediation of lead-contaminated sites.

Mercury (Hg) Bioaccumulation Mercury is a highly toxic heavy metal that poses significant environmental and health risks, particularly in its methylated form (methylmercury), which can bioaccumulate in the food chain (Boening 2000). Wetland plants, such as Juncus effusus (soft rush) and Scirpus spp. (bulrushes), have been studied for their ability to uptake and accumulate mercury from contaminated water and sediments (Weis and Weis 2004). The bioaccumulation of mercury in wetland plants occurs through root uptake, where mercury binds to thiol groups in proteins, forming stable complexes that are stored in the plant tissues (Patra and Sharma 2000). In some instances, mercury can be volatilized by the plant through phytovolatilization, where it is transformed into a less toxic form (elemental mercury) and released into the atmosphere (Meagher and Heaton 2005). However, the efficiency of phytovolatilization depends on the plant species and environmental conditions.Studies have demonstrated that Juncus effusus can accumulate mercury concentrations up to 100 mg/kg in its roots, highlighting its potential for mercury phytoremediation (Weis and Weis 2004). The presence of microbial communities in the rhizosphere also plays a significant role in mercury transformation and uptake, as certain bacteria can methylate or demethylate mercury, influencing its bioavailability and toxicity (Patra and Sharma 2000).

Cadmium (Cd) Bioaccumulation Cadmium is a highly toxic heavy metal commonly found in industrial effluents, mining runoff, and agricultural soils contaminated by phosphate fertilizers (Alloway 2012). Wetland plants such as Phragmites australis and Scirpus validus (soft-stem bulrush) have been shown to bioaccumulate cadmium in their tissues, offering a natural solution for the remediation of cadmium-contaminated water bodies (Liao ShaoWei and Chang WenLian 2004). The uptake of cadmium by wetland plants involves the absorption of Cd^{2+} ions by the roots, where they are often stored in vacuoles or bound to metallothioneins, a group of proteins that help to detoxify heavy metals within the plant (Clemens 2006). Cadmium can also be translocated to the shoots, where it can be harvested and removed from the site. Research has shown that Phragmites australis can accumulate cadmium concentrations up to 500 mg/kg in its roots, making it a suitable candidate for the phytoremediation of cadmium-contaminated wetlands (Liao ShaoWei and Chang WenLian 2004). The efficiency of cadmium bioaccumulation can be enhanced by the presence of mycorrhizal fungi in the rhizosphere, which can increase the surface area for metal uptake and improve plant tolerance to cadmium stress (Göhre and Paszkowski 2006).

Chromium (Cr) Bioaccumulation Chromium, particularly in its hexavalent form (Cr^{6+}), is a highly toxic and carcinogenic heavy metal commonly associated with industrial activities such as leather tanning, electroplating, and textile manufacturing (Alloway 2012). Wetland plants such as Typha angustifolia (narrowleaf cattail) and Phragmites australis have been studied for their ability to bioaccumulate and reduce chromium in contaminated water and sediments (Panda and Choudhury 2005). The mechanism of chromium uptake involves the reduction of Cr^{6+} to Cr^{3+} by plant roots or associated microbial communities, followed by the sequestration of Cr^{3+} in the plant tissues (Shanker et al. 2005). Cr^{3+} is less toxic and less mobile than Cr^{6+}, making its accumulation in plants a key strategy for reducing chromium toxicity in the environment. Studies have shown that Typha angustifolia can accumulate chromium concentrations up to 1200 mg/kg in its roots, demonstrating its potential for chromium phytoremediation (Panda and Choudhury 2005). The presence of certain bacteria in the rhizosphere, such as Pseudomonas spp., can enhance chromium reduction and uptake by producing enzymes that catalyze the reduction of Cr^{6+} to Cr^{3+} (Shanker et al. 2005).

Arsenic (As) Bioaccumulation Arsenic is a toxic metalloid commonly found in groundwater and soils contaminated by mining activities, industrial processes, and the use of arsenic-based pesticides (Smith et al. 1998; Adewumi and Ogundele 2024). Wetland plants such as Pteris vittata (Chinese brake fern) and Eleocharis acicularis (needle spikerush) have been identified as hyperaccumulators of arsenic, capable of accumulating high concentrations of arsenic in their tissues (Ma et al. 2001). The bioaccumulation of arsenic by wetland plants involves the uptake of arsenate (As^{5+}) and arsenite (As^{3+}) ions by the roots, followed by sequestration in the vacuoles or complexation with phytochelatins, which are small peptides that bind heavy metals (Ma et al. 2001). Arsenic can be translocated to the shoots, where it can be harvested and removed from the site. Research has shown that Pteris vittata can accumulate arsenic concentrations up to 20,000 mg/kg in its fronds, making it one of the most effective plants for arsenic phytoremediation (Ma et al. 2001). The presence of certain soil microbes, such as Bacillus spp., can enhance arsenic uptake and tolerance by promoting the reduction of arsenate to arsenite, which is more easily absorbed by plants (Smith et al. 1998).

10.4 Factors Affecting the Efficiency of Phytoremediation in Wetlands

Phytoremediation in wetlands, which utilizes plants to absorb, detoxify, or mitigate contaminants from water, is a promising technique for environmental remediation. However, the efficiency of this process is influenced by various factors, including the selection of plant species, environmental conditions, plant-microbe interactions, and seasonal and climatic variability. Understanding these factors is crucial for optimizing phytoremediation practices in wetland ecosystems.

10.4.1 Plant Species Selection

The selection of appropriate plant species is a critical factor in the efficiency of phytoremediation. Different plants exhibit varying abilities to uptake, accumulate, and degrade pollutants, depending on their physiological and biochemical properties (Salt et al. 1995). The efficiency of phytoremediation can be enhanced by choosing plants that are well-suited to the specific contaminants present in the wetland.

Hyperaccumulators Certain plants, known as hyperaccumulators, have the ability to absorb and concentrate high levels of heavy metals or organic pollutants in their tissues. For instance, Phragmites australis (common reed) and Typha latifolia (cattail) are widely used in wetlands for their ability to accumulate heavy metals such as lead, cadmium, and arsenic (Sas-Nowosielska et al. 2004). The use of hyperaccumulators in phytoremediation can significantly enhance the removal of contaminants from wetland ecosystems.

Root Architecture and Depth The root system of the plant also plays a vital role in phytoremediation. Plants with extensive and deep root systems, such as Scirpus spp. (bulrushes), can access a larger volume of contaminated water and soil, thereby increasing the efficiency of contaminant uptake (Pulford and Watson 2003). Additionally, plants with fibrous root systems can provide a greater surface area for the adsorption and absorption of pollutants.

Tolerance to Contaminants The tolerance of plants to contaminants is another important consideration. Some plants may suffer from phytotoxicity when exposed to high levels of pollutants, leading to reduced growth and efficiency in phytoremediation. Selecting plant species that are tolerant to the specific contaminants in the wetland is essential for maintaining the effectiveness of the remediation process (Cunningham and Ow 1996).

Plant Growth and Biomass Production The growth rate and biomass production of plants also affect the efficiency of phytoremediation. Fast-growing plants with high biomass production, such as Eichhornia crassipes (water hyacinth), can uptake and store larger quantities of contaminants in a shorter time frame (Reddy and DeBusk 1985). However, the disposal of contaminated plant biomass needs to be managed carefully to prevent secondary pollution.

10.4.2 Environmental Conditions

Environmental conditions, including water quality, soil characteristics, and hydrology, play a significant role in determining the success of phytoremediation in wetlands. These factors can influence the availability, mobility, and transformation of contaminants, as well as the growth and health of wetland plants.

Water Quality The quality of water in the wetland, including parameters such as pH, dissolved oxygen, and nutrient levels, affects the efficiency of phytoremediation. For instance, the availability of heavy metals for plant uptake can be influenced by the pH of the water, with certain metals becoming more soluble and bioavailable at lower pH levels (McBride 1995). Maintaining optimal water quality conditions is essential for maximizing the uptake of contaminants by wetland plants.

Soil Characteristics The physical and chemical properties of the wetland soil, including texture, organic matter content, and cation exchange capacity, can impact the efficiency of phytoremediation. Soils with high organic matter content can enhance the sorption of organic pollutants, thereby reducing their bioavailability for plant uptake (Jordahl et al. 1997). Additionally, soils with good drainage and aeration can promote root growth and microbial activity, further enhancing the phytoremediation process.

Hydrology The hydrology of the wetland, including water depth, flow rate, and water retention time, influences the contact time between contaminants and plants, as well as the overall efficiency of phytoremediation (Kadlec and Wallace 2009). Wetlands with slow-moving or stagnant water allow for greater interaction between plant roots and contaminants, thereby increasing the potential for uptake and degradation. Conversely, fast-flowing water can reduce contact time and limit the effectiveness of phytoremediation.

Salinity In coastal wetlands or areas affected by saline intrusion, salinity levels can influence the efficiency of phytoremediation. High salinity can reduce plant growth and inhibit the uptake of contaminants, particularly in salt-sensitive species (Munns and Tester 2008). Selecting salt-tolerant plants, such as Spartina alterniflora (smooth cordgrass), can help mitigate the negative effects of salinity on phytoremediation.

10.4.3 Plant-Microbe Interactions

The interactions between wetland plants and microorganisms, particularly those in the rhizosphere, are crucial for the success of phytoremediation. These interactions can enhance the breakdown and transformation of contaminants, as well as improve the overall health and growth of the plants involved in the remediation process.

Rhizosphere Microbial Communities The rhizosphere is the zone of soil directly influenced by plant roots, where microbial activity is often higher than in the surrounding soil. Microorganisms in the rhizosphere, including bacteria, fungi, and archaea, play a key role in the degradation of organic pollutants and the transformation of inorganic contaminants (Johnson et al. 2005). Wetland plants release root exudates, such as sugars, amino acids, and organic acids, which can stimulate the growth and activity of these microorganisms (Glick 2012).

Biodegradation of Organic Pollutants Rhizosphere microorganisms can enhance the breakdown of organic pollutants, such as hydrocarbons, pesticides, and pharmaceuticals, through processes such as co-metabolism and enzymatic degradation (Siciliano et al. 2003). For instance, certain rhizosphere bacteria possess enzymes such as dehalogenases and oxygenases that can degrade complex organic molecules into simpler, less toxic compounds. The presence of these microorganisms can significantly increase the efficiency of phytoremediation in wetlands.

Transformation of Inorganic Contaminants Microbial communities in the rhizosphere can also influence the transformation and mobility of inorganic contaminants, such as heavy metals and metalloids. For example, certain bacteria can reduce toxic metal ions to less soluble and less bioavailable forms, thereby reducing their mobility and potential for uptake by plants (Gadd 2004). The interactions between plants and these beneficial microorganisms are essential for enhancing the efficiency of phytoremediation.

Mycorrhizal Associations Mycorrhizal fungi form symbiotic associations with the roots of many wetland plants, enhancing nutrient uptake and improving plant tolerance to contaminants (Smith and Read 2010). These fungi can increase the surface area of plant roots, allowing for greater absorption of water and nutrients, as well as the uptake of certain pollutants. Mycorrhizal associations can also protect plants from the toxic effects of heavy metals by sequestering these metals in fungal structures, such as vesicles and spores (Leyval et al. 2002).

10.4.4 Seasonal and Climatic Variability

Seasonal and climatic variability can have a profound impact on the efficiency of phytoremediation in wetlands. Factors such as temperature, precipitation, and photoperiod can influence plant growth, microbial activity, and the availability of contaminants, leading to fluctuations in the effectiveness of the remediation process.

Temperature Temperature is a key factor influencing the growth and metabolism of wetland plants and microorganisms. In temperate regions, phytoremediation efficiency may be reduced during the colder months due to lower temperatures, which can slow down plant growth and microbial activity (Truu et al. 2017). Conversely, higher temperatures during the growing season can enhance the uptake and degradation of contaminants, leading to improved phytoremediation outcomes.

Photoperiod The length of daylight, or photoperiod, can also affect the growth and physiological processes of wetland plants. Longer photoperiods during the summer months can promote greater photosynthetic activity and biomass production, thereby increasing the capacity of plants to uptake and store contaminants (Migliaccio et al. 2010). However, shorter photoperiods during the winter can lead to reduced plant growth and a corresponding decrease in phytoremediation efficiency.

Precipitation and Hydrology Seasonal variations in precipitation can influence the hydrology of wetlands, affecting water levels, flow rates, and the availability of contaminants. During periods of high precipitation, increased water flow can lead to the dilution and dispersion of contaminants, potentially reducing their bioavailability for plant uptake (Kadlec and Wallace 2009). Conversely, low water levels during dry periods can concentrate contaminants, increasing the potential for phytoremediation but also posing a risk of phytotoxicity to wetland plants.

Seasonal Growth Patterns Many wetland plants exhibit seasonal growth patterns, with peak growth occurring during the spring and summer months. This seasonal variation in plant biomass can influence the efficiency of phytoremediation, with higher contaminant uptake and degradation typically observed during the growing season (Vymazal 2011). Managing wetlands to align phytoremediation efforts with these seasonal growth patterns can enhance the overall effectiveness of the process.

Climatic Events Extreme climatic events, such as floods, droughts, and storms, can disrupt phytoremediation processes in wetlands. For example, flooding can lead to the rapid transport of contaminants out of the wetland, reducing the opportunity for plant uptake and microbial degradation (Gill et al. 2007). Drought conditions, on the other hand, can stress wetland plants, reducing their growth and contaminant uptake capacity. Preparing for and mitigating the impacts of these climatic events is essential for maintaining the efficiency of phytoremediation in wetlands.

10.5 Future Perspectives and Researches in Wetland Phytoremediation

Wetland phytoremediation has emerged as a sustainable and effective approach to mitigate environmental contaminants. As the world faces increasing environmental challenges, the potential of phytoremediation in wetland ecosystems continues to grow. Future perspectives and researches in this field lie in innovations in wetland phytoremediation, integrating phytoremediation with other treatment methods, and addressing policy and economic considerations. These aspects are crucial for advancing the application of phytoremediation and ensuring its long-term sustainability and effectiveness.

10.5.1 Innovations in Wetland Phytoremediation

The future of wetland phytoremediation will be shaped by a range of innovative approaches aimed at enhancing the efficiency and scope of this technology. Advances in biotechnology, genetic engineering, and nanotechnology offer promising opportunities to overcome current limitations and expand the application of phytoremediation.

Biotechnology and Genetic Engineering Genetic engineering holds significant potential for enhancing the phytoremediation capabilities of wetland plants. By introducing genes that encode for specific enzymes involved in contaminant degradation, plants can be engineered to metabolize a wider range of pollutants more effectively (Pilon-Smits 2005). For example, transgenic plants with enhanced tolerance to heavy metals or organic pollutants can be developed, enabling them to thrive in highly contaminated environments and remove contaminants more efficiently (Doty 2008). Additionally, advances in synthetic biology could allow for the design of custom-made plants tailored to target specific contaminants, thus improving the precision and effectiveness of phytoremediation efforts.

Nanotechnology Nanotechnology presents another innovative avenue for enhancing phytoremediation in wetlands. The use of nanoparticles in conjunction with phytoremediation can improve the uptake, transport, and degradation of contaminants by plants (Karn et al. 2009). For instance, engineered nanoparticles can be used to increase the bioavailability of hydrophobic pollutants, making them more accessible for plant uptake and degradation. Furthermore, nanoparticles can be functionalized to carry specific enzymes or chemical agents that facilitate the breakdown of complex contaminants within plant tissues (Mustafa et al. 2022). The integration of nanotechnology with phytoremediation offers a promising approach to address the limitations of traditional methods and enhance the overall efficiency of contaminant removal.

Phycoremediation The use of algae in wetland phytoremediation, known as phycoremediation, is an emerging field with great potential. Algae are capable of accumulating heavy metals, nutrients, and organic pollutants, making them valuable agents in the remediation of contaminated water (Olguín 2003; Ogundele et al. 2023). Algae can also be used in combination with higher plants in constructed wetlands to enhance the overall efficiency of phytoremediation. The development of algal-based systems for wetland remediation offers a novel approach to address water pollution, particularly in scenarios where traditional plant-based systems may be less effective.

Microbial-Assisted Phytoremediation The role of microbial communities in enhancing phytoremediation is increasingly recognized. The future of wetland phytoremediation may see greater emphasis on harnessing plant-microbe interactions to improve contaminant degradation. For instance, the use of rhizosphere bacteria and mycorrhizal fungi to stimulate plant growth and enhance contaminant uptake is an area of active research (Glick 2012). The development of microbial inoculants and biofertilizers specifically designed to support wetland plants in phytoremediation applications could lead to significant improvements in the effectiveness of this technology.

10.5.2 Integrating Phytoremediation with Other Treatment Methods

The integration of phytoremediation with other treatment methods is a promising strategy to enhance the overall effectiveness of wetland remediation. By combining phytoremediation with physical, chemical, and biological treatments, it is possible to achieve more comprehensive and efficient contaminant removal.

Phytoremediation and Constructed Wetlands Constructed wetlands are engineered systems designed to mimic the natural processes of wetland ecosystems. The integration of phytoremediation into constructed wetlands can enhance the removal of a wide range of contaminants, including nutrients, heavy metals, and organic pollutants (Kadlec 2009). By selecting appropriate plant species and optimizing the design of the wetland, it is possible to create a synergistic system where plants, microorganisms, and hydrological processes work together to achieve effective contaminant removal. This approach has been successfully applied in the treatment of municipal wastewater, industrial effluents, and agricultural runoff.

Phytoremediation and Bioaugmentation Bioaugmentation involves the introduction of specific microorganisms or microbial consortia into a contaminated environment to enhance the degradation of pollutants. When combined with phytoremediation, bioaugmentation can improve the breakdown of complex organic compounds and enhance the overall efficiency of the remediation process (Thompson et al. 2005). For instance, the introduction of hydrocarbon-degrading bacteria into a wetland system can accelerate the degradation of petroleum pollutants, while the presence of plants provides additional habitat and nutrients to support microbial activity.

Phytoremediation and Phytomining Phytomining is a process that uses plants to extract valuable metals from contaminated soils or water. By integrating phytomining with phytoremediation, it is possible to simultaneously remove contaminants and recover economically valuable metals, such as nickel, zinc, and gold (Chaney et al. 2005). This approach offers a sustainable solution for the remediation of metal-contaminated wetlands, while also providing an economic incentive for the recovery of valuable resources.

Phytoremediation and Bioreactors Bioreactors are engineered systems that use biological processes to treat contaminated water or soil. The integration of phytoremediation with bioreactors can enhance the removal of contaminants, particularly in scenarios where the natural attenuation capacity of wetland systems is insufficient (Rittmann and McCarty 2001). For example, the use of plant roots as a biofilm support in bioreactors can enhance the degradation of organic pollutants, while the plants themselves contribute to the removal of nutrients and heavy metals.

Phytoremediation and Chemical Amendments The use of chemical amendments, such as chelating agents or surfactants, can enhance the bioavailability of contaminants for plant uptake. When combined with phytoremediation, these amendments can improve the efficiency of contaminant removal, particularly for hydrophobic organic pollutants and heavy metals (Evangelou et al. 2007). However, the use of chemical amendments must be carefully managed to avoid potential environmental side effects and ensure the long-term sustainability of the remediation process (Akinyemi et al. 2023).

10.5.3 Policy and Economic Considerations

The widespread adoption of wetland phytoremediation as a viable environmental remediation strategy requires supportive policies and economic incentives. Addressing policy and economic considerations is essential for ensuring the long-term sustainability and effectiveness of phytoremediation efforts.

Regulatory Frameworks Effective regulatory frameworks are crucial for promoting the use of phytoremediation in wetland management. Governments and environmental agencies must establish clear guidelines and standards for the implementation of phytoremediation projects, including the selection of plant species, monitoring and evaluation protocols, and the management of contaminated plant biomass (Moosavi and Seghatoleslami 2013). These regulations should be based on sound scientific principles and take into account the specific characteristics of the wetland ecosystem and the contaminants present.

Incentives for Adoption Economic incentives can play a key role in encouraging the adoption of phytoremediation practices. For example, subsidies or tax credits for landowners and businesses that implement phytoremediation projects can help offset the costs of establishing and maintaining wetland systems (Sas-Nowosielska et al. 2004). Additionally, the development of markets for the sale of phytomined metals or the production of bioenergy from contaminated biomass can provide further economic motivation for the adoption of phytoremediation.

Cost-Effectiveness The cost-effectiveness of phytoremediation compared to traditional remediation methods is a significant consideration for policymakers and stakeholders. Phytoremediation is generally less expensive than conventional methods, such as excavation and landfilling, due to its reliance on natural processes and minimal energy inputs (Pilon-Smits 2005). However, the long-term sustainability of phytoremediation must also be considered, as the process may require extended time frames to achieve the desired levels of contaminant removal. Cost-benefit analyses can help determine the most appropriate remediation strategy for a given site, taking into account both economic and environmental factors.

Public Awareness and Education Public awareness and education are essential for gaining support for phytoremediation projects. Stakeholders, including local communities, landowners, and businesses, must be informed about the benefits and limitations of phytoremediation, as well as the specific requirements for successful implementation (Dietz and Schnoor 2001). Educational programs and outreach efforts can help build public trust and support for phytoremediation initiatives, particularly in areas where the technology is relatively unknown.

Environmental Justice Environmental justice considerations are important in the context of phytoremediation, particularly in communities disproportionately affected by environmental contamination. Policies and programs should ensure that all communities have access to the benefits of phytoremediation and are not disproportionately burdened by the risks associated with contaminated wetlands (Bullard 2018). This includes providing resources and support for the implementation of phytoremediation projects in underserved or marginalized communities.

10.6 Conclusion

In conclusion, phytoremediation in wetlands represents a promising and sustainable approach to managing environmental contamination. The ability of wetland plants to absorb, detoxify, and mitigate pollutants such as heavy metals, organic compounds, and excess nutrients highlights the critical role these ecosystems play in natural water purification. By leveraging the inherent capabilities of wetland plants, phytoremediation offers a cost-effective and environmentally friendly solution for addressing pollution in both natural and constructed wetland systems. The successful application of various phytoremediation techniques, including phytoextraction, phytodegradation, and rhizofiltration, underscores the versatility of this approach across different contaminant types and environmental conditions. As global environmental challenges continue to escalate, the integration of phytoremediation into wetland management practices becomes increasingly important. Future advancements in biotechnology, along with supportive policy frameworks, will further enhance the effectiveness of phytoremediation strategies. This chapter reinforces the potential of wetland phytoremediation not only as a tool for environmental cleanup but also as a critical component in the broader effort to restore and protect vital wetland ecosystems for future generations.

References

Abdullah SRS, Al-Baldawi IA, Almansoory AF, Purwanti IF, Al-Sbani NH, Sharuddin SSN (2020) Plant-assisted remediation of hydrocarbons in water and soil: application, mechanisms, challenges and opportunities. Chemosphere 247:125932

Adewumi AJ, Ogundele OD (2024) Hidden hazards in urban soils: a meta-analysis review of global heavy metal contamination (2010–2022), sources and its ecological and health consequences. Sustain Environ 10(1):2293239

Adewumi AJ, Ogundele OD, Emumejakpor IS (2023) Potentially toxic metals in Africa, fresh and marine environment: marine green contamination, ecological and human health risk. In: Marine greens. CRC Press, pp 213–225

Akinyemi BT, Ogundele OD, Afolabi AB (2023) Advancements in sustainable membrane technologies for enhanced remediation and wastewater treatment: a comprehensive review. Acadlore Trans Geosci 2(4):196–207

Ali H, Khan E, Sajad MA (2013) Phytoremediation of heavy metals—concepts and applications. Chemosphere 91(7):869–881

Alloway BJ (ed) (2012) Heavy metals in soils: trace metals and metalloids in soils and their bioavailability, vol 22. Springer Science & Business Media

Amon JP, Thompson CA, Carpenter QJ, Miner J (2002) Temperate zone fens of the glaciated Midwestern USA. Wetlands 22(2):301–317

Amora-Lazcano E, Guerrero-Zuniga LA, Rodriguez-Tovar A, Rodriguez-Dorantes A, Vasquez-Murrieta MS (2010) Rhizospheric plant-microbe interactions that enhance the remediation of contaminated soils. In: Current research, technology and education topics in applied microbiology and microbial biotechnology, vol 1. Formatex Research Center, pp 251–256

Ansari AA, Gill SS, Khan FA, Naeem M (2014) Phytoremediation systems for the recovery of nutrients from eutrophic waters. In: Eutrophication: causes, consequences and control, vol 2. Springer Netherlands, pp 239–248

Aransiola SA, Ijah UJJ, Abioye OP (2013) Phytoremediation of lead polluted soil by glycine max L. Appl Environ Soil Sci 2013:631619. https://doi.org/10.1155/2013/631619. https://www.hindawi.com/journals/aess/2013/631619/abs/

Aransiola SA, Ijah UJJ, Abioye OP, Bala JD (2019) Microbial-aided phytoremediation of heavy metals contaminated soil: a review. Eur J Biol Res 9(2):104–125. http://www.journals.tmkarpinski.com/index.php/ejbr/article/view/157

Aransiola SA, Ijah UJJ, Abioye OP, Bala JD, Rivadeneira-Mendoza RF, Luque R, Rodríguez-Díaz JM, Maddela NR (2024) Micro and vermicompost assisted remediation of heavy metal contaminated soils using phytoextractors. Case Stud Chem Environ Eng 9:100755. https://doi.org/10.1016/j.cscee.2024.100755
Arias-Estévez M, López-Periago E, Martínez-Carballo E, Simal-Gándara J, Mejuto JC, García-Río L (2008) The mobility and degradation of pesticides in soils and the pollution of groundwater resources. Agric Ecosyst Environ 123(4):247–260
Babaniyi BR, Ogundele OD, Bisi-Omotosho A, Babaniyi EE, Aransiola SA (2023) Remediation approaches in environmental sustainability. In: Microbiology for cleaner production and environmental sustainability. CRC Press, pp 321–346
Babaniyi BR, Ogundele OD, Abe TO, Olowoyeye BR, Jayeola JO, Oyegoke DA et al (2024) Bioenergy: the environmentalist's perspectives. In: Microbial biotechnology for bioenergy. Elsevier, pp 97–113
Baker AJ, McGrath SP, Reeves RD, Smith JAC (2020) Metal hyperaccumulator plants: a review of the ecology and physiology of a biological resource for phytoremediation of metal-polluted soils. In: Phytoremediation of contaminated soil and water. CRC Press, pp 85–107
Barbier EB, Acreman M, Knowler D (1997) Economic valuation of wetlands: a guide for policy makers and planners. Ramsar Convention Bureau, Gland
Boening DW (2000) Ecological effects, transport, and fate of mercury: a general review. Chemosphere 40(12):1335–1351
Bullard RD (2018) Dumping in Dixie: race, class, and environmental quality. Routledge
Bullock A, Acreman M (2003) The role of wetlands in the hydrological cycle. Hydrol Earth Syst Sci 7(3):358–389
Burken JG, Ma X (2006) Phytoremediation of volatile organic compounds. In: Phytoremediation rhizoremediation. Springer Netherlands, Dordrecht, pp 199–216
Camargo JA, Alonso Á (2006) Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. Environ Int 32(6):831–849
Chaney RL, Angle JS, McIntosh MS, Reeves RD, Li YM, Brewer EP et al (2005) Using hyperaccumulator plants to phytoextract soil Ni and Cd. Z Naturforsch C 60(3–4):190–198
Clemens S (2006) Toxic metal accumulation, responses to exposure and mechanisms of tolerance in plants. Biochimie 88(11):1707–1719
Cowardin LM (1979) Classification of wetlands and deepwater habitats of the United States. Fish and Wildlife Service, US Department of the Interior
Cristaldi A, Conti GO, Jho EH, Zuccarello P, Grasso A, Copat C, Ferrante M (2017) Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. Environ Technol Innov 8:309–326
Cunningham SD and Ow DW (1996) Promises and prospects of phytoremediation. Plant physiology 110(3):715
Davidson NC (2014) How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar Freshw Res 65(10):934–941
Dietz AC, Schnoor JL (2001) Advances in phytoremediation. Environ Health Perspect 109(suppl 1):163–168
Doty SL (2008) Enhancing phytoremediation through the use of transgenics and endophytes. New Phytol 179(2):318–333
Dzantor EK (2007) Phytoremediation: the state of rhizosphere 'engineering' for accelerated rhizodegradation of xenobiotic contaminants. J Chem Technol Biotechnol 82(3):228–232
Erwin KL (2009) Wetlands and global climate change: the role of wetland restoration in a changing world. Wetl Ecol Manag 17(1):71–84
Evangelou MW, Ebel M, Schaeffer A (2007) Chelate assisted phytoextraction of heavy metals from soil. Effect, mechanism, toxicity, and fate of chelating agents. Chemosphere 68(6):989–1003
Fitamo D, Leta S (2010) Assessment of plants growing on gold mine wastes for their potential to remove heavy metals from contaminated soils. Int J Environ Stud 67(5):705–724
Gadd GM (2004) Mycotransformation of organic and inorganic substrates. Mycol 18(2):60–70

Gavrilescu M (2022) Enhancing phytoremediation of soils polluted with heavy metals. Curr Opin Biotechnol 74:21–31

Gell PA, Finlayson CM, Davidson NC (2023) An introduction to the Ramsar Convention on wetlands. In: Ramsar wetlands. Elsevier, pp 1–36

Gill RB, Mayewski PA, Nyberg J, Haug GH, Peterson LC (2007) Drought and the Maya collapse. Ancient Mesoamerica 18(2):283–302

Ghavzan NJ, Trivedy RK (2005) Environmental pollution control by using phytoremediation technology. Pollut Res 24(4):875

Ghosh M, Singh SP (2005) A review on phytoremediation of heavy metals and utilization of it's by products. Asian J Energy Environ 6(4):18

Gleba D, Borisjuk NV, Borisjuk LG, Kneer R, Poulev A, Skarzhinskaya M et al (1999) Use of plant roots for phytoremediation and molecular farming. Proc Natl Acad Sci 96(11):5973–5977

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012(1):963401

Göhre V, Paszkowski U (2006) Contribution of the arbuscular mycorrhizal symbiosis to heavy metal phytoremediation. Planta 223:1115–1122

Johnson DL, Anderson DR, McGrath SP (2005) Soil microbial response during the phytoremediation of a PAH contaminated soil. Soil Biol Biochem 37(12):2334–2336

Hussein A, Scholz M (2017) Dye wastewater treatment by vertical-flow constructed wetlands. Ecol Eng 101:28–38

Jordahl JL, Foster L, Schnoor JL, Alvarez PJ (1997) Effect of hybrid poplar trees on microbial populations important to hazardous waste bioremediation. Environ Toxicol Chem 16(6):1318–1321

Joosten H, Tapio-Biström ML, Tol S (2012) Peatlands: guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Food and Agriculture Organization of the United Nations, Rome

Kadlec RH (2009) Comparison of free water and horizontal subsurface treatment wetlands. Ecol Eng 35(2):159–174

Kadlec RH, Wallace SD (2009) Treatment wetlands, 2nd edn. CRC Press

Karn B, Kuiken T, Otto M (2009) Nanotechnology and in situ remediation: a review of the benefits and potential risks. Environ Health Perspect 117(12):1813–1831

Keddy PA (2010) Wetland ecology: principles and conservation. Cambridge University Press

Keller C, Hammer D, Kayser A, Richner W, Brodbeck M, Sennhauser M (2003) Root development and heavy metal phytoextraction efficiency: comparison of different plant species in the field. Plant Soil 249:67–81

Kingsford RT (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. Austral Ecol 25(2):109–127

Kingsford RT, Bino G, Porter JL (2017) Continental impacts of water development on waterbirds, contrasting two Australian river basins: global implications for sustainable water use. Glob Chang Biol 23(11):4958–4969

Kramer U (2010) Metal hyperaccumulation in plants. Annu Rev Plant Biol 61(1):517–534

Kumar N, Jeena N, Gangola S, Singh H (2019) Phytoremediation facilitating enzymes: an enzymatic approach for enhancing remediation process. In: Smart bioremediation technologies. Academic, pp 289–306

Kumpiene J, Lagerkvist A, Maurice C (2008) Stabilization of As, Cr, Cu, Pb and Zn in soil using amendments–a review. Waste Manag 28(1):215–225

Laghlimi M, Baghdad B, El Hadi H, Bouabdli A (2015) Phytoremediation mechanisms of heavy metal contaminated soils: a review. Open J Ecol 5(8):375–388

Leyval C, Joner EJ, Del Val C, Haselwandter K (2002) Potential of arbuscular mycorrhizal fungi for bioremediation. Mycorrhizal technology in agriculture: From genes to bioproducts, 175–186

Liao ShaoWei LS, Chang WenLian CW (2004) Heavy metal phytoremediation by water hyacinth at constructed wetlands in Taiwan. Photogramm Eng Remote Sens 54:177–185

Lin Q, Mendelssohn IA (1998) The combined effects of phytoremediation and biostimulation in enhancing habitat restoration and oil degradation of petroleum contaminated wetlands. Ecol Eng 10(3):263–274
Ma LQ, Komar KM, Tu C, Zhang W, Cai Y, Kennelley ED (2001) A fern that hyperaccumulates arsenic. Nature 409(6820):579–579
Macek T, Macková M, Káš J (2000) Exploitation of plants for the removal of organics in environmental remediation. Biotechnol Adv 18(1):23–34
McBride M B (1995) Toxic metal accumulation from agricultural use of sludge: are USEPA regulations protective?. J Environ Qual 24(1):5–18
McGrath SP, Zhao FJ (2003) Phytoextraction of metals and metalloids from contaminated soils. Curr Opin Biotechnol 14(3):277–282
Meagher RB and Heaton AC (2005) Strategies for the engineered phytoremediation of toxic element pollution: mercury and arsenic. J Ind Microbiol Biotechnol 32(11–12):502–513
Migliaccio KW, Schaffer B, Crane JH, Davies FS (2010) Plant response to evapotranspiration and soil water sensor irrigation scheduling methods for papaya production in south Florida. Agric Water Manag 97(10):1452–1460
Miller RM, Jastrow JD (2013) The role of plant roots and soil microorganisms in organic contaminant degradation. Biorem J 17(4):177–193
Mitsch WJ, Gosselink JG (2015) Wetlands. John Wiley & Sons
Mitsch WJ, Bernal B, Hernandez ME (2015) Ecosystem services of wetlands. Int J Biodivers Sci Ecosyst Serv Manag 11(1):1–4
Moosavi SG, Seghatoleslami MJ (2013) Phytoremediation: a review. Adv Agric Biol 1(1):5–11
Munns R and Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59(1):651–681
Mustafa K, Kanwal J, Farrukh S, Mussaddiq S, Saddiq N, Younas M (2022) Nano-phytoremediation technology in environmental remediation. In: Phytoremediation technology for the removal of heavy metals and other contaminants from soil and water. Elsevier, pp 433–459
Nriagu JO (1990) Global metal pollution: poisoning the biosphere? Environ Sci Policy Sustain Dev 32(7):7–33
Olgún EJ (2003) Phycoremediation: key issues for cost-effective nutrient removal processes. Biotechnol Adv 22(1–2):81–91
Ogundele OD, Anaun TE (2022) Phytoremediation: a green approach for pollution cleanup. In: Phytoremediation technology for the removal of heavy metals and other contaminants from soil and water. Elsevier, pp 49–74
Ogundele OD, Adewumi AJ, Oyegoke DA (2023) Phycoremediation: algae as an effective agent for sustainable remediation and waste water treatment. Environ Earth Sci Res J 10(1):7–17
Panda SK, Choudhury S (2005) Chromium stress in plants. Braz J Plant Physiol 17:95–102
Parish F, Sirin AA, Charman D, Joosten H, Minaeva TY, Silvius M (2008) Assessment on peatlands, biodiversity and climate change
Patra M, Sharma A (2000) Mercury toxicity in plants. Bot Rev 66:379–422
Pilon-Smits E (2005) Phytoremediation. Annu Rev Plant Biol 56(1):15–39
Pilu R, Bucci A, Badone FC, Landoni M (2012) Giant reed (Arundo donax L.): a weed plant or a promising energy crop. Afr J Biotechnol 11(38):9163–9174
Pulford ID, Watson C (2003) Phytoremediation of heavy metal-contaminated land by trees—a review. Environ Int 29(4):529–540
Rascio N, Navari-Izzo F (2011) Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? Plant Sci 180(2):169–181
Reddy KR and DeBusk WF (1985) Growth characteristics of aquatic macrophytes cultured in nutrient-enriched water: II. Azolla, Duckweed, and Salvinia. Economic Botany 39(2):200–208
Reddy KR, Kadlec RH, Flaig E, Gale PM (1999) Phosphorus retention in streams and wetlands: a review. Crit Rev Environ Sci Technol 29(1):83–146
Reinhold D, Vishwanathan S, Park JJ, Oh D, Saunders FM (2010) Assessment of plant-driven removal of emerging organic pollutants by duckweed. Chemosphere 80(7):687–692

Rittmann BE, McCarty PL (2001) Environmental biotechnology: principles and applications. McGraw-Hill Education

Rydin H, Jeglum JK, Bennett KD (2013) The biology of peatlands, 2e. OUP Oxford

Salt DE, Blaylock M, Kumar NP, Dushenkov V, Ensley BD, Chet I, Raskin I (1995) Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. Bio/Technology 13(5):468–474

Salt DE, Smith RD, Raskin I (1998) Phytoremediation. Annu Rev Plant Biol 49(1):643–668

Sarwar N, Imran M, Shaheen MR, Ishaque W, Kamran MA, Matloob A et al (2017) Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosphere 171:710–721

Sas-Nowosielska A, Kucharski R, Małkowski E, Pogrzeba M, Kuperberg JM, Kryński KJEP (2004) Phytoextraction crop disposal—an unsolved problem. Environ Pollut 128(3):373–379

Siciliano SD, Germida JJ, Banks K, Greer C W (2003) Changes in microbial community composition and function during a polyaromatic hydrocarbon phytoremediation field trial. Appl Environ Microbiol 69(1):483–489

Shanker AK, Cervantes C, Loza-Tavera H, Avudainayagam S (2005) Chromium toxicity in plants. Environ Int 31(5):739–753

Sharma P, Dubey RS (2005) Lead toxicity in plants. Braz J Plant Physiol 17:35–52

Sheoran AS, Sheoran V (2006) Heavy metal removal mechanism of acid mine drainage in wetlands: a critical review. Miner Eng 19(2):105–116

Smith VH, Schindler DW (2009) Eutrophication science: where do we go from here? Trends Ecol Evol 24(4):201–207

Smith SE and Read DJ (2010) Mycorrhizal symbiosis. Academic press

Smith ERG, Naidu R, Alston AM (1998) Arsenic in the soil environment: a review. Adv Agron 64(149195):60504-0

Tangahu BV, Sheikh Abdullah SR, Basri H, Idris M, Anuar N, Mukhlisin M (2011) A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. Int J Chem Eng 2011(1):939161

Thompson IP, Van Der Gast CJ, Ciric L, Singer AC (2005) Bioaugmentation for bioremediation: the challenge of strain selection. Environ Microbiol 7(7):909–915

Thompson SO, Ogundele OD, Abata EO, Ajayi OM (2019) Heavy metals distribution and pollution indices of scrapyards soils. Int J Curr Res Appl Chem Chem Eng 3(1):9–19

Tiner RW (2002) Wetland indicators: a guide to wetland identification, delineation, classification, and mapping. Lewis Publishers, CRC Press, Boca Raton, pp 1–397

Truu M, Ostonen I, Preem JK, Lõhmus K, Nõlvak H, Ligi T, et al (2017) Elevated air humidity changes soil bacterial community structure in the silver birch stand. Front Microbiol 8:557

Verbruggen N, Hermans C, Schat H (2009) Molecular mechanisms of metal hyperaccumulation in plants. New Phytol 181(4):759–776

Verhoeven JT, Arheimer B, Yin C, Hefting MM (2006) Regional and global concerns over wetlands and water quality. Trends Ecol Evol 21(2):96–103

Veselá A, Hadincová V, Vandvik V, Münzbergová Z (2021) Maternal effects strengthen interactions of temperature and precipitation, determining seed germination of dominant alpine grass species. Am J Bot 108(5):798–810

Vymazal J (2007) Removal of nutrients in various types of constructed wetlands. Sci Total Environ 380(1–3):48–65

Vymazal J (2010) Constructed wetlands for wastewater treatment. Water 2(3):530–549

Vymazal J (2011) Plants used in constructed wetlands with horizontal subsurface flow: a review. Hydrobiologia 674(1):133–156

Wang QH, Que X (2013) Phytoremediation-a green approach to environmental clean-up. Chin J Eco-Agric 21(2):261–266

Wei Z, Van Le Q, Peng W, Yang Y, Yang H, Gu H et al (2021) A review on phytoremediation of contaminants in air, water and soil. J Hazard Mater 403:123658

Weis JS, Weis P (2004) Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. Environ Int 30(5):685–700

Xu DM, Fu RB, Wang JX, Shi YX, Guo XP (2021) Chemical stabilization remediation for heavy metals in contaminated soils on the latest decade: available stabilizing materials and associated evaluation methods-a critical review. J Clean Prod 321:128730

Yang Y, Shen Q (2020) Phytoremediation of cadmium-contaminated wetland soil with Typha latifolia L. and the underlying mechanisms involved in the heavy-metal uptake and removal. Environ Sci Pollut Res 27(5):4905–4916

Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Crit Rev Plant Sci 23(5):431–452