

PHYTOREMEDIATION: A GREEN APPROACH FOR THE SUSTAINABLE ENVIRONMENTAL POLLUTION CONTROL.

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Abstract

Life without plants is unimaginable on the earth. Starting from sustaining life on the earth to mitigation of various environmental problems, plants are inevitable and irreplaceable. Phytoremediation is a technique for remediation of air, water and soil where plants via various mechanisms can render the harmful pollutants less harmful or completely degrade the pollutants. In recent times phytoremediation has come out as a cost effective, environment friendly and sustainable approach technique of bioremediation. The article gives a comprehensive overview of various primary mechanisms of phytoremediation like Rhizofiltration, Phytovolatilization, Phytostabilization, phytoaccumulation and Phytodegradation for remediation of air, water and soil contaminated with heavy metals, organic pollutants, air pollutants and other contaminants. It further discusses the pros and cons of this mechanism and how modern emerging techniques of nanotechnology, microbial assistance, genetic engineering and biomass valorization are transforming the phytoremediation efficacy. By integration of various technology and environmental policies, phytoremediation can offer powerful and robust pathway to remediate ecosystem for a sustainable future.

Keywords: *Phytoremediation; Phytoextraction; Phytostabilization; Heavy Metals; Sustainable Development; Biotechnology; Genetic Engineering; Microbial Assistance; Environmental Pollution Control; Biomass Valorization.*

1. Introduction

1.1 Definitions and Scope

Phytoremediation is a type of bioremediation mechanism where the plants are used to remediate air, water and soil to remove, relocate, transform or degrade various toxic substances in an ecofriendly and economical manner (Abdel-Shafy et al., 2018; Sharma et al., 2024). Various physiological function of plants like absorption, uptake, accumulation, transpiration and rhizosphere- mediated metabolism are responsible for phytoremediation process (Abdel-Shafy et al., 2018). There are several distinct processes which are collectively known as phytotechnology where natural ability of the plant is used for remediating organic and inorganic pollutants (Meena et al., 2023; Chandra et al., 2017). The greatest advantage of this solar driven in situ technique (Nedjimi, 2021) is that it doesn't cause harm to the environment like the traditional physicochemical methods (Kumar et al., 2022b).

1.2 Historical Context

The development of phytoremediation got importance due to increasing and persistent environmental pollution followed by industrial revolution (Sharma et al., 2024; Meena et al., 2023). Heavy metals and polycyclic aromatic hydrocarbons (PAHs) were introduced into the environment due to Intensified agricultural practices and large-scale industrial activities (Sharma et al., 2024; Malik et al., 2015). As a result, these expensive and environmentally disruptive traditional remediation techniques are being gradually replaced by low impact, environment friendly and sustainable practices (Meena et al., 2023; Saxena et al., 2020). Researchers of 20th century had identified the plants which can accumulate high concentrations of heavy metals in their system called "hyperaccumulators", these were the foundation of modern-day phytoremediation techniques (Nedjimi, 2021; Grzegórska et al., 2020). Research work has expanded from simple enzyme action to the molecular and cellular Level of understanding where plant accumulate substances through transport and tolerance mechanisms (Marmiroli et al., 2006).

1.3 Link to United Nations Sustainable Development

Phytoremediation conserves essential ecosystem services and is affordable and eco -friendly treatment options hence it is linked sustainable development (Malik et al., 2015; Chandra et al., 2017). It strongly aligns with the SDG 3(Good Health and Well-being), SDG 12(Responsible consumption, production, SDG 13 (Climate Action) and SDG 15(Life on Land) by using natural processes and reducing toxic inputs (Kumar et al., 2022b; Yang et al., 2022). It promotes transition towards a circular economy by enabling the green remediation of contaminated soils and wastewater especially in cost sensitive settings (Malik et al., 2015; Saxena et al., 2020). Public acceptance of this in situ method is further increased by the added advantages of carbon sequestration and biodiversity conservation (Kumar et al., 2022a; Lyu et al., 2024).

2. Mechanisms of Phytoremediation

Through several mechanisms, plants carryout the process of phytoremediation. Study suggests five major mechanisms of phytoremediation, each suitable for specific type of environmental issue and contaminant (Ahmad, 2024; Islam et al., 2024).

2.1 Phytoextraction

Phytoextraction is also known as phytoaccumulation and it involves the uptake of contaminants by the roots and their translocation in the harvestable tissue system of the plants, particularly in the shoots and the leaves (Abdel-Shafy et al., 2018; Nedjimi, 2021). The mechanism is particularly effective for heavy metal contaminated soil and water like cadmium (Cd), lead (Pb), zinc (Zn), nickel (Ni), and chromium (Cr) (Meena et al., 2023). Popularly known as hyperaccumulators, these plants are effectively used for the remediation of heavy metal contaminated soils. For instance, *Alyssum* species are used for nickel accumulation, while *Thlaspi caerulescens* can accumulate significant amounts of zinc and cadmium (Meena et al., 2023; Grzegórska et al., 2020). Decent amount of hyperaccumulation has been reported in plants like *Thlaspi caerulescens* shoots accumulated 749 mg/kg of Cd and 4044 mg/kg of Zn (Grzegórska et al., 2020), *Noccaea caerulescens* has been reported to sequester between 1700 and 2300 mg/kg of lead (Saxena et al., 2020) and *Salix caprea* and *Alyssum murale* has also been reported for their ability to sequester zinc, cadmium, and nickel into plant tissue (Pal et al., 2010). Plants are harvested and then removed and treated by incineration or composting to remove the metal from the site, thereby reducing the contaminant load from soil and water (Abdel-Shafy et al., 2018; Grzegórska et al., 2020)

Figure: 1 Various mechanism of phytoremediation by some key species:

Scientific Name	Common Name	Mechanism	Primary Contaminant	Reference(s)
<i>Brassica juncea</i>	Indian Mustard	Phytoextraction	Heavy Metals (Pb, Cd, Zn, Se)	Abdel-Shafy et al. (2018); Sarwar et al. (2017)

<i>Helianthus annuus</i>	Sunflower	Rhizofiltration and Phytoextraction	Radionuclides (U, Sr) and heavy metals Pb, Cr	Meena et al. (2023); Chandra et al. (2017)
<i>Pteris vittata</i>	Chinese Brake Fern	Phytoextraction (Hyperaccumulator)	Arsenic (As)	Saxena et al. (2020); Yang et al. (2022)
<i>Eichhornia crassipes</i>	Water Hyacinth	Phytostabilization, Phytofiltration	Wastewater pollutants and Heavy Metals (Cu, Hg)	Sharma et al. (2024); Abdel-Shafy et al. (2018)
<i>Populus</i> spp.	Poplar Trees	Phytodegradation, Phytovolatilization	Volatile Organic Compounds (VOCs) and Polycyclic Aromatic Hydrocarbons (PAHs), Trichloroethylene (TCE), Nitrates	Lyu et al. (2024); Marmiroli et al. (2006)
<i>Salix</i> spp.	Willow	Phytoextraction, Phytodegradation	Cd, Zn, Organic pollutants	Grzegórska et al. (2020); Kumar et al. (2022)
<i>Thlaspi caerulescens</i>	Alpine Pennycress	Phytoextraction	Zn, Cd, Ni	Malik et al. (2015); Nedjimi (2021)
<i>Phragmites australis</i>	Common Reed	Phytostabilization	Industrial Wastewater, Textile dyes	Chandra et al. (2017); Sharma et al. (2024)
<i>Chlorophytum comosum</i>	Spider Plant	Phytofiltration	Indoor air pollutants (Formaldehyde, CO)	Lyu et al. (2024)
<i>Azolla pinnata</i>	Water Velvet	Biosorption, Rhizofiltration	Cr, Pb, Wastewater nutrients	Pal et al. (2010).

2.2 Phytostabilization

To reduce the bioavailability, mobility and spread of soil contaminants, particularly heavy metals, specifically selected heavy metal tolerant plants are used to remediate the contaminated soil and water (Figure 1). These plants can effectively concentrate the heavy metals in their root zone (rhizosphere) thereby preventing the heavy metal from reaching the underground water-table (Abdel-Shafy et al., 2018; Meena et al., 2023). The mechanism does not eliminate the contaminants but reduces the bioavailability and mobility of heavy metals (Abdel-Shafy et al., Malik et al., 2015). Plants achieve this by absorption of pollutants by the roots, adsorption on the root surface or precipitation or complexation within the root zone rather than removing the contaminants from the site (Nedjimi, 2021).

Several reports show the efficacy of green plants (Figure 1) in phytostabilization, for instance, for phytostabilization of cadmium, *Atriplex halimus* has been utilized and *Vigna radiata* has been reported to show decent performance in phytostabilization of zinc and lead when combined with biochar (Nedjimi, 2021; Grzegórska et al., 2020). Other research work reports the effective role of *Rumex acetosa*, *Oryza sativa*, and *Triticum aestivum* in phytostabilization (Wang et al., 2022).

2.3 Phytovolatilization

Plants displaying phytovolatilization (Figure: 1) take-up water soluble contaminants and convert them into safer volatile substances which are then released into the atmosphere via transpiration (Abdel-Shafy et al., 2018). Contaminants like mercury (Hg) and selenium (Se), as well as volatile organic compounds like trichloroethylene (TCE) and methyl tert-butyl ether (MTBE) are effectively removed by this mechanism. *Brassica juncea* has shown remarkable performance in removal of 95% Hg (Nedjimi, 2021) and has also precipitate selenium (Pal et al., 2010). *Salix Babylonica* has been reported for removal of 94.77mg of MTBE (Grzegórska et al., 2020). While the technique can effectively reduce the level of soil contaminants, the issue of atmospheric risks must be carefully assessed (Abdel-Shafy et al., 2018; Saxena et al., 2020).

2.4 Phytodegradation

Phytodegradation, or phytotransformation, is a bioremediation technique where plants and associated microbes can metabolise and enzymatically breakdown (Abdel-Shafy et al., 2018; Nedjimi, 2021) contaminants like hydrocarbons, pesticides, petroleum and pharmaceuticals into less toxic/ nontoxic substances (Grzegórska et al., 2020; Pal et al., 2010). Research works has shown that plants like ryegrass and alfalfa, when inoculated with *Rhodococcus erythropolis* bacteria, the activity of petroleum degrading rhizospheric bacteria significantly increases (Zhu et al., 2025). Plant species like ryegrass and alfalfa, when inoculated with bacteria such as *Rhodococcus erythropolis*, significantly enhance the activity of petroleum-degrading microbes in the rhizosphere (Zhu et al., 2025).

Plants like *Vetiveria zizanioides* have been reported to degrade 97% of TNT in contaminated soil (Nedjimi, 2021) and *Phragmites australis* is quite efficient in degrading the pharmaceuticals like ibuprofen (Grzegórska et al., 2020).

2.5 Rhizofiltration

Along with the land plants, the root system of aquatic plants is equally efficient in absorbing, concentration and precipitating the contaminants like heavy metals and radioactive elements from the contaminated waterbodies (Abdel-Shafy et al., 2018; Meena et al., 2023). The contaminants get concentrated in the root system in the form of harvestable biomass which are later disposed or treated (Abdel-Shafy et al., 2018; Chandra et al., 2017). Aquatic plants like *Azolla pinnata* have been reported to concentrate heavy metal pollutants like Cd in their roots at levels reaching up to 740 mg/kg (Saxena et al., 2020). *Helianthus annuus* has been reported to remove approximately 80% of Uranium from contaminated waterbodies (Grzegórska et al., 2020; Saxena et al., 2020). Similarly, research report shows that Methyl parathion has been effectively removed from water by *Typha latifolia* (Abdel-Shafy et al., 2018; Chandra et al., 2017).

3. Target Pollutants and Applications

Due to non-degradable nature of heavy metals, phytoremediation targets heavy metals (Figure: 2) (Sarwar et al., 2017). Plants, which are the hyperaccumulators and high biomass species are the choice for this technology for extracting or stabilising, heavy metals, such as lead, zinc, nickel, cadmium and arsenic. Research results have shown that that in microbial assistant technique, the efficiency of phytoremediation increases by many folds (Wang et al., 2022). For instance, effective removal of vanadium has been reported in a microbial-assisted systems using rhamnolipid-producing *Pseudomonas Y3-B1A* and Mercury removal by *Pseudomonas B50A* (Wang et al., 2022).

Apart from heavy metals, organic contaminants (Figure: 2) are also one of the major problems in land and water and phytoremediation is highly effective against a variety of organic pollutants, including pesticides, polycyclic aromatic hydrocarbons (PAHs), and petroleum hydrocarbons (Kumar et al., 2022a). The cumulative effect of plant enzymes and soil microbes enhances the degradation of organic pollutants like PAHs and chlorinated solvents compounds (Marmioli et al., 2006).

Phytoremediation of emerging pollutants (Figure: 2) such as pharmaceuticals, radionuclides, and indoor air contaminants has been explored by many researchers with promising findings, (Saxena et al., 2020; Lyu et al., 2024). *Phragmites australis* have demonstrated potential in breaking down ibuprofen, However, there are insufficient data for other classes, such as microplastics (Grzegórska et al., 2020; Saxena et al., 2020) Recent application in indoor air phytoremediation is very promising which aims to eliminate volatile organic compounds (VOCs) in order to lower energy consumption and enhance urban sustainability in contrast to mechanical filtering (Lyu et al., 2024).

Figure2: Different types of contaminants and their corresponding Pytoremediation techniques.

Type of Contaminant	Example	Plants and microbes	Mechanism	Reference(s)
Heavy Metals	Nickel, Vanadium, Mercury, Lead, Cadmium, Arsenic, Zinc.	<i>Sesbania exaltata</i> , <i>Solanum nigrum</i> , <i>Zea mays</i> , <i>Pseudomonas Y3-B1A</i>	Phytoextraction, stabilization and biomethylation (approx.86% mercury removal).	Nedjimi, 2021, Sarwar et al., 2017, Wang et al., 2022)
Organic Contaminants	Dyes, Herbicides, Pesticides, PAHs, Petroleum, Explosives (TNT).	Rhizosphere microbes and plant-derived enzymes	Enzymatic degradation and microbial action in the rhizosphere.	(Abdel-Shafy et al., 2018); (Kumar et al., 2022a); (Marmioli et al., 2006)
Emerging Pollutants	Microplastics, Pharmaceuticals, (Ibuprofen), Radionuclides.	<i>Phragmites australis</i>	Translocation and biodegradation, research on microplastics are limited.	(Grzegórska et al., 2020); (Saxena et al., 2020)
Indoor Air	Volatile Organic Compounds (VOCs)	Plant-substrate-microbe systems	Translocation and biodegradation. Itq is sustainable than mechanical filtration.	(Lyu et al., 2024)

4. Advantages and disadvantages.

4.1 Benefits

Phytoremediation offers several distinct advantages over traditional methods of remediation of contaminated soil, sediment and water.

- **Cost-Effectiveness:** Compared to excavation, thermal treatment, or intensive chemical stabilization, phytoremediation is a cost-effective technique (Sharma et al., 2024; Chandra et al., 2017).
- **Environmental Friendliness:** It is a solar driven process which minimises the chemical input and preserves the ecosystem balance, soil structure and fertility (Sharma et al., 2024; Wang et al., 2022)
- Phytoremediation is a sustainable, low-cost solution which reduces habitat loss and offers a socially acceptable alternative to traditional invasive cleanup techniques for rehabilitating contaminated soil, sediment and water. (Saxena et al., 2020)
- Further, the in-situ nature of the technique solves the problem of transporting the contaminants to the distant places and minimizes the soil disturbance (Sharma et al., 2024; Pal et al., 2010)

4.2 Limitations

While phytoremediation is a sustainable and eco-friendly technique, there are several functional and environmental drawbacks.

- **Slow process:** to achieve proper cleanup the process requires multiple growing seasons, sometimes several years (Saxena et al., 2020; Pal et al., 2010)
- **Restricted depth:** treatment is limited to the root zone and ineffective for deep seated and high concentration contaminations which could be toxic to the plants (Meena et al., 2023).
- **Climatic and Environmental Sensitivity:** Effectiveness of the process depends on various ecological and environmental factors like soil type, salinity, pH, moisture, salinity. These influence the rhizosphere microbiota, plant survival and the root architecture (Pal et al., 2010; Wang et al., 2022).
- **Contaminant bioavailability:** the efficiency of fighter remediation depends on the bioavailability of the contaminant, such as organic pollutants and metals are often mobilised in spangly soluble soil fractions, sometimes bound to organic matter or situated below the rooting zone. This leads to incomplete remediation due to restricted uptake under heterogeneous field conditions (Marmioli et al., 2006)
- **Secondary Waste Handling:** One of the greatest challenges in phytoremediation is the safe disposal of the hazardous harvestable plant biomass. To avoid secondary pollution and metal re-emission to the environment and food-chain, careful and efficient disposal management system is necessary (Sharma et al., 2024; Nedjimi, 2021).

6. Emerging Technologies

6.1 Nano- bioremediation

To reduce the hazards and modify the contaminant bioavailability, integration of nanotechnology using nanoparticles and nano-enabled amendments are adopted to support plant uptake (Nedjimi, 2021). However, ecotoxicological evaluations of the nanomaterials in the environment are yet to be evaluated properly to avoid new risks (Nedjimi, 2021)

6.2 Genetic Engineering

Genetic engineering aims to improve the metabolic capacity, plant tolerance and heavy metal uptake rates by many folds (Malik et al., 2015; Nedjimi, 2021). These transgenic plants can have better features due to specific genes which can offer better detoxification, translocation and resistance to high levels of toxicity (Grzegórska et al., 2020; Marmioli et al., 2006). Several research are also focussing on the role of phytohormones and omics techniques to design perfect model for detoxification (Nedjimi, 2021).

6.3 Microbial Assistance

There is an excellent array of plant growth-promoting bacteria (PGPB), arbuscular mycorrhizal fungi (AMF), or biodegrading consortia, which can effectively increase the efficiency of these hyperaccumulators (Nedjimi, 2021; Kumar et al., 2022a). Proper understanding of the plant microbial interaction in the rhizosphere at the molecular level is essential for enhancing metal accumulation and detoxification (Grzegórska et al., 2020; Wang et al., 2022).

6.4 Biomass Valorization

One of the smartest ways to reduce the remediation cost and support circular economy principle is to convert contaminated biomass into energy efficient products like biogas, bioethanol, bio-ore or bio-oil (Grzegórska et al., 2020; Saxena et al., 2020). Biomass valorization can provide promising solutions for the hazardous waste generations during phytomining or bio-ore processing techniques (Saxena et al., 2020).

7. Prospects

Certain areas are to be addressed, like large field scale validation, as most of the studies and trials are conducted in controlled greenhouse settings, robust long-term field trials across diverse climate and complex contaminant mixture are needed (Saxena et al., 2020; Wang et al., 2022). Also, critical understanding of molecular and genetic aspects of plant accumulation, transport, and detoxication pathways using omics techniques are lacking (Nedjimi, 2021; Marmioli et al., 2006). Proper understanding of ecological roles of metal hyperaccumulators and the long-term dynamics of synthetic chelators is still at nascent stage (Saxena et al., 2020). Further, data on the effectiveness of phytoremediation for

management of pollutants like microplastics are insufficient (Saxena et al., 2020; Lyu et al., 2024) together with lack of standardised performance matrix and assessment of secondary risks such as volatilisation (Pal et al., 2010).

8. Conclusion

For providing a sustainable and cost-effective solution for environmental pollution, phytoremediation is one of the best green techniques which can be adopted to support the environmental and ecosystem balance. By effectively using the natural potential of the plants and microbes, it tries to mitigate wide range of toxic contaminants such as heavy metals and organic pollutants, while providing significant ecological benefits. Although, several challenges slow down the effectiveness of phytoremediation, emerging technologies like nanotechnologies, genetic engineering, microbial assistance and omics are promising tools for increasing its efficiency and applicability. Through continuous research, robust field trials and designing various biomass valorization strategies, widespread adoption of phytoremediation is possible towards a cleaner and sustainable environment.

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