

PHYTOREMEDIATION: PRINCIPLE, TYPES AND APPLICATIONS

Abstract

An innovative strategy in environmental science known as phytoremediation uses plants' special skills to handle many types of pollution in soil, water, and the air. This chapter presents an in-depth exploration of the principles and applications of phytoremediation. By elucidating the mechanisms through which plants uptake, immobilize, degrade, and volatilize contaminants, this chapter sheds light on the intricate processes that drive this innovative technique. The advantages of phytoremediation, and disadvantages of phytoremediation also explained in this chapter.

Keywords: Phytoremediation, Principles, Types, Applications.

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I. INTRODUCTION

Technologies that use plants to purify chemically damaged land, air, and water are referred to as phytoremediation. Phytoremediation has demonstrated to be a superb solution for all types of environmental issues in addition to being a cost-effective technology for environmental cleanup (1).

A plant-based technique known as phytoremediation makes use of the capacity of plants to concentrate chemicals and environmental pollutants and to metabolize a wide range of compounds in their tissues. With the help of plants, phytoremediation, a cutting-edge strategy in environmental science, it may be possible to reduce different types of pollution. By utilizing plants' inherent capacities to absorb, accumulate, and even degrade pollutants, this ground-breaking method aids in the restoration and repair of contaminated habitats. This chapter explores the methods, uses, and potential difficulties of phytoremediation, shedding light on its value as a long-lasting and reasonably priced response to environmental contamination. It describes a plant's inherent capacity to bioaccumulate, degrade, or render harmful contaminants in the soil, water, or air. The main targets of phytoremediation are organic pollutants and heavy metal poisons (2).

Usually, stationary contaminated soil or water situations are treated via phytoremediation. Examples include cleaning up abandoned metal mine workings and locations where PCBs were dumped during production, as well as mitigating a current coal mine by reducing the impact of poisons in the land, water, or air (3).

II. PRINCIPLE OF PHYTOREMEDIATION

Intrinsic capacities of plants to absorb, collect, and transfer contaminants from their surrounding environment are the foundation of the phytoremediation. Phytoremediation is a sustainable technique that uses plants to remove, detoxify, or immobilize contaminants from soil, water, air. It operates through various mechanisms like absorption, adsorption, volatilization, and rhizodegradation. In this process plants absorb pollutants and either store them in their tissues to break them down into less harmful forms. It is a bioremediation process (4).

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Contaminants like metals, herbicides, solvents, explosives, and crude oil and its byproducts have been decreased in phytoremediation projects around the world (4). Numerous plants, such as mustard plants, alpine pennycress, hemp, and pigweed, have shown successful at hyperaccumulating chemicals at toxic waste sites. Not all plants can accumulate heavy metals or organic pollutants due to physiological differences. Varieties have different abilities to acquire pollutants, even within the same species (6).

III. WHAT IS BIOREMEDIATION

Bioremediation is the process that uses living organisms, such as bacteria, fungi, plants or microorganisms to naturally degrade, transform or remove contaminants from polluted environment like soil, water, and air. These organisms utilize biological processes to naturally degrade or change contaminants into less hazardous compounds. Many different sorts of pollutants, such as heavy metals, organic compounds, and toxins in the soil, water, and air, can be cleaned up via bioremediation. Environmental cleanup projects frequently use this economical and environmentally friendly strategy (7).

Bioremediation Methods:

- **In-Situ Bioremediation:** With in situ bioremediation, the contaminated site is treated directly rather than the contaminated materials being removed. It can be achieved using a variety of methods, including bioventing (which increases the amount of oxygen available), biosparging (which adds air or oxygen), and enhanced natural attenuation (which promotes natural processes).
- **Ex Situ Bioremediation:** In this technique, the contaminated material is removed and treated elsewhere. Common techniques include bioreactors (which treat contaminated water in controlled situations) and biopsies (which treat contaminated soil by piling it up).

IV. CLASSIFICATION OF PHYTOREMEDIATION ON THE BASIS OF MECHANISMS

Following are some of the various phytoremediation techniques utilized to remove or degrade pollutants from soil and water:

1. **Rhizosphere Biodegradation:** In the rhizosphere biodegradation process, the plant secretes natural chemicals from its roots that serve as nutrients for the development of soil microorganisms. The tiny organisms multiply quickly and promote the biological breakdown of soil pollutants. In other words, rhizosphere biodegradation refers to the process of pollutant degradation that occurs in soil surrounding plant roots, known as the rhizosphere. In this process, plants release various organic compounds, such as root exudates, into the soil. These exudates can stimulate the growth and activity of microorganisms, which include bacteria and fungi, which possess the ability to breakdown or transform pollutants (8).

In the rhizosphere, interactions between plants, microbes and pollutants provide a special environment that promotes the biodegradation of pollutants. The organic chemicals that plants emit are used as a carbon source by microorganisms to power their metabolic processes, which include the breakdown of contaminants. This procedure has the potential to reduce the toxicity and environmental impact of complex pollutants by turning them into less dangerous, simpler compounds (9).

Examples:

- **Petroleum Hydrocarbon Phytoremediation:** Willow (*Salix* spp.) and poplar (*Populus* spp.) species have been utilized to naturally clean up petroleum

hydrocarbon-contaminated soil. These plants exude substances from their roots that encourage the development of bacteria that break down hydrocarbons in the rhizosphere, breaking down the pollutants (10).

- **Cleaning up Polycyclic Aromatic Hydrocarbons (PAHs):** Certain grasses and legumes, such as tall fescue (*Festuca arundinaceus*) and alfalfa (*Medicago sativa*), have been shown to enhance the degradation of PAHs in soil. Their root exudates encourage the growth of microorganisms capable of breaking down these complex or organic pollutants (11).
 - **Removal of Chlorinated Compounds:** Sites contaminated with chlorinated solvents have been remedied using reed canary grass (*Phalaris arundinaceus*), willow and poplar trees, and other plants. These plants' root exudates have the potential to activate dechlorinating bacteria, which transform dangerous chlorinated chemicals into benign byproduct.
 - **Degradation of Pesticides:** Sunflowers (*Helianthus spp.*) and Indian mustard (*Brassicajunco*) have been employed to facilitate the degradation of soil-bound pesticides. These plants release root exudates that encourage the growth of pesticide-degrading microorganisms (12).
- 2. Rhizofiltration:** Rhizofiltration is a phytoremediation technology that includes filtering and removing pollutants from water, particularly pollutants like heavy metals and certain organic compounds, using the root systems of plants. Aquatic ecosystems are cleansed using this remediation technique using aquatic or terrestrial plants (13). During this technique, plants are cultivated either on the contaminated site (in situ) or in an ex-situ setting. When a plant's roots have absorbed enough pollutants, they become saturated, and the plant and all of its roots are then removed.

The roots of Rhizofiltration plants act as natural filters, trapping contaminants through processes like ion exchange, adsorption, and complexation. These mechanisms enable the plants to capture heavy metals, organic compounds, and other pollutants from the water. Metals (Cr, Cd, Co, Cu, Ag, Hg, Ni, Mn, Pb, Zn, Mo), metalloids (As, Se), and radioactive elements (¹³⁷Cs, ²³⁹Pu, ⁹⁰Sr, ²³⁴U) can all be removed via Rhizofiltration. Rye, sunflower, tobacco, spinach, Indian mustard, and rye are important plants used in this procedure. Terrestrial plants are typically employed in this strategy because of their rapid growth and fibrous roots (14). Additionally, it has been noted that adding microorganisms to the rhizosphere promotes the uptake of contaminants. The process works by planting these specialized plants in contaminated areas, such as mine tailings or industrial sites.

Advantages:

- **Environmentally Friendly:** Rhizofiltration is a natural and environmentally friendly method of water treatment that relies on the natural abilities of plants to remove contaminants.
- **Low Cost:** Compared to traditional water treatment methods, Rhizofiltration can be cost-effective, requiring minimal infrastructure and energy inputs.
- **Long-Term Solution:** Once established, Rhizofiltration systems can continue to function for an extended period, providing ongoing remediation without the need for continuous human intervention.

- **Removal of individual Pollutants:** By choosing plants based on the individual pollutants present, it is possible to remove certain pollutants in a targeted and efficient manner.

Disadvantages:

- **Slow Process:** Rhizofiltration can be a slow process, especially for contaminants with low mobility in the soil. It may take time for the plants to accumulate and remove a significant number of pollutants.
- **Maintenance Requirements:** Rhizofiltration systems require ongoing maintenance, including monitoring plant health, ensuring proper growth, and managing potential clogging of plant roots.
- **Limited Applicability:** Rhizofiltration is not effective for all types of contaminants. It works best for water-soluble pollutants that can be taken up by plants through their roots.
- **Site-Specific:** The effectiveness of Rhizofiltration depends on factors like soil type, plant species, and contaminant concentration. This makes it a more suitable option for certain sites and pollutants than others.

Examples:

- **Sunflower (*Helianthus annuus*):** Sunflowers are known to accumulate heavy metals like lead, arsenic, and uranium from contaminated water, making them effective for Rhizofiltration (15).
- **Water Hyacinth (*Eichhornia crassipes*):** This floating aquatic plant is excellent at absorbing nutrients like nitrogen and phosphorus, which can help control eutrophication in water bodies (16).
- **Papyrus (*Cyperus papyrus*):** By efficiently eliminating various contaminants through their root systems, papyrus plants have been utilized to filter wastewater in artificial wetlands.

3. **Phytostabilization\Phytosequestration:** Phyto stabilization is the process by which contaminants, especially metals, are absorbed and precipitated by plants, reducing their mobility and preventing their migration into groundwater (leaching), the air (wind transport), or the food chain. This approach is especially effective in dealing with heavy metals and metalloids. By promoting root growth, these plants bind contaminants in their root zones, forming stable complexes that are less likely to leach into groundwater or be taken up by other organisms (16).

They may involve a plant producing biochemicals that are released into the soil or groundwater nearby the roots and that can sequester, precipitate, or otherwise immobilise nearby contaminants. They may also involve roots absorbing pollutants, adsorbing pollutants to the surface of roots, or both (17).

Through the use of metal-tolerant plant species, heavy metals can be immobilised underground and made less bioavailable, reducing their migration into the environment and lowering the likelihood that they will enter the food chain (18). Heavy metal precipitation or a decrease in metal valence in the rhizosphere, absorption and sequestration within root tissues, or adsorption onto root cell walls can all result in Phyto stabilization. Plant growth contributes to the preservation of healthy soil in areas where

heavy metals are present. The created plant cover also restricts the wind-borne dispersion of soil particles containing heavy metals, stabilizing subsurface heavy metals and reducing their leaching into groundwater. While phytoextraction requires the removal of potentially dangerous substances, Phyto stabilization does.

Advantages:

- There is no need to dispose of dangerous biomass.
- Plants decrease soil erosion and the system's water availability.

Disadvantages:

- In some places, pollutants are still present.
- It is vital to monitor frequently.

Examples:

- ***Brassica junco*, or Indian Mustard, in Metal-Contaminated Soils:** Another hyper accumulator plant that has undergone substantial research on Phyto stabilization is Indian mustard. Heavy metals like lead, cadmium, and zinc build up on it. In locations with metal-contaminated soils, researchers have planted Indian mustard, and the plant's roots emit organic molecules that help bind the metals in the soil. The metals are immobilized as a result, which lowers their bioavailability (19).
- **Alpine Penny-cress, *Thlaspi Caerulescens*, Near Contaminated Mining Sites:** The hyper accumulator plant *Thlaspi caerulescens* is renowned for its capacity to store heavy metals including zinc, cadmium, and nickel in its tissues. This plant has been utilized by researchers to Phyto stabilize polluted mining sites. On these locations, the plant is cultivated, and as it develops, it absorbs the heavy metals from the soil, so lowering their mobility. This procedure aids in stopping the metals from eroding away or leaking into groundwater (20).

- 4. Phytoextraction\ Phytoaccumulation:** Phytoextraction is a process where certain plants are used to remove heavy metals and other pollutants from soil or water. These plants, known as hyperaccumulators, absorb the contaminants and store them in their tissues. This method is considered an eco-friendly way to remediate polluted areas, although it might not be suitable for all types of pollutants or soil conditions. To remove heavy metals and other pollutants from soil or water, a procedure known as phytoextraction is performed. The pollutants are absorbed by these plants, which are hyperaccumulators, and are then stored in their tissues. Although it might not be appropriate for all sorts of pollutants or soil conditions, this procedure is thought of as an environmentally beneficial solution to clean up polluted areas (21, 22, 23).

Working of Phytoextraction:

- **Choosing and Screening Plants:** Based on their capacity to withstand and accumulate particular pollutants, hyperaccumulator plants are chosen. These plants have evolved defense systems that enable them to flourish in settings with high concentrations of heavy metals or other contaminants. The contaminated region is subsequently seeded with seeds or young plants that are hyperaccumulators. The species and location circumstances affect planting methods.
- **Soil Preparation and Planting:** Before planting hyper accumulator plants, the contaminated site may need some preparatory work. This could involve improving

soil structure, pH adjustment, and adding nutrients to ensure optimal plant growth. Hyper accumulator seeds or young plants are then planted in the contaminated area. Planting techniques depend on the species and site conditions.

- **Root Uptake of Contaminants:** As hyper accumulator plants grow, their roots extend into the soil, where they come into contact with the contaminants. Through a process called Rhizofiltration, the roots release compounds that can alter the chemical forms of contaminants in the soil, making them more easily absorbable by the plant.
- **Harvesting:** The hyper accumulator plants are cut down and removed from the contaminated area once they have matured and gathered a significant number of metals. This successfully cleans the soil of the contaminants.
- **Metal Recovery:** Following harvest, the plant material that is rich in metals is treated to remove the accumulated metals. This can be accomplished using techniques like chemical extraction or incineration. The metals that were removed may be securely recycled or disposed of.
- **Soil Improvement:** Following phytoextraction, the polluted soil may still contain trace amounts of metals, but these metals are now much less concentrated. It may be necessary to perform additional treatments to further improve the soil's quality.
- **Monitoring:** Consistent site monitoring is necessary to guarantee that metal levels stay low and that the remediation process is successful. If metal levels rise again, this might entail growing fresh rounds of hyper accumulator plants. It's crucial to remember that phytoextraction is a long process, and it can take several years to noticeably lower levels of metal contamination. The choice of plant, the state of the soil, the climate, and the particular pollutants involved all have an impact on how well phytoextraction works.
- **Hyperaccumulation:** When grown in metal-contaminated soils, hyperaccumulators concentrate trace and heavy metals in their shoots, which can be eliminated by harvesting the fields of these trace metal-loaded plants. The creation of phytoextraction is the result of studies examining the usefulness of these hyperaccumulators for environmental cleanup. The large biomass of plant species and the bioavailability of metals for plant uptake are essential for phytoextraction to be successful. Soil-related elements like pH have an impact on the Phyto availability of metals (24).

Examples:

- **Indian Mustard (*Brassica junco*) for Cadmium:** Indian mustard is a well-known hyperaccumulator for cadmium. It's often used to remediate soils contaminated with cadmium, a toxic heavy metal commonly found in industrial and mining areas.
- **Sunflowers (*Helianthus annuus*) for Lead:** Sunflowers are used to remove lead from soil. Lead-contaminated sites, such as those near old paint factories or highways, can benefit from this phytoextraction method.
- **Poplar trees (*Populus spp.*) for Organic Pollutants:** Poplar trees are used to remediate sites contaminated with organic pollutants like hydrocarbons. These trees have an extensive root system that can absorb and break down these contaminants.
- **Water Hyacinth (*Eichhornia crassipes*) for water bodies:** Water hyacinth is employed to clean up polluted water bodies. It can absorb pollutants such as heavy metals and excess nutrients from the water, improving water quality.

5. Phytovolatilization: Pollutants that can be converted into volatile chemicals are subjected to phytovolatilization. These pollutants are absorbed by specialized plants, where they are then vaporized and released into the atmosphere. Both heavy metals like mercury and volatile organic compounds (VOCs) can be removed using this method. This method makes use of some plants' innate capacity to take in contaminants from the soil or water and transform them into gas-phase compounds that may be spread more freely (25).

Contaminants that are amenable to phytovolatilization include volatile organic compounds (VOCs) and certain heavy metals. VOCs are organic chemicals that have a tendency to vaporize at relatively low temperatures, and they are often found as pollutants in soil and water. Some plants have the capacity to take up these VOCs through their roots and transport them to their leaves or other aerial parts. Once in the leaves, the plants can metabolize or transform the VOCs into volatile gases, such as water vapor or carbon dioxide, which are then released into the air (26).

Similar to this, plants can absorb some heavy metals like selenium and mercury, which are then released into the atmosphere via a variety of biochemical processes. The presence of these metals in the soil or water is decreased as a result of the plants' assistance in converting them into forms that can be released into the atmosphere (27).

Phytovolatilization can be beneficial in situations where removing contaminants from the environment through other methods might be difficult or costly. However, it's important to consider factors such as the plant species' ability to tolerate the contaminants, the rate of volatilization, and potential secondary environmental impacts. Monitoring and proper management are essential to ensure that the released gases do not cause air pollution or pose risks to human health. Overall, Phytovolatilization is a novel method for phytoremediation that allows for the conversion of some pollutants into less dangerous forms and makes it easier to remove them from damaged areas.

Advantages:

- It is possible to change pollutants into a less dangerous state.
- The amount of diluted and less dangerous pollutants emitted into the atmosphere is enormous.

Disadvantages:

- Pollutants can build up in vegetation.
- Low levels of pollutants have reportedly been found in plant tissue.

Examples:

- **Volatile Organic Compounds (VOCs):** Toluene: Some plants like poplar trees (*Populus spp.*) have been shown to take up toluene through their roots and release it into the air as less harmful compounds (28).
- **Trichloroethylene (TCE):** Hybrid poplar and willow trees are often used to Phytovolatilize TCE, converting it into less harmful forms (28).
- **Mercury: Indian Mustard (*Brassica junco*):** This plant is known to accumulate mercury in its tissues and can volatilize some forms of mercury into the atmosphere. (29)

- **Sunflowers (*Helianthus spp.*):** Certain sunflower species have been found to take up mercury and convert it into a volatile form that can be released through the leaves.
- **Selenium: *Stanley pinnata (Prince's Plume)*:** This plant is native to North America and has the ability to accumulate selenium in its tissues and subsequently release volatile forms of selenium into the air.

V. PHYTOREMEDIATION ADVANTAGES

1. **Environmentally Friendly:** Phytoremediation is a natural, non-intrusive process that doesn't involve significant ecosystem disruption or digging. It makes use of plants' innate capacity to absorb and collect pollutants. (30)
2. **Cost Effective:** Phytoremediation is frequently more cost-effective than more established remediation techniques. It may be used on-site without the transportation of pollutants, eliminates the need for large machinery, and lowers labor expenses.
3. **Aesthetic and Habitat Benefits:** Beyond its primary remediation purpose, phytoremediation can enhance the aesthetic value of polluted sites. Planting a variety of vegetation not only helps in contaminant removal but also beautifies the area. Additionally, the vegetation can create habitats for various wildlife species, contributing to biodiversity and ecosystem restoration. (31)
4. **Long Term Solution:** Phytoremediation provides a long-term answer to the pollution problem. Plants can continue to remove toxins for extended periods of time, unlike other conventional approaches which may only offer short-term respite, providing a progressive and sustained cleanup process. This is especially useful for places with mild to moderate pollution levels where quick remediation might not be as important.
5. **Reduced Energy Consumption:** Phytoremediation is a low-energy process, relying on natural mechanisms within the plants and their associated microorganisms. This reduces the overall energy consumption and carbon footprint compared to more energy-intensive methods like thermal treatments or incineration.
6. **Public Acceptance:** Because phytoremediation is natural and non-invasive, it frequently enjoys greater support from the public and the local community. Instead of procedures that require considerable digging, the transportation of pollutants, or the use of harsh chemicals, communities are more likely to support solutions that employ plants to heal the environment.

VI. PHYTOREMEDIATION DISADVANTAGES

1. **Limited Applicability:** One of the significant disadvantages of phytoremediation is its limited applicability to certain contaminants and conditions. Not all pollutants can be effectively taken up and detoxified by plants. For instance, heavy metals and certain organic compounds might not be suitable for phytoremediation due to plants' limited capacity to accumulate or degrade them.

- 2. Time-Consuming:** Phytoremediation is often a laborious procedure, particularly at locations with high pollution levels. For plants to considerably lower pollution concentrations, several years may be required. For places that need to be cleaned up quickly or where there are immediate environmental concerns, this might not be appropriate.
- 3. Plant Species Selection:** Successful phytoremediation relies on selecting the appropriate plant species for a given site and contaminant. Not all plants can tolerate the specific pollutants present, and the wrong choice can lead to poor growth or even plant death. Extensive research is needed to identify and introduce suitable plant species.
- 4. Monitoring:** The efficacy of phytoremediation might be unpredictable and inconsistent. Its success may be influenced by elements like the kind of soil, the climate, the health of the plants, and the presence of required microbes. To make sure the process is going as planned, frequent observation and potential modifications are needed.
- 5. Incomplete Removal:** Phytoremediation might not completely eliminate contaminants from a site. While it can significantly reduce pollutant levels, achieving complete removal might be challenging, especially for highly persistent or complex pollutants. In such cases, additional treatment methods might be necessary to reach the desired cleanup standards.

In conclusion, phytoremediation offers a holistic and eco-friendly approach to environmental cleanup. Its advantages include its environmentally friendly nature, cost-effectiveness, aesthetic benefits, and long-term potential. However, its limitations, such as limited applicability, time-consuming process, and uncertainties, need to be carefully considered when deciding whether to employ phytoremediation as a remediation strategy. Successful implementation requires thorough research, site-specific planning, and ongoing monitoring to ensure optimal results (32).

VII. APPLICATIONS OF PHYTOREMEDIATION:

- 1. Heavy Metal Contamination:** Phytoremediation is used to remove heavy metals like lead, cadmium, and arsenic from soil and water. Plants such as sunflowers and willows can accumulate these metals in their tissues, helping to reduce contamination levels.
- 2. Oil Spill Cleanup:** Plants like saltmarsh grasses and mangroves are employed in phytoremediation to clean up oil spills in coastal areas. These plants can absorb and break down hydrocarbons from the spilled oil.
- 3. Brownfield Reconstruction:** Using specialized plants that can absorb and digest contaminants, phytoremediation is utilized to rehabilitate polluted industrial sites (brownfields), enabling safe reconstruction.
- 4. Treatment of Landfill Leachate:** Cattail and reed-planted constructed wetlands are used to treat landfill leachate, or liquid runoff. The plants aid in removing impurities and enhancing water quality.

5. **Nutrient Pollution Control:** Water hyacinths are used in phytoremediation, a process that removes excess nutrients from water bodies to avoid problems like algae blooms and oxygen depletion.
6. **Cleaning Up Radioactive Soil:** Some plants, like mustard plants, are employed in the removal of radioactive materials from the soil surrounding nuclear installations, such as uranium and cesium.
7. **Mining Site Restoration:** Phytoremediation is used to rehabilitate areas affected by mining activities. Plants can stabilize soil, absorb heavy metals, and improve overall ecosystem health.
8. **Wastewater Treatment:** Constructed wetlands planted with various vegetation are used to treat wastewater from industries or municipalities. Plants help filter out pollutants and improve water quality before discharge.
9. **Air Quality Improvement:** Using plants and trees to absorb air pollutants including carbon dioxide, Sulphur dioxide, and volatile organic compounds helps to improve air quality in metropolitan areas.
10. **Improvement of Soils Affected by Salt:** To remediate soils with excessive salinity, plants like salt-tolerant grasses and shrubs are used, which helps to enhance soil structure and quality. These applications demonstrate how adaptable and effective phytoremediation is in tackling a variety of environmental pollution problems. This method offers an economical and sustainable answer to environmental cleansing and restoration by utilizing plants' inherent powers (32).

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