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Phytoremediation of Contaminated Soils: Mechanisms, Applications, Limitations, and Emerging Enhancement Strategies

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ABSTRACT
Phytoremediation of contaminants in soil is among the most suitable technologies for the treatment of pollutants and for the preservation of green spaces. The approach mainly focuses on selecting plants which can endure pollution, have huge biomass and are non-economic plants. The development of a phytoremediation process is a combination of phytotechnology with the stimulation and the enhancement of the microorganisms in the soil. The challenges are that the technology is for low pollution locations and it takes more time. The phytotechnology process is developed by merging stimulation and enhancement of the role of microorganisms in the root zone to assist the plant absorb and accumulate contaminants in the tissues.

INTRODUCTION

Soil pollution has become one of the escalating environmental problems in our times that has far-reaching impacts beyond the soil. It poses serious threats to the human health, affects the delicate balance of ecosystems and undermines the reliability and safety of food supply chain globally (Singh et al., 2020). In the last few decades, this has become an increasingly important topic with far reaching consequences for biodiversity, agricultural productivity and the wellbeing of people. In addition to the loss of soil biota, soil degradation affects critical ecological processes soil does such as filtering water, recycling key soil nutrients, and storing carbon long-term that play key roles in supporting the environmental stability, or resilience, needed to sustain human life (Ekka et al., 2023).

In this context, phytoremediation has become a desirable and sustainable technology that utilises the inherent ability of plants to treat various contaminated sites (Pilon-Smits 2005; Jiang et al. 2024). Polychlorinated Biphenyls (PCBs) are one example of persistent organic pollutants (POPs) with other hazardous chemicals such as hexachlorobenzene (HCB), dioxins, dichloro-diphenyltrichloroethane (DDT) and furans being highlighted in what is known as the 'dirty dozen'. In addition to other known hazardous compounds such as furans, DDT, dioxins and hexachlorobenzene (HCB), Polychlorinated Biphenyls (PCBs) are among the persistent organic pollutants (POPs) featured in the 'dirty dozen'. PCBs are man-made compounds of several species with an aromatic chemical structure that are not found in nature. The swiftness by which they colonise their surroundings, can be partly attributed to their unique physicochemical properties, allowing them to interact extensively with them and influence their neighbouring ecosystems by direct interaction with different environmental compartments such as sediments and soils, ground water and surface water, and even the wider food web (Jing et al., 2018; Mao et al., 2021).

Phytoremediation has gained significant scientific and public interest because of its environmentally friendly and sustainable approach along with low cost as compared to conventional remediation technologies. These methods make the most of the ability of plants to uptake, breakdown, bind, and trap a wide range of contaminants in the soil, water, and air (Kafle et al., 2022). Because of its low ecological impact, its beauty and ability to restore and rehabilitate damaged habitats (Rocha et al., 2022), it is even more appealing.

However, the process of phytoremediation depends on the growth rate of the plants used in the remediation process, so-site contaminant removal can often take several growing seasons. In addition to this temporal limitation, the technique often is limited by the availability of the contaminants, which are not easily taken up in plant tissues or are in the deep soil layers or in the sediments that are not within plant root zones (Gavrilescu, 2022). This reduced availability reduces pollutant removal efficiency and thus slows remediation time.

Added to these obstacles, the effectiveness of phytoremediation may be dependent on the location, as soil pH values, nutrient levels and weather conditions can vary from site to site, affecting how well the treatment works at any particular site (Wang and Delavar, 2023). Another major challenge is the potential phytotoxicity from the contaminants themselves: If concentrations of the target pollutants, such as organic pollutants, heavy metal pollutants, phosphate pollutants, or other pollutants, reach high levels, they may negatively affect plant life, or even kill it, reducing the effectiveness of the remediation action (Zhao et al., 2022; Rocha et al., 2022).

The contaminants in soil can mainly be divided into two categories (Ali et al., 2013; Pilon-Smits, 2005):

Inorganic pollutants - These are non-biodegradable heavy metals and metalloids (like cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), nickle (Ni), zinc (Zn) and mercury (Hg)). These substances remain in the environment for an ever-larger amount of time and are able to build up in the food chain to ever higher levels, called biomagnification (Krämer, 2010; Salt et al., 1998).

Organic pollutants - include the petroleum hydrocarbons, PAHs, pesticides, herbicides, and other halogenated compounds (Gerhardt et al., 2009; Suresh and Ravishankar, 2004).

In essence, phytoremediation uses biology on site to naturally draw on sunlight and nature to remove contaminants from the soil. The role of plants in stabilizing the soil's physical structure, modifying the chemical conditions under their roots, sequestering potentially toxic components, and transforming harmful organic compounds to non-toxic or less harmful forms (Pilon-Smits, 2005; Yan et al., 2020).

Fundamental Sub-Technologies and Mechanisms

The phytoremediation mechanisms are complex and interconnected physical, chemical and biological processes, and the activation of each of them is dependent on a number of factors such as the chemical characteristics of the target contaminant, plant species to be used to perform the job, and the environmental and growing conditions at the site (Ali et al., 2013; Salt et al., 1998).

Phytoextraction

The mechanism is based on the plants being able to extract inorganic pollutants (e.g. heavy metals) from the soil solution around the roots. This uptake takes place in two ways; apoplastic which is passive without expenditure of energy and symplastic which requires an active transport mechanism that expends energy (Yan et al., 2020). After being taken up by the root tissues, the contaminants are moved upwards in the xylem vessels into the aerial parts of the plant including stems and leaves (Krämer, 2010).

Hyperaccumulator plants are selected as the best for this technique as they are special plants that hyperaccumulate heavy metals by taking up 100 to 1,000 times more than these ordinary plants without any indications of toxicity. Significant examples of these kinds of plants are Noccaea caerulescens, which specializes in metal accumulation (zinc and cadmium), and Pteris vittata, which specializes in arsenic accumulation (Krämer, 2010; Salt et al., 1998).

Phytostabilization

Unlike phytoextraction where the intent is to extract pollutants from the soil, the main purpose of phytostabilization is to limit the movement of pollutants and to keep them "locked" in the soil (Ali et al., 2013). It is mediated by plants exuding different organic acids and root exudates that change the pH and redox potential in the rhizosphere of the roots which cause precipitation of heavy metal and/or adsorption and binding to the root surfaces (Mahar et al., 2016). This process results in a reduction in the potential for contaminants to wash into the groundwater with rainwater and limits the dissemination of these contaminants in the air by wind.

Rhizodegradation and Enzymatic Phytodegradation

Plants have an internal enzymatic network containing enzymes such as cytochrome P450, dehalogenases, peroxidase and laccases. These enzymes can degrade complex organic pollutants and transform it into simpler metabolic products and further metabolism into fully harmless products (Suresh & Ravishankar, 2004).

In addition to this internal enzymatic process, plant roots release different types of nutrient compounds from the rhizosphere, such as carbohydrates, amino acids and organic acids. The exudates, in turn, stimulates growth of beneficial microbial communities that consist of bacteria and arbuscular mycorrhizal fungi which have the ability to degrade the hard to break down and highly resistant hydrocarbon compounds (Gerhardt et al., 2009).

Phytovolatilization

This mechanism involves the uptake of heavy metal contaminants by plants and their subsequent transformation within the plant to less harmful gaseous chemical species and their subsequent volatilization from the plant via transpiration. It should be noted that, in particular, heavy metals such as mercury (Hg) and selenium (Se) are naturally occurring and are found in the environment primarily in the gaseous phase (Chandra et al., 2015).

Rhizofiltration

Rhizofiltration or the "hydraulic control" is a method that involves the use of the root system to uptake and sequester metallic contaminants from the water. It has been found to be very efficient method to extract a wide range of heavy metals including cadmium, chromium, copper, nickel, lead and vanadium, and also for the treatment of radioactive materials like uranium and cesium (Jabeen et al., 2009; Singh and Santal, 2015).

Molecular and Cellular Detoxification Mechanisms

Under stress conditions caused by toxic and harmful heavy metal concentrations, plant cells need to engage in a complex and coordinated system of tolerance and detoxification to survive and grow, otherwise they would undergo catastrophic metabolic disruption that the heavy metals can cause (Krämer, 2010; Sharma et al., 2023):

First: Metal-Binding Proteins

Two different types of short-chain polypeptides are produced by plants: phytochelatins (PCs) and metallothioneins (MTs). They have low molecular weight and high cysteine content (Amino acid with thiol (-SH) group, which has strong binding affinity to metal ion). These proteins are said to work by a process called chelation, which means they enclose and bind to toxic free metal ions and keep them from reacting indiscriminately with important cellular components. This will then prevent any direct interference by these reactive ions in the cytoplasm, thereby protecting the enzymes and cellular organelles from the damage they would inflict (Sharma et al., 2023).

Second: Transport and Sequestration in the vacuole.

After chelating metal ions into metal-ligand complexes, the metal ions in the complexes must be completely eliminated from the pathway of active metabolic reactions in the cell. This is done by energy dependent active transport systems, including ATP-binding cassette (ABC) transporters, and cation exchange systems. These systems carry the metal complexes across the tonoplast membrane that forms the central vacuole, where they are deposited and kept completely removed from sensitive biological processes. This way the vacuole provides a safe "toxic waste repository" inside the cell, which (Krämer, 2010; Yan et al., 2020) turn into.

Third: Oxidative Stress due to Reactive Oxygen Species (ROS): Countering it

Excessive production of Reactive Oxygen Species (ROS) is one of the serious side effects of heavy metal toxicity which leads to oxidation of membranes, proteins and DNA. Plants respond to this danger with a double defense system that involves:

A series of enzymes known as enzymatic antioxidants, which include Superoxide Dismutase (SOD), Catalase (CAT) and Ascorbate Peroxidase (APX), which together transform harmful free radicals into harmless ones.

Non-enzymatic antioxidants, like glutathione and proline, which synergistically collaborate with the enzymes discussed above to increase the ability of the cell to absorb excess free radicals and minimise the extent of oxidative harm brought on by metal-induced stress (Sharma et al., 2023).

Optimisation Techniques for Field Productivity and Contaminant Absorption

However, conventional phytoremediation has several shortcomings that reduce its effectiveness, such as low biomass production, low growth rates of plants, and low bioavailability of pollutants in the soil, making plants less efficient in absorbing and accumulating contaminants. However, these limitations are often overcome by combining agricultural and biotechnological methods, thus increasing the efficiency of the overall remediation.

Incorporating nanotechnology into phytoremediation

Nanotechnology is one of the most potential solutions in this regard with the primary benefit being increase in plant uptake efficiency of pollutants (Mahar et al., 2016; Sessitsch et al., 2013; Song et al., 2019). Nano-zerovalent iron and fullerene are examples of nanoparticles that can be applied to enhance the bioavailability of contaminants in the soil, thus allowing for their uptake via the root system (Rajput et al., 2022; Zeb, Liu, & Zhang, 2022). In addition, these nanoparticles can change the chemistry of the heavy metal by reducing its oxidation state, thus making it more accessible for hyperaccumulating plants to take up (Imperiale, 2022).

Microbe-Assisted Phytoremediation

The use of the Plant Growth-Promoting Rhizobacteria (PGPR) bacteria species (Pseudomonas and Bacillus) applied as soil or seed treatment, as well as the use of Arbuscular Mycorrhizal Fungi (AMF) have a significant effect on the efficiency of remediation. These microorganisms have several functions, such as:

1. To increase the surface area of plant roots, which increases the contact with contaminated soil.
2. Secreting plant growth promoting hormones like indole-3-acetic acid (IAA).
3. Siderophores production for the help of metal ion chelation.
4. Release of chemically bound metal ions from soil particles that can help get absorbed by the roots (Sharma et al., 2023).
5. The use of soil amendments and chelating agents.

Biochar and Compost: They can increase the cation exchange capacity (CEC), water retention capacity of the soil, and contribute to the phytostabilization of free hazardous metals (Mahar et al., 2016).

Chemical Chelating Agents: These are synthetic compounds including EDAT (ethylenediaminetetraacetic acid) and citric acid, that help to make metals more soluble in soil solution, thereby increasing uptake rates in phytoextraction systems. However, it is important to manage the doses to prevent leaching of these metals into groundwater (Ali et al., 2013; Mahar et al., 2016).

Genetic Engineering and Transgenic Approaches

Recombinant DNA technology allows the introduction of genes that encode metal transporters, including genes from the ZIP and HMA families, into fast-growing species of plants, such as Populus (poplar) and Salix (willow), that have a high biomass. The idea for this gene transfer is to integrate the outstanding abilities of microorganisms and metabolic pathways into plants with higher growth potential and biomass to increase the overall efficiency of the bioremediation process (Doty, 2008; Pilon-Smits, 2005).

Plant species

Nanoparticles are in close contact with plants and interact with them in a specific way; the physiologic and biochemical properties of the plant are critical to the nature and effectiveness of this interaction. The knowledge of the response of the hyperaccumulator plants to nanoparticles should not be restricted to the general accumulation ability but should take into account several interrelated factors together including:

1. The capacity of absorption of the target element by the plant from the surrounding medium (soil or nutrient solution).
2. The shape and extent of the root system (how developed and spread out the root is) as the root is the direct and central point of contact between the plant and the nanoparticles.
3. The ability to move the element from the root to above-ground parts of the plant, which is necessary for effective accumulation.

A well-developed and vast root system will enable more effective engagement with the soil; more bioavailable nanoparticles will be able to engage with the soil, and will, in turn, allow for the uptake of the targeted metals or contaminants.

It is worth noting, as an example of such a positive interaction, that crops of rice and wheat, when treated with iron oxide nanoparticles (Fe_3O_4) and zinc oxide nanoparticles (ZnO) demonstrated an increase in their resistance to stress and growth rates. This improvement is due to the high efficiency of uptake of nutrients in these two crops and the activation of antioxidant enzyme activity in plant tissues.

Therefore, for selecting an appropriate plant species for its phytoremediation or related studies, the primary consideration should be the extent to which such plants can induce antioxidant defence mechanisms in response to the stress induced by exposure to nanoparticles or contaminants (Jalil & Ansari, 2021).

Enhancing vegetative development and resilience to stress

Nanotechnology plays a crucial role in the improvement of plant growth and in increasing plant resilience to contaminated environments. Using nanoparticles, plants can be assisted with counteracting the negative effects of the pollutants, specifically oxidative stress and nutrient deficiencies. This involves, for instance, an increase in the activity of some of the primary antioxidant enzymes, including ascorbate peroxidase and superoxide dismutase which play a protective role in the plant, preventing oxidative damage caused by exposure to heavy metals and other toxic substances (Al-Khayri et al., 2023).

Moreover, nanoparticles can alleviate nutrient deficiencies and boost the overall health of plants by enhancing the function of key plant enzymes and encouraging beneficial microbial growth. Furthermore, nanoparticles have been shown to improve plant nutrient levels and enhance plant health by stimulating beneficial plant-associated microbes and increasing key plant enzymes (Yavaş, 2021; Khalid et al., 2022). This synergistic effect will make the plant more resilient to environmental stressors and continue its growth, thereby increasing its long-term phytoremediation efficiency (Yavaş, 2021).

Moreover, nanoparticles help plants to adapt to heavy metal toxicity in various ways, such as binding metals in the soil and immobilizing them, converting metals from toxic forms into less harmful ones, and enhancing soil properties that promote better root system development (Rizwan and Ali, 2023).

The main disadvantages and risks nanoparticles in soil remediation

Phytotoxicity

Oxidative Stress

In the normal plant cell, metallic nanoparticles (ZnO, Cu, Ag, etc.) at levels higher than safe or even at levels not precisely known lead to an increase in generation of ROS. These molecules are capable of reacting to various parts of cells, destroying cell wall and breaking or bending DNA. This disturbs the plant's normal vital functions and makes it less able to grow and reproduce.

Growth and Respiration Obstruction

Certain nanoparticles have the ability to infiltrate root tissues and become lodged within the tiny pores present in root cell walls. This physical obstruction directly impacts the ability of the roots to absorb water and essential nutrients from the soil, thus reducing seed germination rates and slowing the growth of roots. It also can disrupt the plant's entire metabolic respiration.

Ecotoxicity

Removal of the Good Bacteria

Many of the nanoparticles have antibacterial and anti-microbial properties and are effective – albeit inadvertently – in killing beneficial microorganisms that are already in the soil, including nitrogen-fixing bacteria and symbiotic mycorrhizal fungi. These microorganisms are extremely important in the maintenance of soil fertility and plant health. As such, their destruction can cause ecological imbalance of the agriculture system and causes long-term reduction in soil vitality (Ridoy. & Supto, 2026).

Phytoremediation of organic pollutants

Nanoparticles have been identified as highly efficient agents for the removal of heavy metal contaminants and have also been shown to be a key element in improving the remediation processes of organic contaminants by phytoremediation. This can be achieved by utilizing three different types of nanoparticles:

First: Chitosan Nanoparticles

Apart from the natural biodegradability in the environment without leaving harmful residues, chitosan nanoparticles also have unique properties for use in the environment, especially the high biocompatibility in biological systems. Research has shown the ability of these nanoparticles to improve both adsorption and degradation of organophosphate pesticides, especially chlorpyrifos and diazinon, which are common agricultural pesticides and are toxic.

The mode of action of these nanoparticles is associated with an increase in the Bioconcentration Factor (BCF) and the Translocation Factor (TF) in plant tissues. The higher the values of these two factors, the more efficient the plant is in its capacity to uptake higher amounts of organic pollutants from the environment (soil or water), and then move them from the root to the top of the plant where the pollutants are subjected to metabolic degradation processes and ultimately reduced or neutralized in toxicity or removed entirely (Singh & Saxena, 2022; Sarma et al., 2022).

Second: Magnetic Nanoparticles (Fe_3O_4)

Magnetic nanoparticles of iron oxide (Fe_3O_4) have drawn significant interest for novel remediation methods for complex organic contaminants, such as petroleum hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), because of their unique properties to degrade these contaminants, which are notoriously resistant to degradation and chemically stable in the environment.

The process is a twofold action of the nanoparticles: The magnetic and surface characteristics of the nanoparticles bind the pollutants onto the surface of the particles which aggregate and concentrate the pollutants at a certain location. Second, they enhance the efficiency of the biodegradation processes in the rhizosphere (root zone with high microbial activity) either because of the enzymes produced by the plants or by microorganisms in the rhizosphere in association with the root (Singh & Saxena, 2022).

Third: Carbon Nanotubes

With success, carbon nanotubes have been implemented to improve the degradation of a variety of highly toxic organic compounds, such as benzene, toluene and bisphenol A (BPA), a chemical compound of concern because of its action as an endocrine disruptor in an industrial application.

The special mechanism of these nanotubes is to enhance electron transport processes in the rhizosphere, which act as conductive channels or pathways to help enzymes break down organic pollutants and transform them into less hazardous and more readily degradable compounds (Sarma et al., 2022).

Comparative Evaluation: Advantages vs. Limitations

Advantages

1. Cost Effective: There are significant economic benefits associated with using phytoremediation over traditional physical and chemical soil remediation methods, and these savings can be as high as 60-80%. This makes it a very attractive and economical choice, particularly for a large or long-term remedial action where budget is a significant concern (Ali et al., 2013; Mahar et al., 2016).
2. Ecological Integrity: Phytoremediation does not change soil structure and maintains its natural composition, keeps the organic matter content, and reduces disturbance to the soil's overall ecological integrity, thereby preserving indigenous biological

processes and microbial communities, as opposed to conventional remediation method (Pilon-Smits, 2005).

3. In Situ Implementation: Less soil excavation and less transport to other treatment facilities are required since the treatment occurs at the contaminated site. This will reduce logistical costs, and greatly reduce the likelihood that workers will be exposed to hazardous contaminants from logistical, digging and transporting operations (Salt et al., 1998).
4. Aesthetic and Ancillary Benefits: The technique is a part of vegetation re-establishment on degraded and polluted landscapes, improving the visual and ecological value of the area. Besides, it promotes carbon sequestration and reduces the soil erosion, which enhances the environment stability in the treated area (Yan et al., 2020).

Limitations

Labour intensive: Soil clean up to the desired level can be accomplished over several consecutive cropping seasons, requiring a certain amount of time and human labor and management over time to achieve this compared to remediation options that give quicker results (Ali et al., 2013).

Phytoremediation is also limited in terms of the depth to which the plants will grow their root system to reach contamination that occurs beyond the plant root zone (Pilon-Smits, 2005).

However, when the soil is highly contaminated with the contaminant, its toxicity can completely prevent the seed germination and plant growth, which may reduce the applicability of this method for highly contaminated sites (Mahar et al., 2016).

Phytoextraction Waste: Plant biomass that contains high concentrations of contaminants needs to be disposed of. This type of hazardous biomass must be treated in a special way, either by targeted metal recovery methods, called phytomining (Krämer, 2010) or by safe disposal or incineration.

CONCLUSION

Characterising a method for soil restoration as universally effective oversimplifies the intricate dynamics inherent to each site. The practical implementation is hindered by restricted biomass generation, extended cleanup periods, and possible phytotoxic effects. To advance phytoremediation from experimental potential to effective field implementation, forthcoming studies should emphasise (1) validations at field scale in various climatic contexts, (2) prolonged ecological assessments to guarantee contaminant management, and (3) sustainable methods for biomass disposal and resource recovery, including phytomining or bioenergy generation. Moreover, assessing performance in multi-contaminant situations in conjunction with thorough techno-economic evaluations will be essential for determining its commercial feasibility and regulatory approval.

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