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Phytoremediation of Heavy Metals from Polluted Soils

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Abstract: -

Phytoremediation is an innovative and rapidly developing technology that utilizes higher plants to remediate polluted environments. Both fundamental and applied research have clearly shown that certain plant species have the genetic capacity to extract, degrade, metabolize, or immobilize a wide variety of contaminants. Despite its significant potential, phytoremediation has not yet matured into a fully commercialized technology. One of the main obstacles is the limited understanding of the basic physiological and molecular mechanisms underlying plant-based remediation. Moreover, the influence of agronomic practices on these mechanisms remains poorly characterized. Another challenge stems from the inherent biological complexity of this approach. The success of phytoremediation relies on dynamic interactions between soil, contaminants, microbes, and plants. These interactions are further influenced by environmental variables such as climate, soil characteristics, and site-specific hydrogeology, making it difficult to generalize results across different locations. Therefore, a deeper understanding of plant mechanisms and the influence of agronomic practices on plant soil contaminant interactions is necessary to optimize phytoremediation strategies and tailor them to specific sites.

Introduction:

The idea of using plants to remediate contaminated environments has historical roots. As early as 300 years ago, plants were suggested for wastewater treatment. In the late 19th century, *Thlaspi caerulescens* and *Viola calaminaria* were the first species reported to accumulate high levels of metals in their leaves. Byers (1935) later discovered that *Astragalus* species could accumulate up to 0.6% selenium in their dry biomass. A decade

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later, Minguzzi and Vergnano (1948) identified plants capable of accumulating up to 1% nickel in shoots, and Rascio (1977) reported *T. caerulescens* as tolerant to and capable of storing high levels of zinc. Although reports have suggested the existence of cobalt, copper, and manganese hyperaccumulators, the presence of plants that truly hyperaccumulate metals other than cadmium, nickel, selenium, and zinc remains controversial and requires further validation.

The concept of using plants for metal extraction from contaminated soils was revisited and refined, leading to the first field trial on zinc and cadmium phytoextraction in 1991. In recent years, substantial research has focused on understanding the biological basis of metal phytoextraction. Nevertheless, the mechanisms enabling plants to accumulate and tolerate metals are still not fully understood, and applied aspects such as the role of agronomic practices in enhancing metal removal remain underexplored. Advancing phytoextraction into a practical, commercial technology will require deeper insights into plant mechanisms and the development of effective management strategies. The natural occurrence of plant species capable of accumulating exceptionally high metal concentrations makes this field particularly promising for future research.

Merit and Demerits of phytoremediation

Soils contaminated with metals are particularly difficult to remediate. Conventional approaches typically involve excavation of the soil, followed by landfilling or soil washing and subsequent physical or chemical separation of contaminants. The overall cost of remediation varies greatly depending on the type of contaminant, soil characteristics, and site-specific conditions.

Traditional engineering-based soil cleanup methods can be prohibitively expensive, especially when dealing with sites polluted by heavy metals or a mixture of heavy metals and organic compounds. This high expense highlights the need for more affordable solutions. Phytoremediation has gained attention as a cost-effective alternative, with multiple studies showing that the cost of metal phytoextraction can be a fraction of conventional remediation techniques. Furthermore, because phytoremediation is performed in situ, it avoids large-scale soil disturbance and helps maintain the integrity of the landscape and ecosystem. However, despite these advantages, the approach still faces several limitations and practical constraints that restrict its broader application.

TOXIC METALS IN SOIL

Sources of contamination

Heavy metals are typically defined as elements that exhibit metallic characteristics such as ductility, electrical conductivity, cationic stability, and specific ligand-binding properties and possess an atomic number greater than 20. The most common heavy metal pollutants include cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), lead (Pb), and zinc (Zn). Although metals naturally occur in soils, contamination has been significantly amplified by human activities, including mining and smelting of metal ores, electroplating, emissions from vehicles, energy and fuel production, use of fertilizers and pesticides, and the disposal of municipal waste Typical soil concentration ranges and regulatory thresholds for major heavy metal contaminants. Excessive metal concentrations in soil can be toxic to plants, resulting in reduced growth and poor soil coverage. Such conditions may enhance metal mobilization into runoff, leading to deposition in adjacent water bodies. Additionally, bare soils are more prone to wind erosion, which can disperse contaminated particles over a wider area. Therefore, the immediate priority of remediation efforts in such cases is to restore vegetation cover to stabilize the soil, reduce erosion, and limit the further spread of contaminants.

Risk assessment

Remediation of contaminated soils is essential to mitigate risks posed by toxic metals to both human health and the environment. Numerous studies have linked soil cadmium (Cd) contamination to human diseases, while selenium (Se) toxicity in soil has been associated with health problems in humans as well as poisoning incidents in livestock and wildlife. Moreover, contamination with metals such as zinc (Zn), nickel (Ni), and copper (Cu) from mining and smelting activities has been shown to be toxic to sensitive plant species. Among toxic metals, lead (Pb) contamination represents one of the most significant threats to human health. Lead exposure may occur through several routes, including inhalation of contaminated air and ingestion of polluted food, water, soil, or dust. Chronic exposure to elevated Pb levels can result in severe health outcomes, such as seizures, cognitive impairment, and behavioral abnormalities. The risks posed by Pb contamination are further heightened by its low mobility in the environment, even under conditions of high rainfall, which allows it to persist and accumulate over time.

Effect of soil properties on metal bioavailability

The interaction between metals and the soil matrix plays a crucial role in the success of phytoremediation. Generally, metals become less active when they are adsorbed onto soil particles, which reduces their mobility and availability. Soils with a higher cation exchange capacity (CEC) tend to immobilize metals more effectively due to stronger sorption. However, in acidic soils, competition from hydrogen ions (H^+) promotes metal desorption from soil binding sites, increasing their presence in the soil solution.

Soil pH not only influences the bioavailability of metals but also impacts their uptake by plant roots, and this effect varies depending on the specific metal. For instance, in *Thlaspi caerulescens*, zinc (Zn) uptake shows minimal dependence on pH, whereas manganese (Mn) and cadmium (Cd) uptake are more strongly affected by soil acidity.

Phytoremediating plants

For successful growth and completion of their life cycle, plants must absorb not only macronutrients such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg), but also essential micronutrients including iron (Fe), zinc (Zn), manganese (Mn), nickel (Ni), copper (Cu), and molybdenum (Mo). To achieve this, plants have evolved specialized mechanisms for nutrient uptake, translocation, and storage. The transport of metals across cell membranes is facilitated by specific proteins that function as transporters. These systems carefully regulate the intracellular concentration of metal ions, keeping them within physiologically safe limits. In general, nutrient uptake is highly selective, with plants favoring certain ions over others. This selectivity is determined by the structural and biochemical properties of the membrane transporters, which can specifically recognize and transport certain ions. For instance, some transporters facilitate the uptake of divalent cations while excluding mono- or trivalent ions. Essential micronutrients such as Zn, Mn, Ni, and Cu are typically accumulated in amounts just sufficient to meet metabolic requirements (<10 ppm) in nonaccumulator plants. However, hyperaccumulator species can store metals at extremely high levels sometimes thousands of ppm. Because metal uptake and storage require significant energy, researchers have questioned the evolutionary advantage of such accumulation. Recent findings suggest that the high metal content in leaves may act as a defense mechanism, deterring herbivores, pathogens, and insects such as caterpillars.

Interestingly, hyperaccumulators do not limit themselves to essential micronutrients they can also take up large quantities of nonessential metals like cadmium (Cd). Although the exact mechanism for Cd accumulation remains unclear, it is hypothesized that Cd is absorbed through the same transport systems used for essential divalent micronutrients, particularly Zn^{2+}, as cadmium is chemically similar and may not be distinguished by the plant's transport machinery.

Mechanisms of metals uptake into roots and translocation to shoots

Due to their electrical charge, metal ions are unable to freely diffuse across cellular membranes, which are inherently lipophilic. As a result, their entry into cells must be facilitated by specialized membrane proteins known as transporters. These transmembrane transporters have two key components: an extracellular binding domain, which selectively binds specific ions, and a transmembrane region that enables ion passage through the hydrophobic membrane interior into the cell. Transporters are characterized by kinetic parameters such as transport capacity (Vmax) and ion affinity (Km). Vmax indicates the maximum possible rate of ion transport, whereas Km reflects the concentration of ions required to reach half of that maximum rate (Vmax/2). A low Km signifies high affinity, meaning efficient ion uptake even at low external concentrations. By analyzing these kinetic parameters, researchers can understand the specificity and selectivity of the transport process. It is also important to distinguish between ions physically bound to the root surface and those that actually enter the cells. A considerable proportion of ions adhere to negatively charged groups (COO^-) in the root cell walls. Since these cell wall-bound ions cannot move to the shoots, they cannot be removed via harvesting, limiting the effectiveness of phytoextraction. For instance, many plants readily accumulate lead (Pb) in their roots but show very limited Pb translocation to shoots. Blaylock and Huang (1999) suggested that the primary limitation for Pb phytoextraction is its long-distance movement from roots to aerial parts. Metal immobilization in roots is not limited to cell wall binding. Some metals are sequestered inside root cells, often stored in compartments such as vacuoles, which prevent their translocation to shoots. Additionally, certain plant species, known as “excluders,” have evolved mechanisms to restrict metal uptake altogether, although the exact exclusion mechanisms remain poorly understood.

Metal uptake into root cells represents the critical first step in phytoextraction, but effective remediation also requires metal transport from the roots to the shoots. This long-distance movement, called translocation, is driven largely by root pressure and leaf transpiration. Once metals reach the leaves, they can be reabsorbed from the xylem sap into leaf tissues, completing the process.

Future Thrust

Optimizing agronomic practices is essential to enhance the metal cleanup efficiency of phytoremediating plants. Since metal uptake by roots is often restricted by the low solubility of metals in the soil solution, further research is needed on the use of chemical amendments that increase metal bioavailability. While progress has been made in this area, there remains a need to identify cost-effective and environmentally safe chelating agents. Additionally, research should focus on selecting and developing phytoremediator species that can be rotated in cropping systems to maintain consistent rates of metal removal. Another important aspect is determining the optimal harvest time. Plants should be collected once their metal accumulation rate begins to slow, which would shorten the growth cycle and enable multiple harvests within a single growing season, thereby improving overall remediation efficiency.

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