Chapter 5

Phytoremediation

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Abstract

With the rapid growth of the global population, demands for food, water, and energy have led to significant environmental stress. Heavy metals, organic pollutants, waste (oil, solvents), military activities (explosives, chemical weapons), agricultural chemicals (pesticides, herbicides), and industrial waste (chemicals, petrochemicals) resulting from agricultural activities and industrialization cause serious environmental pollution. Phytoremediation is a technique that uses plants to remove, transform, evaporate, or fix these pollutants found in air, soil, water, sludge, and sediments. Phytoremediation is an effort to remediate contaminated areas using nature's own mechanisms. Pollutants can be taken up by plants, degraded within the plant or in the plant root zone, retained through conjugation, or vaporized.

Phytoremediation offers a green alternative to traditional physical and chemical cleaning methods with its low cost, direct use of solar energy, and ability to restore habitats. Thanks to these natural mechanisms, plants not only contribute aesthetically and ecologically to human life but also play an active role in combating pollution from industrial activities. This review provides general information about phytoremediation.

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1. Introduction

What is Phytoremediation?

With the rapid increase in the global population, demands for food, water, energy, and other ecosystem services have led to serious stresses on the environment (Kamran et al., 2021; Saleem et al. 2020; Zaheer et al., 2020). Agricultural activities (Mózner et al., 2012), industrialization (Cherniwchan, 2012; Wu et al., 2016), heavy metals (Anyakora et al., 2013; He et al., 2015; Su, 2014), radionuclides (Hu et al., 2010; Prakash et al., 2013), organic compounds (Afzal et al., 2014), chemicals used in agriculture, chemical fertilizers (Malik et al., 2017; Sunitha et al., 2012), and oil spills (Ron and Rosenberg, 2014) cause environmental pollution (Kafle et al., 2022). Heavy metals play a major role among these.

Metals such as copper, zinc, iron, manganese, molybdenum, nickel, and cobalt are defined as micronutrients that play an important role in the growth and development of plants and animals. Some heavy metals, such as arsenic, mercury, cadmium, and lead, are not essential for life development. Whether essential for plants or not, heavy metal levels above the threshold set by nature are a serious problem that leads to environmental pollution, reduces soil quality, and reduces crop yields.

Plants can directly absorb these pollutants through their roots, rendering them harmless, or stabilize the environment by reducing the mobility of toxic substances in soil and water. Phytoremediation is a sustainable strategy that uses plants to remove, transform, volatilize, or fix pollutants found in air, soil, water, sludge, and sediments (Munive Cerron et al., 2018; Santana Flores et al., 2020). Phytoremediation is an environmentally friendly pollution removal method that uses the natural abilities of plants to clean environmental pollutants (Basharat et al., 2018).

The use of phytoremediation is not limited to soil; it is also used in water purification. Phytoremediation is an economically and environmentally advantageous technique because it uses green plants to capture, trap, or detoxify contaminants in contaminated soil and water (Ashraf et al., 2019). These plants are capable of absorbing heavy metals, accumulating them at high levels in their tissues and neutralizing them after various processes. These plants are called hyperaccumulators. Hyperaccumulators are plants that can uptake one or more contaminant elements at very high rates and accumulate 50-500 times more metals in their leaves, branches, and trunks than in the soil. Many plants, such as *Thlaspi caerulescens*, *Arabidopsis thaliana*, *Brassica juncea*, *Lycopersicon esculentum*, *Zea mays*, *Hordeum vulgare, Oryza sativa,* *Pisum sativum, and Sedum alfredii*, are known to have phytoremediation potential for various heavy metals. *Thlapsi caerulescens*, known as the most common hyperaccumulator plant, accumulates over 26.000 ppm of zinc, while most plants found in nature have been found to accumulate around 100 ppm (Lasat, 2000). These characteristics make plants ideal for both phytoremediation and phytomassing activities (Basharat et al., 2018).

Phytoremediation, which has become widespread in many countries in recent years, is considered a passive technology for cleaning heavy metal-contaminated soils, offering advantages such as being relatively inexpensive, aesthetically pleasing, easy to implement, and quick to implement (Glass, 1999). Phytoremediation encompasses many different technologies, each serving different purposes. These can be categorized as phytoextraction, rhizofiltration, phytostabilization, phytovolatilization, phytodegradation, rhizodegradation, and phytodesalination (Pivetz, 2001).

2.Types of Phytoremediation

2.1. Phytoextraction

This technique is performed in areas with low or moderate metal pollution using natural hyperaccumulator plants (Baker et al., 1994; Padmavathiamma and Loretta, 2007). Plant growth cannot be sustained in more heavily polluted areas. It involves the uptake of contaminants by plant roots, their accumulation in above-ground organs, and the subsequent harvesting and destruction of the plants. This technique is used to remove actively absorbed nutrients such as copper and zinc, as well as non-nutrient heavy metals such as cadmium, nickel, and lead (Padmavathiamma and Loretta, 2007). Chelating agents can also be added to this technique to increase the solubility of metals with low solubility in the soil solution and promote their uptake (Evangelou et al., 2007).

2.2. Rhizofiltration

Rhizofiltration is the removal of toxic substances using plant roots and the uptake of pollutants by the roots of metal-tolerant aquatic plants or other underwater organs (Jadia and Fulekar, 2009). This method is often effective in purifying soil and water heavily contaminated with nutrients such as nitrogen and phosphorus (Mithembu, 2012). Hyperaccumulator plants selected for rhizofiltration undergo specific stages of adaptation before being planted in the original environment. First, the plants are kept in clean water instead of soil until their roots develop to the desired level. They are then transferred to an artificial, contaminated water source for adaptation.

Once acclimated, they are planted in the original contaminated area where rhizofiltration will be applied. Once the roots are saturated, harvesting begins and they are safely disposed of.

2.3. Phytostabilization

Phytostabilization is a method often used to prevent erosion in erosion-prone areas, prevent pollutant leaching into groundwater, and prevent direct contact with the soil (Bert et al., 2005). Hyperaccumulator plants used in phytostabilization are plants that can grow and thrive in soils contaminated with heavy metals and convert toxic metals into less toxic forms. These plants have extensive root systems that can alter the physical, chemical, and biological properties of the soil (Berti and Cunningham, 2000; Rizzi et al., 2004). For example, ryegrass can take up the herbicide trifluralin and convert it into a bound residue (Li et al., 2002).

2.4. Phytovolatilization

This method, known as phytovolatilization, is applied primarily to groundwater, soil, sludge, and sediment, and is taken up by plant roots, converting the majority of contaminant-containing water into less pollutant and volatile forms before being released into the air. This technique is effective when evaporated contaminants have less toxic effects when transferred from the soil to the atmosphere. The evaporation method is generally effective for organic contaminants (Limmer and Burken, 2016). Trifluralin compounds have been reported to be bound to residue and excreted by rye grass through transpiration from the leaves (Li et al., 2002).

2.5. Phytodegradation and Rhizodegradation

Phytodegradation is the metabolism of pollutants within plant tissues. Organic pollutants are degraded by the rhizospheric interaction between plant metabolic processes and soil microorganisms. Organic pollutants, such as pesticides, can be removed by various plant parts through degradation or transformation. Because plants lack active transporters, these organic pollutants are absorbed through passive uptake.

Chlorinated hydrocarbons can be dechlorinated and converted into non-toxic chemicals by plants such as *Tegetes patula, Ipomea balsamina,* and *Mirabilis jalapa*. Reductive dehalogenation of DDT has also been observed in the aquatic plant Elodea and the terrestrial plant Kudzu (Garrison et al., 2000). *I. balsamina* and *P. nil* have been found to absorb and degrade petroleum hydrocarbons (Liu et al., 2017). When pollutant degradation occurs in the rhizosphere, this process is called rhizodegradation. Rhizodegradation is the decomposition of organic pollutants by microorganisms in the root zone. While sugars, amino acids, organic acids, fatty acids, sterols, nucleotides, and enzymes released from the roots influence microbial activity in the root environment, contaminants are also present.

2.6. Phytodesalination

Some salt-tolerant plants can extract significant amounts of salt from the soil, allowing saline soil to be reclaimed (Arif et al., 2020). As a biological and clean approach, halophytic plants are used for desalination. Halophytic plants tolerate higher halogen levels in soil or groundwater. These plants take in $Na+$ and $Cl-$ and accumulate these salt ions in plant roots and shoots (Kafle et al., 2022).

Phytoremediation is another practice used to remove pollutants flowing into streams by planting strips of suitable plants along the banks. This prevents pollution from spreading into the environment and contaminating groundwater. Furthermore, erosion is controlled, reducing transport. Studies in Canada have shown that this technique reduces soil erosion by 90% and herbicide runoff by 42-70%. In addition, sediment in the water can be reduced by 71-91%, nitrogen by 67-96%, phosphorus by 27-97%, pesticides by 8-100% and fecal coliforms by 70-74% (Gabor et al., 2001; Hamutoğlu et al., 2012).

3. Advantages of Phytoremediation

- It is more economical than other remediation technologies. With its direct use of solar energy and its ability to restore habitats, it offers a green alternative to traditional physical and chemical cleaning methods.

- It does not require a new plant population to re-invade the site.

- It does not require an additional site for waste disposal.

- Compared to other methods, it creates an aesthetically pleasing appearance that is well-received by the public.

- Its in-situ remediation feature prevents the spread of contaminants without the need to relocate the contaminated area.

- It can simultaneously address multiple contaminants beyond a single type of contaminant, enabling site remediation (Basharat et al., 2018).

4. Disadvantages of Phytoremediation

- Phytoremediation is not effective under all conditions. First, contaminants must be present in the plant root zone; it may not be directly effective for deep underground contamination.

- Environmental factors such as climatic conditions, plant growth process, and soil structure also directly affect success. The success rate depends on the plants used in the area's adaptation to the site's edaphic and biotic factors, as well as the plant's resistance to the contaminant.

- In areas heavily exposed to contaminants, plants may have difficulty growing, which can slow down the remediation process. Therefore, phytoremediation is generally most effective in low- to moderately contaminated areas.

- Contaminants accumulated in leaves may re-enter the soil with leaf fall in the fall.

- Contaminants may accumulate in the tissues of plants used for firewood.

- Remediation time may be longer compared to other methods. Phytoremediation for the treatment of industrial wastewater also requires a large area (Abdullah et al., 2020). These problems are closely related to the rate of degradation of pollutants by plants during treatment. Biological treatment has a different reaction pattern compared to chemical treatment (Imron et al., 2020). Many researchers recommend using phytoremediation as a secondary or tertiary treatment technique to treat wastewater before discharge into water bodies (Yuliasni et al., 2023).

- If pollutants are not safely harvested and disposed of after being accumulated by plants, environmental risks may persist. Therefore, phytoremediation applications must be carefully planned and managed. The likelihood of pollutants leaching into the soil may increase (Basharat et al., 2018). As plants grow during treatment, plant biomass is produced, and this amount can be considered abundant. If phytoremediation is applied to treat toxic substances (usually heavy metals), the produced plant biomass must be processed according to standard toxic substance treatment procedures (Kwoczynski and Čmelík, 2021). If phytoremediation is applied to treat organic or nutrient-rich wastewater, various conversion options can be selected. Various biomass utilization studies have been successfully implemented to convert biomass into animal feed (Kadir et al., 2020), biochar (Das et al., 2021), adsorbent (Alshekhli et al., 2020), biofuel (Correa et al., 2019; Rezania et al., 2020), and even fertilizer (Diacono et al., 2019; Kurniawan et al., 2020). With these conversion options, wastewater treatment using phytoremediation can lead to a cleaner production strategy through the utilization of treatment byproducts.

5. Some Studies in Phytoremediation

In a study on phytoremediation, grass plants (*Lolium perenne* L.) were used in soils contaminated with nickel (Ni) and cadmium (Cd) heavy metals at different concentrations (1000, 4000, and 8000 ppm). The experiments were conducted in greenhouses using pots. Twenty-five kilograms of soil was prepared for each heavy metal. To obtain results closer to real-field conditions, no additives (such as chelate) were used in the soil; instead, completely natural field soil was used. Throughout the experiment, samples were taken at regular intervals when the grasses reached 10 cm in height, and heavy metal accumulation was measured over four periods. The results indicated that the grasses continuously absorbed heavy metals from the soil. However, in the cadmium experiments, a decrease in the amount of metal absorbed by the grasses was observed over time. While they initially took up more metals, this amount decreased in later periods (Arıkan and Bağdatlı, 2021).

Plant species such as *Brassica napus* L. (canola), *Chenopodium quinoa* Willd. (quinoa), and *Allium cepa* L. (onion) were used to remove lead contamination using chelate-assisted phytoremediation. During the research, chelating agents such as EDTA and humic acid, as well as microbial fertilizers, were added to the soil to improve plant performance. It was determined that the plants retained more lead, especially when supplements such as humic acid and EDTA were used. In the study, it was determined that onion and quinoa plants transported lead more effectively from the root to the shoot. Quinoa, in particular, performed quite well when nitro chelate was used, while canola did not always exhibit the expected hyperaccumulator properties (Kılıç and İpek, 2019).

Sunflower, corn, and canola plants were used in a study aimed at cadmium stabilization through sequential application of phytoremediation and pyrolysis. To reduce cadmium pollution, first phytoremediation with plants and then pyrolysis were applied. High removal rates ranging from 89.6% to 93.5% were achieved through phytoremediation. The harvested plants were then pyrolyzed in a special reactor at 500°C. It was determined that the accumulated cadmium from this process was stabilized in the solid products. This technique both cleaned the soil and controlled the metal risk in the plants (Özkan et al., 2015).

The phytoextraction capacity of the cocklebur (*Xanthium strumarium* L.) plant was evaluated in soils artificially contaminated with copper. The plant was effective in soil cleansing by accumulating copper (Eren, 2018). The potential of ornamental plants such as petunia, ice plant, mustard, cabbage, and honeysuckle to remove contaminants such as arsenic, chromium, and textile dyes was investigated. *Alyssum maritima*, in particular, demonstrated high chromium accumulation capacity (Özay and Mammadov, 2013).

The removal of pollutants from wastewater was investigated using duckweed (*Lemna minor*) and floating fern (*Salvinia natans*) in constructed wetlands. Both plants were evaluated as effective phytoremediation agents in aquatic environments (Kaya and Yıldız 2017).

In recent years, it has been discovered that genetic engineering techniques, particularly next-generation genome editing tools like CRISPR-Cas9, can increase the potential for phytoremediation. Researchers are working to make plants more efficient in polluted environments by modifying genes that control metal tolerance, pollutant uptake, and detoxification mechanisms. For example, by increasing the production of metal transporter proteins, metal chelators (such as metallothioneins and phytochelatins), or growth hormones (auxins and cytokinins), plants can be made more resilient to pollutants (Basharat et al., 2018).

Phytoremediation is not limited to plants; it has also begun to be supported by the genetic engineering of beneficial bacteria (PGPR - Plant Growth Promoting Rhizobacteria) that live in the root zone of plants. These bacteria can provide numerous benefits, such as accelerating plant growth, reducing toxic effects, and facilitating the mobilization of pollutants. CRISPR technology is also enhancing the phytoremediation capabilities of these bacteria, making environmental cleanup processes faster and more effective. As a result, it is anticipated that phytoremediation technologies will continue to evolve, and gene editing techniques like CRISPR will allow us to precisely optimize plant traits, resulting in greater pollutant tolerance and higher uptake capacity. This will enable cleaning of larger areas in shorter periods of time, while also providing economic benefits such as the recovery of precious metals. Innovative approaches such as combining phytoremediation with energy production also hold great promise for sustainable environmental management (Basharat et al., 2018).

6. Conclusion

Phytoremediation is one of the oldest techniques used to remove pollutants, particularly those found in water and soil, from the environment.

The basic principle of phytoremediation is to degrade, remove, transform, or immobilize toxic compounds found in soils, groundwater, and surface water by exploiting the interaction between plant roots and root microorganisms. Phytoremediation offers several advantages over traditional techniques, including its low cost and environmental friendliness. Disadvantages include climatic and geological limitations, the phytotoxicity of the pollutant, its potential for entry into the food chain, and its longer processing time compared to other technologies. Phytoremediation of wastewater or polluted water can remove organic and inorganic pollutants, but it can also release unknown contaminant derivatives into the environment. Therefore, compared to phytoremediation of polluted soils, further research is needed on the removal of pollutants from wetlands.

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