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Plant-Mediated Removal of Environmental Pollutants: Mechanisms of Pollution Remediation, Ecological Sustainability and Restoration of Degraded Ecosystems.

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Abstract- Environmental pollution remains a major global challenge, threatening human health, ecological stability and sustainable development. This review examines plant-mediated removal of environmental pollutants, with emphasis on pollution remediation mechanisms, ecological sustainability and the restoration of degraded ecosystems. It discusses the fundamental principles of phytoremediation, plant species employed in environmental remediation and the interactions between plants, soil and microorganisms. Major remediation mechanisms, including phytoextraction, phytostabilization, rhizofiltration, phytodegradation, phytovolatilization and rhizodegradation, are examined in relation to their roles in removing, immobilising and transforming environmental contaminants. The review further highlights the application of phytoremediation in managing heavy metals, petroleum hydrocarbons, organic pollutants, contaminated soils and industrial wastewater. Additionally, it explores the contributions of plant-based remediation to soil and water quality improvement, biodiversity conservation, carbon sequestration and ecosystem restoration. Factors influencing remediation efficiency, including plant characteristics, pollutant properties, soil conditions and microbial activities, are also discussed. Despite its environmental benefits, phytoremediation faces limitations associated with slow remediation rates, plant toxicity and contaminated biomass disposal. Emerging approaches, particularly genetic engineering and microbial-assisted remediation, offer opportunities for improving its effectiveness. The review concludes that phytoremediation represents a promising complementary strategy for sustainable pollution management and ecological restoration.

Keywords: Environmental, pollutants, ecological, ecosystem, heavy metals, petroleum

I. Introduction

1.1 Overview of Environmental Pollution

Environmental pollution is one of the major challenges affecting human health, ecological stability and sustainable development worldwide (Etus and Erienu, 2026). It occurs when harmful substances or forms of energy are introduced into the natural environment at concentrations capable of causing adverse effects on living organisms and ecosystem processes. Rapid industrialisation, urbanisation, population growth, agricultural intensification and increasing dependence on fossil fuels have contributed significantly to the accumulation of pollutants in soil, water and air. These pollutants include heavy metals, petroleum hydrocarbons, pesticides, industrial chemicals, plastics and other persistent organic compounds (Alloway, 2013; Ali et al., 2013). Soil pollution is particularly important because soil serves as a major reservoir for contaminants released through industrial waste disposal, mining, agricultural activities and petroleum exploration. Contaminated soils may experience reduced fertility, altered microbial activities and impaired nutrient cycling. Similarly, water pollution resulting

from industrial effluents, agricultural runoff, sewage discharge and oil spills threatens aquatic organisms, drinking-water quality and ecosystem productivity (Umudi et al., 2025). Air pollution, on the other hand, is associated with the release of particulate matter, nitrogen oxides, sulphur dioxide and volatile organic compounds, which contribute to respiratory diseases, acid deposition and climate-related environmental problems (Alloway, 2013; Tchounwou et al., 2012). Conventional environmental remediation techniques, including excavation, chemical treatment, soil washing and thermal treatment, have been employed to manage contaminated environments. However, these approaches may be expensive, energy-intensive and disruptive to natural ecosystem structures. Consequently, increasing attention has been directed towards environmentally friendly remediation approaches that can reduce pollutant concentrations while supporting ecological recovery. Plant-mediated remediation, particularly phytoremediation, has emerged as a promising alternative because of its ability to utilise natural plant processes to remove, immobilise or transform environmental contaminants (Ali et al., 2013; Raskin et al., 1997).

1.2 Sources and Effects of Environmental Pollutants

Environmental pollutants originate from both natural and anthropogenic activities. Natural sources include volcanic eruptions, weathering of mineral deposits, wildfires and decomposition of organic materials. However, human activities constitute major sources of many forms of environmental contamination. Industrial activities release heavy metals, chemical solvents, petroleum derivatives and other hazardous substances into surrounding environments. Mining and smelting operations contribute to the accumulation of lead, cadmium, arsenic, mercury and chromium in soils and water bodies. Agricultural activities introduce pesticides, herbicides, fertilisers and other agrochemicals into the environment through runoff, leaching and improper application. Similarly, petroleum exploration, transportation, refining and accidental oil spills release hydrocarbons that can persist in contaminated soils and aquatic ecosystems. The effects of environmental pollutants depend on their chemical properties, concentration, exposure duration and interactions with environmental components. Heavy metals may interfere with enzymatic activities, damage cellular structures and disrupt plant growth and development. In humans, exposure to certain toxic metals is associated with neurological disorders, kidney damage, developmental abnormalities and other chronic health conditions (Tchounwou et al., 2012). Organic pollutants such as petroleum hydrocarbons, pesticides and industrial solvents may exhibit toxicity, persistence and bioaccumulation (Obruche et al., 2025). Their presence can reduce soil microbial diversity, inhibit plant development and threaten aquatic organisms. Furthermore, pollutants can move through food chains, resulting in ecological disturbances and increased exposure risks to humans and wildlife. These effects demonstrate the importance of developing sustainable approaches for environmental pollution management.

1.3 Concept and Importance of Plant-Mediated Remediation

Plant-mediated remediation refers to the use of plants and their associated microorganisms to remove, immobilise, degrade or transform pollutants present in contaminated environmental media. The approach is commonly referred to as phytoremediation and relies on natural plant physiological, biochemical and ecological processes to reduce environmental contamination (Jacintha et al., 2025). Plants can remediate polluted environments through several mechanisms, including phytoextraction, phytostabilization, rhizofiltration, phytodegradation, phytovolatilization and rhizodegradation. These processes enable plants to absorb contaminants, accumulate them in their tissues, immobilise them within the soil, or facilitate their transformation through plant enzymes and rhizosphere microorganisms (Cunningham et al., 1995; Salt et al., 1998). The

importance of plant-mediated remediation lies in its relatively low cost, environmental compatibility and potential for application over large contaminated areas. Unlike some conventional remediation techniques, phytoremediation can maintain soil structure, reduce erosion, support microbial activities and contribute to vegetation recovery. It can also provide additional ecological benefits, including carbon sequestration, habitat development and improved landscape aesthetics (Ekpo et al., 2023). Nevertheless, its effectiveness depends on the type and concentration of pollutants, plant species, environmental conditions and duration of treatment. Therefore, plant-mediated remediation should be regarded as a complementary environmental management strategy rather than a universal replacement for conventional remediation technologies (Ali et al., 2013).

1.4 Aim and Scope of the Review

The aim of this review is to examine the role of plant-mediated processes in removing environmental pollutants, with particular emphasis on the mechanisms of phytoremediation, ecological sustainability and restoration of degraded ecosystems. Specifically, the review examines the fundamental principles and classification of phytoremediation, the plant species employed in environmental remediation, and the physiological, biochemical and microbial mechanisms responsible for pollutant removal. It further evaluates the applications of phytoremediation in the treatment of contaminated soils, water bodies and petroleum-polluted environments. The review also discusses the ecological benefits of plant-based remediation, including soil quality improvement, biodiversity conservation and ecosystem restoration. In addition, it evaluates the environmental factors influencing remediation efficiency, identifies major limitations and examines emerging technologies that could improve the effectiveness of plant-mediated pollution control.

II. Fundamentals Of Plant-Mediated Pollution Remediation

2.1 Concept and Classification of Phytoremediation

Phytoremediation is an environmentally friendly remediation technology that involves the use of green plants and their associated microorganisms to remove, contain, degrade or detoxify pollutants from contaminated soil, water and sediments. It relies on the natural capacity of plants to absorb substances from their surroundings, transport them through vascular tissues, accumulate them in specific organs or transform certain contaminants into less harmful compounds. The technology has attracted considerable scientific interest because it offers an alternative to expensive and disruptive conventional remediation techniques (Salt et al., 1998; Ikechukwu et al., 2026). Phytoremediation can be classified according to the mechanisms through which plants interact with environmental pollutants. Phytoextraction involves the absorption and accumulation of contaminants, particularly heavy metals, in harvestable plant tissues. Phytostabilization reduces pollutant mobility and bioavailability through immobilisation within the soil or root zone. Rhizofiltration uses plant roots to absorb or adsorb contaminants from polluted water, while phytodegradation involves the enzymatic breakdown of organic pollutants within plant tissues. Other important processes include phytovolatilization, in which plants absorb and release certain contaminants into the atmosphere in volatile forms, and rhizodegradation, which involves microbial breakdown of pollutants stimulated by plant root activities (Ali et al., 2013; Salt et al., 1998). The selection of a particular phytoremediation technique depends on pollutant characteristics, environmental conditions, plant tolerance and the intended remediation outcome. For example,

phytoextraction is appropriate for certain metal-contaminated soils, whereas rhizofiltration is more suitable for contaminated water. These different approaches demonstrate the versatility of phytoremediation in environmental pollution management.

2.2 Types of Plants Used in Environmental Remediation

Different plant species have been investigated for their ability to remediate contaminated environments. Their suitability depends on characteristics such as root development, biomass production, pollutant tolerance, accumulation capacity, growth rate and adaptability to environmental conditions. Hyperaccumulator plants are particularly important in the remediation of heavy metal-contaminated soils because they can accumulate high concentrations of specific metals in their above-ground tissues without experiencing severe toxicity. Examples include Pteris vittata, which is recognised for arsenic accumulation, and Noccaea caerulescens, which can accumulate zinc and cadmium. Other terrestrial plants, including Brassica juncea, sunflower (Helianthus annuus) and vetiver grass (Chrysopogon zizanioides), have also been investigated for their potential in the remediation of contaminated soils (Ali et al., 2013; Salt et al., 1998). Aquatic plants are useful in the treatment of polluted water and wastewater because their roots and other tissues can absorb nutrients, metals and certain organic contaminants. Examples include water hyacinth (Eichhornia crassipes), duckweed (Lemna minor), water lettuce (Pistia stratiotes) and common reed (Phragmites australis). These plants can contribute to pollutant removal through nutrient uptake, filtration, adsorption and interactions with microorganisms around their roots (Odimgbe et al., 2026). The application of these plants in environmental remediation has also been explored in Nigerian communities. Water hyacinth, water lettuce and duckweed have been identified as potential macrophytes for wastewater treatment, particularly in constructed wetland systems (Ojo et al., 2022). However, the invasive potential of some aquatic species, particularly water hyacinth, requires appropriate management to prevent additional ecological problems.

Table 1: Examples of plant species used in environmental pollution remediation

Plant species	Plant category	Major remediation application
Pteris vittata	Terrestrial fern	Arsenic-contaminated soils
Noccaea caerulescens	Hyperaccumulator	Zinc and cadmium removal
Brassica juncea	Terrestrial herb	Heavy metal accumulation
Helianthus annuus	Terrestrial herb	Heavy metals and contaminated water
Chrysopogon zizanioides	Perennial grass	Soil stabilisation and metal contamination
Eichhornia crassipes	Aquatic macrophyte	Wastewater and heavy metal removal
Lemna minor	Floating aquatic plant	Nutrients, metals and organic pollutants
Pistia stratiotes	Floating aquatic plant	Wastewater and nutrient removal
Phragmites australis	Emergent aquatic plant	Wetland and wastewater remediation

Salt et al. (1998), Ali et al. (2013), and Ojo et al. (2022).

The table demonstrates that plant selection should be based on the type of pollutant and environmental medium rather than on plant availability alone. Furthermore, the ability of a plant to accumulate contaminants does not automatically establish its effectiveness under field conditions. Its growth performance, contaminant tolerance and biomass management requirements must also be considered.

2.3 Plant–Soil–Microorganism Interactions in Pollutant Removal

The effectiveness of phytoremediation is strongly influenced by interactions among plant roots, soil properties and microorganisms inhabiting the rhizosphere. The rhizosphere refers to the narrow region of soil surrounding plant roots, where biological and chemical activities are considerably influenced by root growth and exudation. Plant roots release organic compounds, including sugars, amino acids, organic acids and phenolic substances, which serve as energy sources for microorganisms. These compounds stimulate microbial growth and enzymatic activities, thereby promoting the degradation of organic contaminants such as petroleum hydrocarbons and certain pesticides. Some microorganisms also produce biosurfactants and other substances that increase pollutant solubility and availability for microbial degradation (Hussain et al., 2018). Microorganisms associated with plant roots may also improve plant tolerance to toxic environments by producing growth-promoting substances, increasing nutrient availability and reducing the harmful effects of pollutants (Etus and Erienu, 2026). Certain bacteria and fungi can immobilise heavy metals, transform contaminants into less toxic forms or enhance their uptake by plant roots. Mycorrhizal fungi, for example, establish associations with plant roots that can influence nutrient acquisition, metal immobilisation and plant resistance to environmental stress. These interactions create a mutually beneficial relationship in which plants provide carbon sources and habitats for microorganisms, while microorganisms support plant growth and pollutant transformation. This combined activity is particularly important in the remediation of petroleum-contaminated environments, where microbial degradation is often more significant than direct plant uptake of hydrocarbons (Hussain et al., 2018). Therefore, understanding plant–soil–microorganism interactions is essential for developing effective and sustainable phytoremediation systems.

III. Mechanisms of Plant-Mediated Pollutant Removal

Plant-mediated pollutant removal occurs through several mechanisms (figure 1), including phytoextraction, phytostabilization, rhizofiltration, phytodegradation, phytovolatilization and rhizodegradation. These processes enable plants and associated microorganisms to absorb, immobilise, transform or degrade contaminants, while biochemical and molecular defence systems enhance plant tolerance to toxic environmental substances.

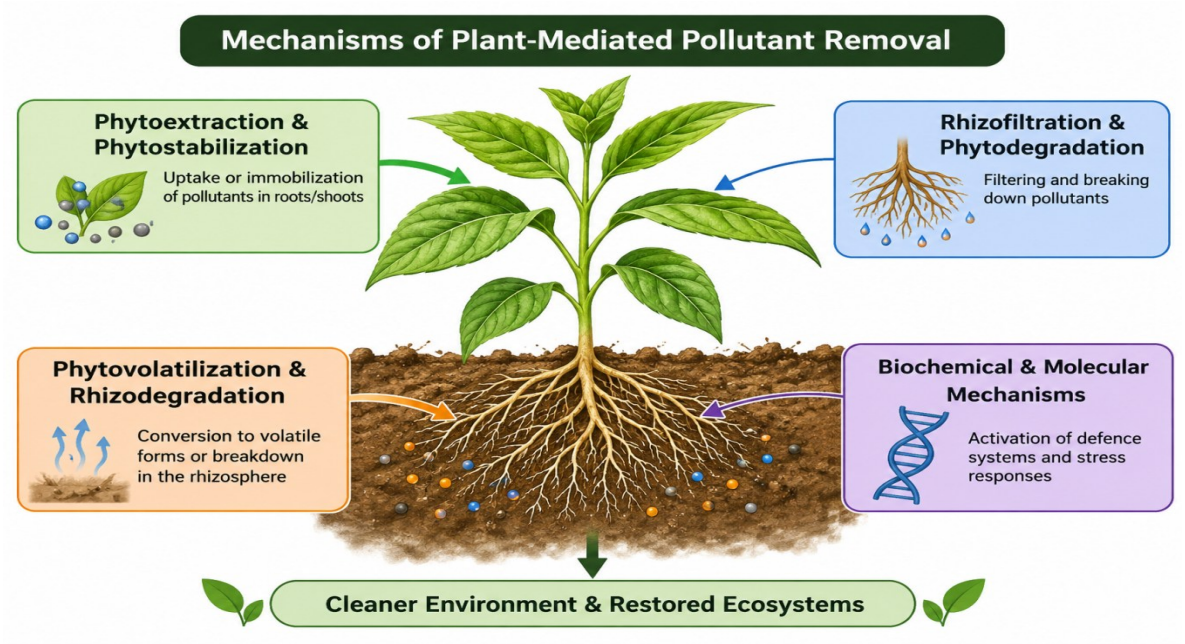


Figure 1: Mechanisms of Plant-Mediated Pollutant Removal

3.1 Phytoextraction and Phytostabilization

Phytoextraction is a phytoremediation mechanism through which plants absorb contaminants, particularly heavy metals, from the soil through their roots and transport them to above-ground tissues such as stems and leaves (Ugochukwu et al., 2025). The contaminated plant parts are subsequently harvested and properly managed to remove the accumulated pollutants from the site. This method is particularly useful for soils contaminated with metals such as cadmium, nickel, zinc, lead and arsenic, although the uptake capacity varies considerably among plant species and chemical forms of the contaminants (Ali et al., 2013). The effectiveness of phytoextraction depends on the ability of plants to tolerate toxic substances, produce sufficient biomass and transport absorbed contaminants from roots to shoots (Umudi et al., 2025). Hyperaccumulator plants are particularly valuable because they can accumulate high concentrations of selected metals in their tissues. However, many hyperaccumulators produce relatively low biomass, which may limit the quantity of contaminants removed within a given period. Phytostabilization, in contrast, involves the use of plants to reduce the mobility, solubility and bioavailability of contaminants in soil. Plant roots, root exudates and associated microorganisms may promote the adsorption, precipitation or immobilisation of pollutants, thereby limiting their movement into groundwater or their uptake by other organisms. Vegetation also reduces soil erosion, dust generation and the transport of contaminated sediments. Unlike phytoextraction, phytostabilization does not necessarily remove contaminants from the environment. Instead, it reduces their potential to cause ecological and human health problems. It is therefore particularly suitable for severely contaminated sites where complete removal of pollutants may be impractical or where the establishment of vegetation is necessary to control erosion and stabilise the soil (Cunningham et al., 1995).

3.2 Rhizofiltration and Phytodegradation

Rhizofiltration involves the use of plant roots to remove contaminants from polluted water through absorption, adsorption and precipitation processes. Plant roots provide extensive surfaces that can trap dissolved pollutants and facilitate their accumulation within root tissues. This mechanism is particularly useful for the treatment of wastewater contaminated with heavy metals and certain radionuclides (Umudi et al., 2025). Aquatic plants such as water hyacinth, duckweed and water lettuce have demonstrated potential for removing nutrients and selected metals from wastewater. Their extensive root systems provide surfaces for contaminant retention and microbial colonisation. Rhizofiltration can also be incorporated into constructed wetland systems to improve wastewater treatment and reduce the concentration of contaminants before discharge into natural water bodies (Ojo et al., 2022). Phytodegradation, also known as phytotransformation, involves the breakdown or transformation of organic pollutants through metabolic activities within plant tissues. Plants produce enzymes capable of transforming certain organic compounds into less toxic substances. Enzymes such as peroxidases, oxygenases and other metabolic proteins participate in the transformation of selected pesticides, solvents and industrial chemicals (Ekpo et al., 2025). In some cases, the transformed products are incorporated into plant metabolic pathways or stored in plant tissues. However, transformation does not always result in complete detoxification. Some intermediate products may remain toxic or persistent, making it necessary to evaluate the chemical identity and environmental fate of degradation products (Salt et al., 1998).

3.3 Phytovolatilization and Rhizodegradation

Phytovolatilization occurs when plants absorb certain contaminants from soil or water, transform them into volatile forms and release them into the atmosphere through transpiration. This process has been investigated for contaminants such as selenium and mercury, depending on their chemical forms and the metabolic capacity of the plant species. Although phytovolatilization can reduce contaminant concentrations in soil and water, it does not necessarily eliminate environmental risks because some pollutants may be transferred into the atmosphere. The released substances may undergo atmospheric transport, chemical transformation or redeposition (Sarah et al., 2026). Therefore, the environmental safety of phytovolatilization must be assessed before its application in contaminated environments. Rhizodegradation involves the breakdown of organic pollutants by microorganisms living around plant roots. Plants stimulate this process by releasing root exudates that support microbial growth and increase biological activity within the rhizosphere. These microorganisms produce enzymes that degrade petroleum hydrocarbons, pesticides and other organic contaminants into simpler compounds. Rhizodegradation is particularly important in petroleum-contaminated soils because hydrocarbons are often degraded more effectively through microbial metabolism than through direct plant uptake. Plant species with extensive root systems can improve soil aeration, provide microbial habitats and stimulate the growth of hydrocarbon-degrading microorganisms. This makes rhizodegradation an important mechanism for the restoration of oil-polluted environments (Hussain et al., 2018).

3.4 Biochemical and Molecular Mechanisms of Plant Tolerance to Pollutants

Plants exposed to environmental pollutants develop several biochemical and molecular defence mechanisms that enable them to survive under toxic conditions. Heavy metals, for example, may induce oxidative stress through the excessive production of reactive oxygen species, which can damage cell membranes, proteins, nucleic acids and other cellular components

(Abeokuta et al ., 2025). To reduce these effects, plants activate antioxidant defence systems involving enzymes such as superoxide dismutase, catalase, glutathione reductase and peroxidases. These enzymes help regulate reactive oxygen species and protect cellular structures from oxidative damage. Non-enzymatic antioxidants, including glutathione, ascorbic acid and other protective compounds, also contribute to plant tolerance (Itodo et al., 2021). Another important mechanism involves the production of phytochelatins and metallothioneins, which bind toxic metal ions and reduce their harmful interactions with cellular components. The resulting metal complexes may be transported into vacuoles, where they are compartmentalised and prevented from interfering with normal metabolic processes (Hall, 2002). Plants also possess specialised membrane transport proteins that regulate the uptake, movement and storage of metals. These transporters influence the movement of contaminants from roots to shoots and their distribution within plant tissues (Erienu et al., 2022). The expression of particular genes involved in metal transport, detoxification and stress responses can determine the ability of plants to survive in contaminated environments. Understanding these biochemical and molecular processes is important for selecting suitable remediation plants and developing improved plant varieties with enhanced pollutant tolerance and accumulation capacities (Yang et al., 2005).

IV. Applications of Phytoremediation in Environmental Pollution Control

Phytoremediation is widely applied in controlling environmental pollution through the use of plants to remove, absorb, immobilise or degrade harmful contaminants as shown in figure 2. It helps eliminate heavy metals and organic pollutants, clean petroleum-contaminated soils, treat industrial wastewater, and restore polluted terrestrial and aquatic ecosystems sustainably.

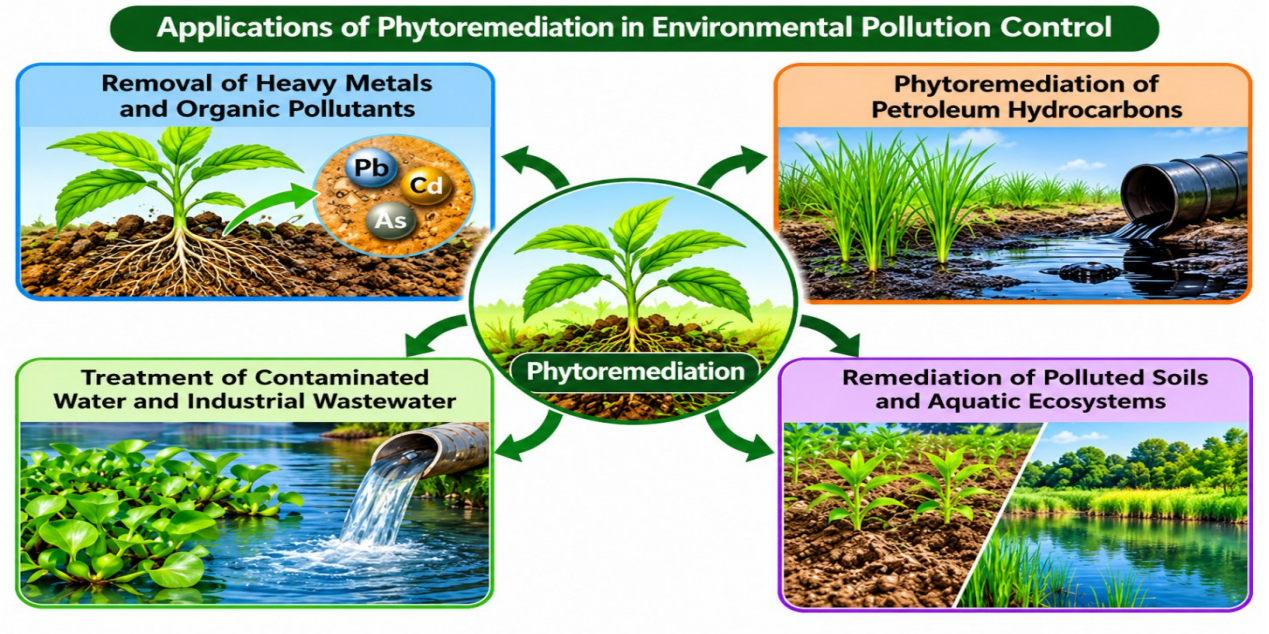


Figure 2: Applications of Phytoremediation in Environmental Pollution Control

4.1 Removal of Heavy Metals and Organic Pollutants

Phytoremediation has been widely investigated as a method for reducing heavy metal contamination in soils and water (Obruche et al., 2018). Metals such as lead, cadmium, chromium, arsenic, nickel and mercury may enter the environment through mining, industrial discharge, waste disposal and agricultural activities. Because many metals cannot be biologically degraded, their remediation requires processes that remove, immobilise or transform their chemical forms. Plants such as Pteris vittata, Brassica juncea and Noccaea caerulescens have been investigated for their ability to accumulate selected metals in their tissues. Their application can reduce the concentration or mobility of contaminants, depending on the remediation mechanism employed (Ali et al., 2013). Organic pollutants, including pesticides, petroleum derivatives, industrial solvents and polycyclic aromatic hydrocarbons, can also be managed through plant-mediated remediation. Unlike metals, many organic compounds can undergo enzymatic transformation or microbial degradation. Plants contribute to these processes through direct metabolism and stimulation of rhizosphere microorganisms. However, the effectiveness of phytoremediation varies with pollutant structure, concentration, bioavailability and plant tolerance. Therefore, selecting appropriate plant species and understanding pollutant-specific remediation mechanisms are essential for achieving satisfactory environmental outcomes.

4.2 Phytoremediation of Petroleum Hydrocarbons and Oil-Contaminated Environments

Petroleum hydrocarbon pollution is a major environmental concern in regions involved in crude oil exploration, transportation, refining and storage. Accidental oil spills and operational discharges introduce hydrocarbons into soil, sediments, wetlands and aquatic ecosystems. These substances can reduce soil fertility, interfere with plant development, alter microbial communities and threaten aquatic organisms (Ogwuche and Obruche, 2020). Phytoremediation offers an environmentally compatible approach for managing petroleum-contaminated environments. Its major contribution occurs through rhizodegradation, in which plant roots stimulate the activities of hydrocarbon-degrading microorganisms. Root exudates provide carbon sources that support microbial populations capable of breaking down petroleum compounds (Micheal et al., 2026). In addition, plant roots improve soil structure and create favourable conditions for microbial activity (Hussain et al., 2018). Grasses such as vetiver (Chrysopogon zizanioides), ryegrass (Lolium perenne) and other tolerant plant species have been investigated for their potential in petroleum-contaminated soils. Their extensive root systems and relatively high biomass production make them useful candidates for stabilising contaminated soil and stimulating microbial degradation (Obruche et al., 2019). Nevertheless, petroleum hydrocarbons may inhibit seed germination, root development and photosynthesis when present at high concentrations. The effectiveness of plant-assisted remediation therefore depends on selecting tolerant species, managing soil conditions and allowing sufficient treatment periods. Combining plants with hydrocarbon-degrading microorganisms and suitable soil amendments may further improve remediation performance (Hussain et al., 2018).

4.3 Treatment of Contaminated Water and Industrial Wastewater

Plant-mediated remediation is increasingly being considered for wastewater treatment because aquatic plants can absorb nutrients, retain suspended materials and facilitate the removal of selected contaminants. Constructed wetlands are particularly important in this regard because they combine vegetation, microorganisms and suitable substrates to improve water quality.

Aquatic macrophytes such as water hyacinth, duckweed, water lettuce and common reed have been investigated for treating domestic and industrial wastewater. These plants can contribute to the removal of nitrogen, phosphorus, suspended solids and selected heavy metals. Their roots also support microbial communities responsible for the transformation of organic matter and other pollutants. In Nigeria, locally available aquatic macrophytes have been identified as potential resources for low-cost wastewater treatment. Ojo et al. (2022) reported that water lettuce, water hyacinth and duckweed have potential applications in reducing several wastewater quality indicators, including biological oxygen demand, chemical oxygen demand, nutrients and heavy metals. Despite these advantages, harvested aquatic plants must be properly managed because accumulated contaminants may be released back into the environment during decomposition. Furthermore, invasive aquatic species require controlled cultivation and harvesting to prevent ecological disturbance.

4.4 Remediation of Polluted Soils and Aquatic Ecosystems

Phytoremediation has applications in the restoration of both terrestrial and aquatic environments affected by chemical contamination (Micheal et al., 2026). In polluted soils, vegetation can reduce contaminant mobility, improve soil structure, control erosion and stimulate microbial degradation. These functions are important in agricultural lands, industrial sites, mining areas and petroleum-contaminated locations. In aquatic ecosystems, floating and emergent plants can remove selected pollutants from water and sediments while providing habitats for microorganisms and other aquatic organisms (Obruche et al., 2019). Constructed wetlands can also act as natural treatment systems that improve water quality before treated water enters rivers, lakes and other receiving environments. The restoration of polluted environments requires more than a reduction in contaminant concentrations. It also involves the recovery of ecological functions, including nutrient cycling, vegetation development, microbial diversity and habitat quality. Consequently, phytoremediation is most effective when integrated into broader ecosystem restoration programmes that consider both pollution reduction and long-term ecological recovery.

V. Ecological Sustainability and Ecosystem Restoration

5.1 Effects of Phytoremediation on Soil and Water Quality

Phytoremediation contributes to the improvement of soil and water quality by reducing the concentration, mobility and environmental availability of pollutants. In contaminated soils, plant roots help stabilise soil particles, reduce erosion and improve soil structure. The decomposition of plant materials also contributes organic matter, which can improve soil aggregation, nutrient availability and water retention. Furthermore, root exudates stimulate microbial activities that support nutrient cycling and the degradation of organic contaminants. These processes can improve the biological properties of contaminated soils and create favourable conditions for vegetation recovery. However, improvements in soil quality depend on the plant species used, the type of contaminant and the duration of remediation. In aquatic environments, phytoremediation contributes to water purification through the absorption of excess nutrients, retention of suspended particles and removal of selected chemical contaminants. Aquatic vegetation can also provide surfaces for microbial activities involved in organic matter decomposition. These processes help improve water quality and support the recovery of aquatic ecosystems (Ojo et al., 2022).

5.2 Biodiversity Conservation and Restoration of Ecosystem Functions

Environmental pollution often causes the destruction of natural habitats, reduction in species diversity and disruption of ecological relationships. The establishment of vegetation on contaminated land can contribute to biodiversity conservation by providing food, shelter and breeding habitats for microorganisms, insects, birds and other wildlife. Plant-mediated remediation also supports the recovery of important ecosystem functions, including nutrient cycling, soil formation, organic matter decomposition and regulation of water movement. As vegetation becomes established, the improved environmental conditions may encourage the return of organisms that were previously affected by pollution. The use of native plant species is particularly important because they are generally better adapted to local environmental conditions and may support indigenous biodiversity. However, the introduction of non-native or invasive plants for remediation should be carefully controlled to prevent competition with native species and further ecological disturbance. Therefore, phytoremediation should be planned not only to reduce pollution but also to promote the recovery of biological communities and ecological interactions.

5.3 Rehabilitation of Degraded Lands, Wetlands and Aquatic Ecosystems

The rehabilitation of degraded ecosystems involves restoring environmental conditions and ecological processes that have been disrupted by pollution, deforestation, industrial activities and other forms of environmental disturbance (Ugochukwu et al., 2025). Phytoremediation provides an important biological approach to this process through vegetation establishment, contaminant immobilisation and stimulation of microbial activities. In degraded terrestrial environments, suitable grasses, shrubs and trees can be introduced to stabilise contaminated soils, reduce erosion and support the gradual recovery of soil fertility (Festus-Amadi et al., 2021). In petroleum-polluted environments, plant roots can stimulate hydrocarbon-degrading microorganisms, thereby contributing to the reduction of petroleum contaminants. Wetlands are particularly important because they provide natural filtration, nutrient retention, flood regulation and habitats for diverse organisms. The establishment of suitable wetland vegetation can improve sediment stability, enhance microbial degradation and support the recovery of wetland functions. Similarly, aquatic plants can contribute to the rehabilitation of polluted rivers, lakes and ponds by removing selected contaminants and improving water quality. However, successful ecosystem restoration requires long-term monitoring to establish whether improvements in vegetation cover are accompanied by reductions in pollution and recovery of ecological functions.

5.4 Contribution of Phytoremediation to Climate Change Mitigation

Phytoremediation can contribute indirectly to climate change mitigation through vegetation establishment, biomass production and carbon sequestration. During photosynthesis, plants absorb atmospheric carbon dioxide and convert it into organic compounds, some of which are stored in plant biomass and soil organic matter. The establishment of vegetation on degraded lands can increase carbon storage while reducing soil erosion and supporting soil restoration. Trees, grasses and wetland plants may also contribute to improved microclimatic conditions and the recovery of ecological processes. Wetlands are particularly significant because healthy wetland ecosystems can store substantial quantities of organic carbon in their vegetation and sediments. Consequently, restoring degraded wetlands through appropriate vegetation management may provide both pollution-control and climate-related benefits. Nevertheless, the climate benefits of phytoremediation depend on plant productivity, biomass management, soil carbon storage and the overall greenhouse gas balance of the remediation

system. For instance, decomposition of harvested or accumulated biomass may release carbon, while some wetland conditions may promote methane production. Therefore, the climate mitigation potential of phytoremediation should be evaluated alongside its broader environmental effects.

VI. Factors Affecting the Efficiency of Phytoremediation

The effectiveness of phytoremediation depends on several biological, chemical and environmental factors. These factors determine the ability of plants to survive in contaminated environments, absorb pollutants, stimulate microbial activities and support contaminant transformation. Understanding these conditions is essential for selecting suitable plant species and designing effective remediation systems (Ali et al., 2013).

6.1 Plant Species and Pollutant Characteristics

Plant species selection is one of the most important factors influencing phytoremediation efficiency. Different plants possess different capacities for pollutant absorption, accumulation, transformation and tolerance. Hyperaccumulator plants are particularly suitable for extracting certain heavy metals, while plants with extensive root systems are useful for stabilising contaminated soils and stimulating rhizosphere microbial activities (Okpanachi et al., 2025). The growth rate, root depth, biomass production and tolerance to toxic substances also influence remediation performance. Plants that produce large amounts of biomass may remove greater quantities of accumulated contaminants when their above-ground tissues are harvested. Conversely, plants with limited growth under contaminated conditions may have reduced remediation potential (Umudi et al., 2025). Pollutant characteristics are equally important. Heavy metals cannot be biologically degraded, although plants can absorb, immobilise or alter their chemical forms. Organic pollutants, on the other hand, may undergo enzymatic transformation or microbial degradation. The chemical structure, concentration, solubility and bioavailability of contaminants therefore determine the mechanisms through which plants can contribute to remediation.

6.2 Soil Properties and Environmental Conditions

Soil properties significantly influence the movement and availability of pollutants to plant roots. Soil pH is particularly important because it affects the solubility and chemical availability of many heavy metals. In acidic soils, some metals become more soluble and may be more readily absorbed by plants, although excessive metal availability can also increase phytotoxicity. Soil organic matter influences pollutant retention, microbial activity and nutrient availability. Similarly, soil texture, moisture content, aeration and nutrient composition affect root development and the movement of contaminants within the soil profile (Umudi et al., 2025). Environmental conditions such as temperature, rainfall, sunlight and seasonal variations also influence plant growth and remediation performance (Nathan et al., 2025). Adequate moisture and suitable temperatures generally support plant development and microbial activities, while drought, excessive flooding and extreme temperatures may reduce remediation efficiency.

6.3 Influence of Rhizosphere Microorganisms

Rhizosphere microorganisms play an important role in determining the efficiency of plant-mediated remediation. Bacteria and fungi associated with plant roots can degrade organic contaminants, influence metal mobility and improve plant tolerance

to toxic substances. Plant growth-promoting rhizobacteria may produce substances that stimulate root development, improve nutrient uptake and enhance plant resistance to environmental stress

Table 2: Major factors influencing the efficiency of phytoremediation

Factors	Major characteristics	Effects on remediation efficiency
Plant species	Root development, biomass and pollutant tolerance	Determines pollutant uptake, accumulation and transformation
Pollutant characteristics	Concentration, toxicity and chemical structure	Determines contaminant availability and remediation mechanisms
Soil pH	Soil acidity and alkalinity	Influences metal solubility and availability
Soil organic matter	Organic carbon and humic substances	Affects pollutant retention and microbial activities
Soil moisture	Water availability and drainage	Influences root growth and microbial metabolism
Temperature	Environmental and seasonal conditions	Affects plant growth and contaminant degradation
Nutrient availability	Nitrogen, phosphorus and other essential nutrients	Supports plant development and microbial activities
Rhizosphere microorganisms	Bacteria, fungi and mycorrhizal associations	Enhances degradation, nutrient acquisition and pollutant transformation
Treatment duration	Period of plant establishment and growth	Determines the extent of pollutant reduction

Adapted from Ali et al. (2013), Hall (2002), and Hussain et al. (2018).

. Some microorganisms also produce biosurfactants that increase the availability of hydrophobic pollutants, including petroleum hydrocarbons, for microbial degradation. Mycorrhizal fungi can improve nutrient acquisition and influence the uptake or immobilisation of certain heavy metals. These beneficial interactions may enhance plant establishment and improve remediation performance, particularly under stressful environmental conditions. The combination of suitable plants and pollutant-degrading microorganisms is therefore an important strategy for improving phytoremediation efficiency, especially in petroleum-contaminated environments (Hussain et al., 2018).

The table indicates that phytoremediation efficiency is controlled by the interaction of several factors rather than by plant characteristics alone. Consequently, successful remediation requires an integrated understanding of plant physiology, soil chemistry, pollutant behaviour and microbial ecology.

VII. Challenges, Emerging Technologies and Future Prospects

7.1 Limitations and Environmental Risks of Phytoremediation

Despite its environmental advantages, phytoremediation has several limitations that may restrict its application under certain conditions. One major limitation is its relatively slow remediation rate compared with some physical and chemical treatment methods. Plants require sufficient time to establish their roots, produce biomass and accumulate or transform contaminants. Consequently, heavily contaminated sites may require several growing seasons before significant improvements are achieved. Another limitation is the dependence of phytoremediation on plant growth and environmental conditions. High pollutant concentrations may inhibit seed germination, root development and photosynthesis, thereby reducing plant survival.

Furthermore, phytoremediation is generally limited to the depth reached by plant roots, making it less suitable for deeply contaminated soils and groundwater. The accumulation of toxic substances in plant tissues also presents environmental risks. If contaminated plants are consumed by grazing animals or enter the food chain, accumulated pollutants may be transferred to other organisms. Therefore, harvested plant materials must be properly managed through appropriate treatment, controlled disposal or recovery of valuable metals where feasible. Additionally, phytovolatilization may transfer certain contaminants from soil or water into the atmosphere rather than completely eliminating environmental risks. The potential spread of invasive plant species and the release of pollutants during plant decomposition are further considerations. These limitations demonstrate the need for careful site assessment, appropriate plant selection and continuous environmental monitoring (Ali et al., 2013; Salt et al., 1998).

7.2 Genetic Engineering and Microbial-Assisted Phytoremediation

Recent advances in biotechnology have created opportunities for improving the efficiency of plant-mediated remediation through genetic engineering and microbial-assisted approaches. Genetic engineering involves modifying plant genetic characteristics to improve pollutant tolerance, uptake, accumulation and detoxification.

Researchers have investigated genes involved in metal transport, antioxidant defence, chelation and cellular compartmentalisation as potential targets for improving phytoremediation performance. The development of plants with enhanced root systems, higher biomass production and greater tolerance to toxic substances may improve the remediation of contaminated environments (Yang et al., 2005). Microbial-assisted phytoremediation involves the use of beneficial bacteria and fungi to enhance plant growth and pollutant removal. These microorganisms may increase nutrient availability, stimulate root development, improve pollutant bioavailability and promote the degradation of organic contaminants. Plant growth-promoting rhizobacteria and hydrocarbon-degrading microorganisms are particularly relevant to petroleum-contaminated soils. Their combination with suitable plant species may increase the degradation of petroleum hydrocarbons and improve vegetation establishment in polluted environments (Hussain et al., 2018). However, the application of genetically modified plants and introduced microorganisms requires appropriate ecological risk assessment. Their potential effects on native species, microbial communities and environmental stability must be carefully evaluated before large-scale application.

7.3 Integration of Phytoremediation with Other Remediation Technologies

The integration of phytoremediation with other remediation technologies provides an opportunity to overcome some of the limitations associated with plant-based treatment alone. Combined remediation approaches may improve pollutant availability, accelerate contaminant degradation and enhance plant survival under contaminated conditions. For example, phytoremediation can be combined with bioremediation through the introduction of pollutant-degrading microorganisms into the rhizosphere. This approach is particularly useful in petroleum-contaminated environments because plant roots stimulate microbial activities responsible for hydrocarbon degradation. Soil amendments such as compost, biochar and selected organic materials may also improve soil structure, nutrient availability and plant establishment. However, amendments must be selected carefully because some substances may immobilise contaminants that are intended for extraction or alter their environmental mobility. Constructed wetlands provide another example of an integrated phytoremediation system. They

combine aquatic plants, microorganisms and suitable substrates to improve wastewater treatment. Similarly, physical or chemical pretreatment may be used to reduce pollutant concentrations before plant-based remediation is introduced. The integration of these methods offers a more flexible approach to environmental restoration because treatment strategies can be adjusted according to the nature and severity of contamination.

7.4 Research Gaps and Future Perspectives

Although considerable progress has been made in phytoremediation research, several knowledge gaps remain. Many studies have focused on laboratory and greenhouse experiments, while fewer have examined the long-term performance of plant-based remediation under complex field conditions. Differences between controlled experimental environments and natural ecosystems may affect the reliability of laboratory findings when applied to large contaminated sites. There is also a need for more research on the interactions among plants, pollutants and indigenous microorganisms, particularly in environments contaminated with mixtures of heavy metals, petroleum hydrocarbons and industrial chemicals. The long-term ecological effects of phytoremediation, including changes in soil microbial communities, biodiversity and food-web interactions, also require further investigation. In petroleum-producing regions such as the Niger Delta, greater attention should be given to the identification of indigenous plant species capable of surviving in oil-contaminated soils and wetlands. Research should also examine the effectiveness of native plant–microorganism combinations under local climatic, hydrological and soil conditions. Future studies should prioritise field-based trials, improved molecular techniques, microbial-assisted remediation and the development of integrated treatment systems. Furthermore, the safe management of contaminated plant biomass and the economic feasibility of large-scale phytoremediation require additional investigation. Addressing these research gaps will improve the scientific understanding and practical application of plant-mediated remediation while strengthening its contribution to sustainable environmental management.

Conclusion

Plant-mediated remediation represents a promising and environmentally sustainable approach to the management of polluted soils, water bodies and degraded ecosystems. Through mechanisms such as phytoextraction, phytostabilization, rhizofiltration, phytodegradation, phytovolatilization and rhizodegradation, plants and their associated microorganisms can remove, immobilise or transform different categories of environmental pollutants. The review demonstrates that the effectiveness of phytoremediation depends on plant species, pollutant characteristics, soil properties, environmental conditions and rhizosphere microbial activities. Its applications in the remediation of heavy metals, petroleum hydrocarbons, industrial wastewater and other environmental contaminants highlight its potential as a complementary approach to conventional pollution-control technologies. Beyond contaminant reduction, phytoremediation contributes to soil quality improvement, biodiversity conservation, vegetation establishment and the recovery of ecosystem functions. These benefits make it particularly relevant to the rehabilitation of degraded agricultural lands, wetlands and petroleum-contaminated environments. However, challenges associated with slow remediation rates, limited root penetration, plant toxicity, contaminated biomass disposal and possible pollutant transfer through food chains must be adequately addressed. Advances in genetic engineering, microbial-assisted remediation and integrated treatment technologies provide opportunities for improving its effectiveness. Overall, the successful application of plant-mediated remediation requires a combination of

appropriate plant selection, scientific understanding of remediation mechanisms, ecological risk assessment and long-term environmental monitoring. Greater emphasis on field-based research and indigenous plant resources will further strengthen the contribution of phytoremediation to ecological sustainability and the restoration of degraded ecosystems.

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