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Review Article

Plant Based Sustainable Technology: Phytoremediation

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ABSTRACT

Phytoremediation cleans contaminated areas with plants. Metals, pesticides, explosives, and oil can be removed by plants. These approaches work best in low-polluted environments because high levels can slow plant growth and delay cleanup. Plants also prevent wind, rain, and groundwater from spreading pollutants close to or deeper below. Some plants absorb water and nutrients through their roots to remove or breakdown harmful chemicals from soil, sediment, or groundwater. Plants use natural methods to eliminate pollutants. These pollutants might be stored in roots, stems, or leaves. Plants can also transform poisonous compounds into less dangerous ones in the root zone. They discharge pollutants into the air by turning them into vapours. Roots absorb poisons and use soil microbes like bacteria to breakdown them. Polluted groundwater migration is often slowed by phytoremediation. Trees collect groundwater through their roots to prevent displacement. Reduces polluted groundwater movement to uncontaminated areas beyond the site. Phytoremediation includes constructed wetlands. Wetlands can be created to treat acid mine drainage or water from other treatment systems. Indigenous marsh grasses and other species are grown in the area. Some plants remove contaminants better. Phytoremediation plants must be able to withstand current contaminants. They must also thrive and survive in the local climate. The level of pollutants also matters. Ferns and grasses have remedied shallow pollution. Due to their large root systems, poplar and willow trees are used for hydraulic control and cleanup of deep soil contamination and polluted groundwater.

Keywords: *Heavy metal Contamination, Phytodegradation, Phytofiltration, Rhizodegradation*

INTRODUCTION

Phytoremediation is the process of utilizing plants to purify polluted areas. Plants possess the ability to effectively remove various forms of pollutants, such as metals, pesticides, explosives, and oil[1]. Nevertheless, these methods are most effective in environments with minimal amounts of pollutants, as excessive quantities might impede plant development and prolong the remediation process. Plants additionally aid in the prevention of toxins being transported by wind, rain, and groundwater, thereby limiting their spread to nearby areas or deeper down [2].

Some plants possess the ability to eliminate or decompose detrimental substances from the soil, sediment, or groundwater by absorbing water and nutrients through their roots. Plants have the ability to remove contaminants from the environment by utilising natural mechanisms. They can store these contaminants in their roots, stems, or leaves. Additionally, plants can convert these harmful substances into less toxic chemicals, usually within the root zone[3]. Another method employed by plants is converting contaminants into vapours, which are then released into the air.

Plants absorb toxins through their roots and utilise microorganisms, such bacteria, present in the soil to decompose them. Phytoremediation is frequently employed to decelerate the migration of polluted groundwater. Trees function as a mechanism that extracts groundwater through their roots in order to prevent its displacement. The technique of phytoremediation referred to as "hydraulic control" is employed. It mitigates the migration of polluted groundwater towards uncontaminated areas outside the site[4].

Constructed wetlands are a type of phytoremediation. A wetland can be established at a specific location to remediate acid mine drainage that passes through it or as a concluding treatment measure for water discharged from alternative treatment systems[5]. Treated water from manmade wetlands typically contains minimal levels of pollutants that must be eliminated prior to its release into a lake or stream. The establishment of wetlands may necessitate excavation or regrading of the soil at the location to facilitate the natural flow of water without the need for artificial pumping[6].

The region is cultivated with indigenous wetland flora, including grasses and other vegetation commonly seen in the area. Some plants have superior efficacy in eliminating pollutants compared to others[7]. Plants utilised for phytoremediation must possess the capacity to endure the specific types and levels of pollutants that are now present. Additionally, they must possess the capability to thrive and endure in the indigenous climatic conditions[8]. The extent of pollution is another contributing element. Shallow areas of contamination have been remediated using small vegetation such as ferns and grasses. Poplar and willow trees are utilised for hydraulic control and remediation of deep soil contamination and polluted groundwater due to their ability to develop extensive root systems[9].

Phytoremediation has several advantages, including its cost-effectiveness, sustainability, and aesthetic appeal. It applies to a wide range of contaminants and can be used in conjunction with other remediation techniques. However, it also has limitations, such as the relatively slow rate of remediation, dependency on specific plant species, and the need for long-term monitoring[10].

Researchers continue to explore and develop new plant species and strategies to enhance the efficiency and applicability of phytoremediation in different environmental contexts.

1. **Phytoextraction**

   Phytoextraction is a process that involves using plants to remove, transfer, or stabilize contaminants from the soil or water. This method is particularly employed for the removal of heavy metals and other pollutants from contaminated sites[11]. The plants used in phytoextraction are called hyperaccumulators, as they have the ability to absorb and accumulate high concentrations of specific metals or contaminants in their tissues without being significantly affected.

1.1 How it works???

1.1.1 **Plant Selection:** Hyperaccumulator plants are chosen based on their ability to thrive in contaminated environments and accumulate specific pollutants in their tissues. Examples of hyperaccumulator plants include certain species of willow, poplar, and various metal-accumulating ferns.

1.1.2 **Planting and Growth:** The selected hyperaccumulator plants are cultivated on the contaminated site. These plants absorb pollutants from the soil through their roots and translocate them to the above-ground parts, such as leaves and stems.

1.1.3 **Harvesting:** After a certain period of growth, the plants are harvested. The above-ground biomass containing the accumulated contaminants is then removed from the site.

1.1.4 **Disposal or Recovery:** Depending on the contaminants and the intended goal, the harvested biomass may be disposed of properly or processed to recover valuable metals. In some cases, the process may be repeated over several growth cycles to achieve significant contaminant reduction.

2. Phytodegradation

Phytodegradation is a process by which plants and their associated microorganisms are used to break down, detoxify, and eliminate pollutants in the environment[12]. This approach relies on the ability of certain plant species, known as hyperaccumulators, to absorb and concentrate pollutants from the soil or water into their tissues[13].The primary mechanism of phytodegradation involves the uptake of contaminants by plant roots and their subsequent transformation or degradation within the plant or in the rhizosphere (the region of soil influenced by root activity). This process can be particularly effective for organic pollutants, such as certain pesticides and hydrocarbons[14].

2.1 How it works???

2.1.1 **Contaminant Identification and Site Assessment:** Identify the specific organic contaminants present in the soil or water. Conduct a comprehensive site assessment to understand the extent of contamination, soil characteristics, and environmental conditions.

2.1.2 **Plant Selection:** Choose plant species that have the ability to either directly metabolize the target contaminants or enhance microbial activity in the rhizosphere for degradation. Selecting appropriate plant species is crucial for the success of phytodegradation.

2.1.3 **Soil Preparation:** Prepare the soil to create favorable conditions for plant growth. This may involve adjusting pH levels, addressing soil compaction, and providing essential nutrients to support both plant growth and microbial activity.

2.1.4 **Planting:** Plant the selected species in the contaminated area. Proper spacing and coverage are essential to maximize the contact between plant roots and the contaminated soil. Planting can be done directly in the soil or in hydroponic systems for water treatment.

2.1.5 **Root Uptake:** Plants take up contaminants from the soil or water through their roots. This process involves the absorption of organic pollutants, which are then transported within the plant.

2.1.6 **Metabolism in Plant Tissues:** In certain cases, plants have the ability to metabolize organic contaminants within their tissues. This can involve enzymatic processes that break down complex pollutants into simpler and less harmful compounds.

2.1.7 **Rhizosphere Microbial Activity:** Plants release root exudates into the rhizosphere, which is the zone of soil surrounding the roots. These exudates serve as a carbon source for microorganisms. The enhanced microbial activity in the rhizosphere contributes to the degradation of organic contaminants.

2.1.8 **Enzyme Production:** Microorganisms in the rhizosphere may produce enzymes that facilitate the degradation of organic pollutants. These enzymes break down complex molecules into smaller, more manageable compounds.

2.1.9 **Synergistic Plant-Microbe Interactions:** The synergy between plants and rhizospheric microorganisms is crucial for effective phytodegradation. Plants support microbial growth through root exudation, and microorganisms contribute to the breakdown of contaminants.

3. Rhizofiltration

Rhizofiltration is a phytoremediation technique that utilizes the root systems of plants to remove, degrade, or immobilize contaminants in soil or water[15]. The term is derived from "rhizo," which refers to roots, and "filtration," indicating the process of filtering or removing impurities. In rhizofiltration, certain plants, known as hyperaccumulators, are selected for their ability to absorb and accumulate high concentrations of specific contaminants from the soil or water into their root tissues. These plants then act as natural filters, helping to reduce the concentration of pollutants in the environment[16]. Common contaminants targeted through rhizofiltration include heavy metals, such as lead, cadmium, and arsenic. The process works by the roots of the hyperaccumulator plants selectively taking up these pollutants, which are then stored in the plant's biomass. Once the plants have absorbed a significant amount of contaminants, they can be harvested and properly disposed of, removing the pollutants from the environment[17]. Rhizofiltration is considered an environmentally friendly and cost-effective method for remediating contaminated sites, especially in areas where conventional cleanup methods may be impractical or expensive. Additionally, it can be implemented in conjunction with other phytoremediation techniques to address a broader range of contaminants and environmental conditions[18].

3.1 How it Works??

3.1.1 Plant Selection: The first step involves selecting appropriate plant species for rhizofiltration. Certain plants, known as hyperaccumulators, have the ability to absorb and accumulate high concentrations of specific contaminants.

3.1.2 Root Uptake: Once the suitable plant species are chosen, they are planted in the contaminated site, either directly in the soil or in hydroponic systems for water treatment. The roots of these plants play a crucial role in the process.

3.1.3 Contaminant Absorption: As the plants grow, their roots absorb water along with dissolved contaminants from the soil or water. The contaminants may include heavy metals such as lead, cadmium, and zinc, as well as other pollutants like organic compounds.

3.1.4 Transport and Accumulation: The contaminants taken up by the roots are transported through the plant's vascular system. Some contaminants are sequestered in the root tissues, while others may be translocated to above-ground parts of the plant, such as leaves or stems.

3.1.5 Storage in Plant Tissues: The contaminants are often stored in the plant's tissues, with a concentration higher than that in the surrounding environment. This accumulation can be significant, especially in hyperaccumulator plants.

3.1.6 Harvesting and Disposal: Once the plants have absorbed a substantial amount of contaminants, they can be harvested and removed from the site. This process effectively removes the pollutants from the environment.

3.1.7 **Revegetation:** In some cases, the harvested plants are replaced with new ones to continue the rhizofiltration process. This helps in maintaining the long-term effectiveness of the remediation technique.

3.1.8 **Monitoring and Optimization:**Throughout the rhizofiltration process, it's important to monitor the concentration of contaminants in both the plant tissues and the surrounding environment. This information helps in optimizing the efficiency of the remediation process.

4 Phytostabilization

Phytostabilization is a technique used in environmental management and remediation to control or reduce the mobility of contaminants in soil through the use of plants[19]. This approach relies on the ability of certain plants, known as hyperaccumulators, to absorb and accumulate pollutants from the soil. The goal is to stabilize the contaminants in place, preventing their migration to groundwater or their uptake by other plants[20].

4.1 How it Works???

4.1.1 **Plant Selection:** Hyperaccumulator plants are selected based on their ability to absorb and tolerate high concentrations of specific contaminants, such as heavy metals. These plants can accumulate metals in their tissues without displaying significant adverse effects.

4.1.2 **Root Uptake:** The roots of hyperaccumulator plants play a crucial role in the process. They absorb contaminants from the soil and transport them to the above-ground parts of the plant. This prevents the contaminants from leaching into the groundwater.

4.1.3 **Stabilization of Contaminants:** Once absorbed by the plants, contaminants are immobilized or stabilized in the plant tissues. This reduces their bioavailability and mobility in the soil, making it less likely for them to be taken up by other organisms or transported through the environment.

4.1.4 **Soil Structure Improvement:** The growth of plant roots also contributes to the improvement of soil structure, which can further reduce the potential for contaminant migration. The roots bind soil particles together, enhancing soil stability.

4.1.5 Long-Term Management: Phytostabilization is often considered a long-term management strategy. Over time, as the plants grow and accumulate contaminants, the concentration of pollutants in the soil may decrease, leading to improvements in soil quality.

4.1.6 Site-Specific Approach: The success of phytostabilization depends on the specific characteristics of the contaminated site, such as soil type, climate, and the types of contaminants present. Site-specific factors influence the selection of appropriate hyperaccumulator plants and the overall effectiveness of the technique.

Phytostabilization is one of several phytoremediation techniques used to address soil contamination[21]. Other phytoremediation methods include phytoextraction (removal of contaminants from the soil by plants) and phytodegradation (breakdown of contaminants by plant-associated microorganisms). The choice of the most suitable technique depends on the nature and extent of contamination at a particular site[22].

5. Phytovolatilization

Phytovolatilization is a process by which plants absorb contaminants from the soil through their roots and then release or volatilize these contaminants into the atmosphere in the form of gases[23]. This method is often used as a phytoremediation strategy to mitigate soil and water pollution. In the context of environmental remediation, phytovolatilization is particularly effective for volatile organic compounds (VOCs) and certain heavy metals. Plants take up these contaminants through their roots and, in some cases, transform them into less harmful substances or store them in plant tissues. The contaminants are then released into the air through the plant's leaves[24.] This process can be a sustainable and cost-effective way to remediate contaminated sites, especially in areas where traditional methods like excavation and disposal are impractical or expensive. Certain plant species, known as hyperaccumulators, are especially adept at accumulating and translocating pollutants from the soil[25].

5.1 How it works???

5.1.1 **Plant Selection:** Choose plant species with the ability to accumulate and volatilize contaminants. Some plants, known as hyperaccumulators, are particularly effective in this process. The selection depends on the specific contaminants present in the soil or water.

5.1.2 **Site Preparation:** Prepare the contaminated site for planting. This may involve soil amendment or other measures to enhance plant growth and optimize the conditions for phytovolatilization.

5.1.3 **Planting:** Plant the selected species in the contaminated area. The plants should be strategically placed to cover the affected zone adequately. The root system of the chosen plants plays a crucial role in the subsequent steps.

5.1.4 **Contaminant Uptake:** The plants absorb contaminants from the soil or water through their roots. In the case of volatile organic compounds, this uptake involves the movement of contaminants into the plant tissues.

5.1.5 **Translocation:** Once absorbed, the contaminants are transported within the plant through its vascular system. This process may involve movement from the roots to the shoots, where the contaminants can be further processed.

5.1.6 **Transformation and Volatilization:** Within the plant tissues, certain enzymes or biochemical processes may transform the absorbed contaminants into volatile compounds. These volatile forms are then released into the atmosphere through processes like transpiration from leaves.

5.1.7 **Airborne Emission:** The contaminants in volatile form are released into the air, effectively removing them from the soil or water. This airborne emission is a key aspect of phytovolatilization, as it facilitates the transfer of pollutants from the plant to the atmosphere.

5.1.8 Harvesting and Disposal: Depending on the specific goals of the remediation project, plants may be harvested after a certain period. The harvested plants, now containing the contaminants, need to be properly disposed of to prevent recontamination.

5.1.9 Monitoring and Assessment: Throughout the phytovolatilization process, continuous monitoring of contaminant levels in both the plants and the surrounding environment is essential. This helps in assessing the effectiveness of the remediation and making any necessary adjustments[26].

It's worth noting that the effectiveness of phytovolatilization depends on various factors, including the type of contaminant, the plant species involved, and environmental conditions. Researchers continue to explore and optimize the use of phytovolatilization as a viable and eco-friendly approach to environmental remediation[27].

6. **Rhizodegradation**

Rhizodegradation is a process in which the roots of plants enhance the microbial activity in the rhizosphere (the soil region influenced by plant roots) to break down and degrade organic pollutants[28]. This phenomenon is particularly important in the context of phytoremediation, which is a method of using plants to clean up contaminated soil, water, or air.The root exudates released by plants into the soil provide a carbon source for microorganisms, stimulating their growth and activity. These microorganisms, in turn, can metabolize and degrade various organic pollutants present in the soil[29]. The process is highly effective for the degradation of certain organic compounds, including hydrocarbons, pesticides, and other pollutants.

6.1 How it Works???

6.1.1 **Site Assessment:** Conduct a thorough assessment of the contaminated site. Identify the types and concentrations of organic contaminants present in the soil, as well as the characteristics of the surrounding environment.

6.1.2 **Plant Selection:** Choose plant species that are well-suited for the specific contaminants present. Some plants, known as hyperaccumulators, have the ability to accumulate higher concentrations of certain contaminants. Consider factors such as the plant's root architecture, adaptability to local conditions, and ability to produce exudates that stimulate microbial activity.

6.1.3 **Soil Preparation:** Prepare the soil to create optimal conditions for plant growth. This may involve addressing soil compaction, adjusting pH levels, and providing necessary nutrients. Soil amendments can be used to enhance the availability of nutrients and improve microbial activity.

6.1.4 **Planting:** Plant selected species in the contaminated area. Ensure proper spacing and coverage to maximize the rhizosphere's impact. Planting can be done directly in the soil or in raised beds, depending on the site conditions.

6.1.5 **Root Exudation Stimulation:** Foster the release of root exudates by promoting plant health. Adequate irrigation, nutrient supply, and overall plant care contribute to increased exudation. Healthy plants release a variety of compounds, such as sugars, amino acids, and organic acids, which serve as a carbon source for rhizospheric microorganisms.

6.1.6 **Microbial Inoculation:** Inoculate the soil with microbial strains that are known to be effective in degrading the target contaminants. This can be done through the introduction of microbial consortia or specific strains that possess the enzymatic capabilities to break down the contaminants.

6.1.7 **Monitoring:** Implement a monitoring program to assess the progress of rhizodegradation. Regularly sample soil and plant tissues to analyze contaminant levels. Monitoring may also include assessing the microbial community structure and activity in the rhizosphere.

6.1.8 **Nutrient Management:** Manage nutrient levels in the soil to support both plant and microbial growth. This may involve adjusting fertilizer application based on plant needs and microbial requirements for optimal rhizodegradation.

6.1.9 **Adaptive Management:** Regularly evaluate the effectiveness of the rhizodegradation process and plan as needed. This may involve modifying plant species, adjusting nutrient levels, or introducing additional microbial strains to enhance degradation.

6.1.10 **Harvest and Disposal:** Depending on the specific goals of the remediation project, harvest the plants once they have contributed to the degradation of contaminants. Proper disposal of the harvested plants is essential to prevent recontamination.

Rhizodegradation has been studied and applied in the remediation of polluted environments. Plants with a high rhizodegradation potential are chosen for phytoremediation projects to enhance the breakdown of contaminants in the soil[30]. This environmentally friendly approach offers an alternative to traditional remediation methods and can be particularly useful in cases where other methods may be impractical or cost-prohibitive. The success of rhizodegradation depends on various factors, including the plant species, the type of contaminants present, and the microbial community in the rhizosphere. Researchers continue to explore and optimize the use of rhizodegradation in environmental remediation strategies[31].

7. Phytofiltration

Phytofiltration specifically refers to the use of plants to remove pollutants from water. In phytofiltration, plants are selected for their ability to absorb, accumulate, and transform pollutants from water[32]. The roots of these plants play a crucial role in this process, as they take up water and associated contaminants. The contaminants can then be either stored in the plant tissues or transformed into less harmful substances through various biochemical processes. Common contaminants that can be targeted through phytofiltration include heavy metals, organic pollutants, nutrients, and certain pathogens[33]. Some plants are naturally adept at accumulating specific pollutants, while others may require genetic modification or engineering to enhance their capabilities. Phytofiltration is often considered an environmentally friendly and cost-effective method for water purification. It can be used in various settings, including wastewater treatment, stormwater management, and the remediation of contaminated water bodies[34].

7.1 How it Works???

7.1.1 Site Assessment: Conduct a thorough assessment of the water source to identify the types and concentrations of contaminants present. Consider factors such as the water flow rate, pH, temperature, and the specific pollutants to determine the suitability of phytofiltration.

7.1.2 Plant Selection: Choose aquatic plant species that are well-suited for the identified contaminants. Some plants have a natural affinity for certain pollutants and can accumulate them in their tissues. Consider factors such as plant growth rate, adaptability to water conditions, and ability to thrive in the specific environment.

7.1.3 System Design: Design the phytofiltration system based on the characteristics of the water source and the selected plant species. This may involve the creation of floating or submerged beds, channels, or ponds where the plants can be cultivated.

7.1.4 Planting: Plant the selected aquatic species in the designated phytofiltration system. Ensure proper spacing and coverage to maximize the surface area available for the plants to interact with the water and absorb contaminants.

7.1.5 Water Circulation: Implement a system for water circulation within the phytofiltration setup. Adequate water flow helps in bringing contaminants in contact with the plant roots and facilitates the absorption process. Circulation can be achieved through pumps or natural water movement.

7.1.6 **Contaminant Uptake:** The aquatic plants absorb contaminants through their roots and, to some extent, their above-ground parts. Contaminants may include heavy metals, nutrients, and organic pollutants. The plants serve as natural filters, removing these substances from the water.

7.1.7 **Accumulation in Plant Tissues:** Contaminants are accumulated in the tissues of the plants. Some plants have the ability to hyperaccumulate certain metals, meaning they accumulate concentrations much higher than those found in the surrounding water.

7.1.8 **Harvesting:** Depending on the specific goals of the phytofiltration project, the plants can be harvested once they have accumulated a significant amount of contaminants. Harvesting prevents the potential re-release of the contaminants back into the water.

7.1.9 **Disposal or Resource Recovery:** Dispose of the harvested plants properly to prevent recontamination of the water. In some cases, the harvested plants may be subjected to further processing for resource recovery, especially if they contain valuable metals.

7.1.10 **Monitoring and Adjustment:** Implement a monitoring program to assess water quality and contaminant levels throughout the phytofiltration process. Adjust the system parameters or plant species as needed based on the monitoring results to optimize performance.

One example of a plant used in phytofiltration is the water hyacinth (Eichhornia crassipes), which is known for its ability to absorb and accumulate nutrients and heavy metals from water[35]. However, it's essential to carefully select the appropriate plants for the specific contaminants present in a given water source and to consider potential ecological impacts[36].

CONCLUSION

As a sustainable and eco-friendly environmental cleanup method, phytoremediation has great potential. As worldwide soil and water pollution issues develop, phytoremediation technology may be used more. Plant biotechnology and genetic engineering may create hyperaccumulator plants that absorb and accumulate certain pollutants. Researchers are also developing "phytonanoremediation" methods that use nanoparticles to improve plant-microbe interactions and pollutant removal. Using phytoremediation in conjunction with microbial-assisted methods or electrokinetics may provide comprehensive solutions for difficult pollution scenarios. As we learn more about plant-soil-microbe interactions, phytoremediation techniques for different pollutants and environments may be developed. A significant role in future environmental management methods, phytoremediation can restore and sustain ecosystems damaged by anthropogenic activity due to its adaptability, cost-effectiveness, and low environmental impact.

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Phytoextraction:

Plants absorb contaminants from the soil into their roots and accumulate them in their above-ground biomass. Once the plants have taken up the contaminants, they can be harvested and disposed of properly.

Phytodegradation

Some plants have the ability to break down or transform contaminants into less toxic substances through metabolic processes. This is particularly effective for organic pollutants.

Rhizofiltration

This involves using plant roots to filter and absorb contaminants from water. Plants with extensive root systems, such as certain species of aquatic plants, are often used in this proces

Phytostabilization

- In this approach, plants are used to immobilize contaminants in the soil, preventing their movement or uptake by other organisms. This is often employed for metals and metalloids.

Phytovolatilization

Some plants can absorb contaminants from the soil and release them into the air as volatile compounds. This is particularly relevant for certain volatile organic compounds

Rhizodegradation

- Microorganisms in the root zone (rhizosphere) of plants can enhance the degradation of contaminants in the soil. The plants release root exudates that stimulate microbial activity.

Phytofiltration

- Phytofiltration is a plant-based water treatment method that uses aquatic plants to absorb, accumulate, and filter contaminants from water.

Figure 1: Mechanism of Phytoremediation