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Plants as Natural Purifiers: A Review on Phytoremediation of Heavy Metals in Soil

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Abstract-
Environmental pollution is becoming a serious public health issue that affects the survival and sustainability of nature worldwide. The use of plants and related soil bacteria to lessen the absorption of harmful substances from the environment is known as phytoremediation. It is a relatively new technology that is well-liked by the public and is seen to be economical, productive, innovative, eco-friendly, and solar-powered. The use of plants and related soil bacteria to lower the levels of harmful chemicals in the environment is known as phytoremediation. It is a relatively new technology that is well-liked by the general public and is seen to be innovative, efficient, economical, and solar-powered. The only practical way to lessen the detrimental effects on ecosystem health may be to remediate soil contaminated by heavy metals. Similar processes to those of phytodegradation, phytovolatilization, phytoaccumulation, and phytoextraction form the basis of phytoremediation. These designs are lucrative, eco-friendly, and successful.

Keyword: Phytoremediation, Heavy Metals, Reactive Oxygen Species, and Chlorophyll Content.

Introduction

Heavy metals are, of course, linked to forest fires, wind corrosion, stormy eruptions, and the overall functioning of fossil fuels. In contrast to metals from anthropogenic sources such smelters, thermal power plants, mines, and foundries, which are hazardous to humans, metals from natural sources often cause less harm to the environment (Naja, G. M., et al. 2017). Through polluted subterranean water, chemical redox reactions, leaching, or external weathering processes, heavy metals accumulate in living cells and tissues within the soil ecosystem (Bhat, S. A., et al. 2019). All things considered, heavy metal contamination of sediments, soils, and water is becoming a serious problem. Rapid development and urbanization have had a significant impact on metal pollution (Oladoye, 2022).

There are essential and non-essential forms of heavy metals. As cofactors of numerous enzymes and in electron-transferring proteins, essential metals such as copper (Cu), zinc (Zn), manganese (Mn), nickel (Ni), and iron (Fe) play crucial regulatory functions in a variety of natural processes (Fageria et al., 2009; Chaffai and Koyama, 2011). Conversely, non-essential metals, such as lead (Pb), mercury (Hg), and cadmium (Cd), have no specific biological purpose. In response to heavy metal stress, plants change their gene expression (Hussain et al., 2004; Chaffai and Koyama, 2011) and cellular processes (Choppala et al., 2014). Beyond their toxic limits, all heavy metals have the potential to affect the production of reactive oxygen species (ROS).

Nevertheless, non-essential metals affect the structure of biomolecules and crucial stress-regulatory proteins, or can replace essential metals, inhibiting a variety of biological processes (Sarwar et al., 2010). Therefore, it becomes crucial to remove these metal contaminants in order to lessen the harm to all living things and our natural environment. To remove the HMs from the environment, a variety of techniques have been implemented, including reverse osmosis (A. F. Al-Alawy et al. 2017), chemical precipitation (H. Huang et al. 2017), ion exchange (Levchuk et al. 2018), adsorption and and solvent extraction (Burakov et al. 2018). These approaches, however, are typically not sustainable and entail substantial preserving functionality and costs.

As a cost-effective and essential method of decontaminating HM-contaminated areas, phytoremediation is one of the ecologically friendly ways to combat harmful essence pollution (Figure 1) (Nedjimi, B. 2021). Because phytoremediation is less expensive than traditional remediation techniques, it is widely used around the world (Lone,

M. I., et al. 2008; Yao, Z., et al. 2012). Since there is no need to alter the soil structure, this technology has the least negative environmental impact (He, S., et al. 2012).

According to Sarwar et al. (2010), variations in the amount of chlorophyll in leaves are often signs of nutritional deficits that might be brought on by environmental factors such pollution absorption in the canopy.

Each leaf's color is determined by its chlorophyll content and pigments, and variations in these pigments' amounts have been utilized in a number of statistical correlations and studies to infer the chemistry, physiology, and health of plants. Heavy metal sources in agricultural soil. Large volumes of pollutants, such as heavy metals and metalloids, are introduced into face soils by industrial and urban growth (Mishra, S., et al. 2023). Because they infiltrate the food chain and represent a serious risk to natural health, the buildup of heavy metals and metalloids in agricultural soil has garnered major attention (Cai et al., 2022). According to Rahman et al. (2019), excessive consumption of heavy metals and metalloids might cause irreversible harm to the body's neurological, secretory, and susceptible systems.

The improper dumping of municipal solid trash, manufactured garbage, and electronic waste (e-waste) can contaminate nearby soils. These waste products can release metals like cadmium, lead, mercury, and copper into the soil, particularly if they are not effectively handled in landfills or dumpsites close to agricultural areas (A. A. Agbeshie et al. 2020). The usage of fungicides, livestock manures, sewage sludge, and contaminated composts—particularly phosphate composts that include cadmium—are important contributors. Metals like lead, arsenic, and cadmium are released into the environment by industrial activities including mining, smelting, and manufacturing, usually through wastewater discharge or air pollution (Nathana'a Timothy, E. T. W. 2019).

Soils can become further contaminated by irrigation with contaminated water and atmospheric metal deposits from far-off manufacturing locations. Additionally, soil quality may continue to be impacted by legacy contamination from previous uses of prime gasoline, biopesticides based on arsenic, and other manmade processes. Because heavy metal impurities may damage living things through bioaccumulation, they have drawn attention from all around the world (Ekmekyapar et al., 2012). Typically, metals or metalloids with an increased essential viscosity are categorized as heavy metals.

. These are separated according to atomic number, weight, or density (Kumar et al., 2017; Ali and Khan, 2018). Citing Cd, Cr, Co, Cu, Pb, Hg, Zn, and other metals as examples, Ali et al. (Ali et al., 2019) suggested a new standard that states that HM should have an infinitesimal viscosity of > 41 g/ cm3. Terrestrial and aquatic ecosystems are severely impacted by even minute concentrations of heavy metals (HMs) in the system (Bansod et al., 2017).

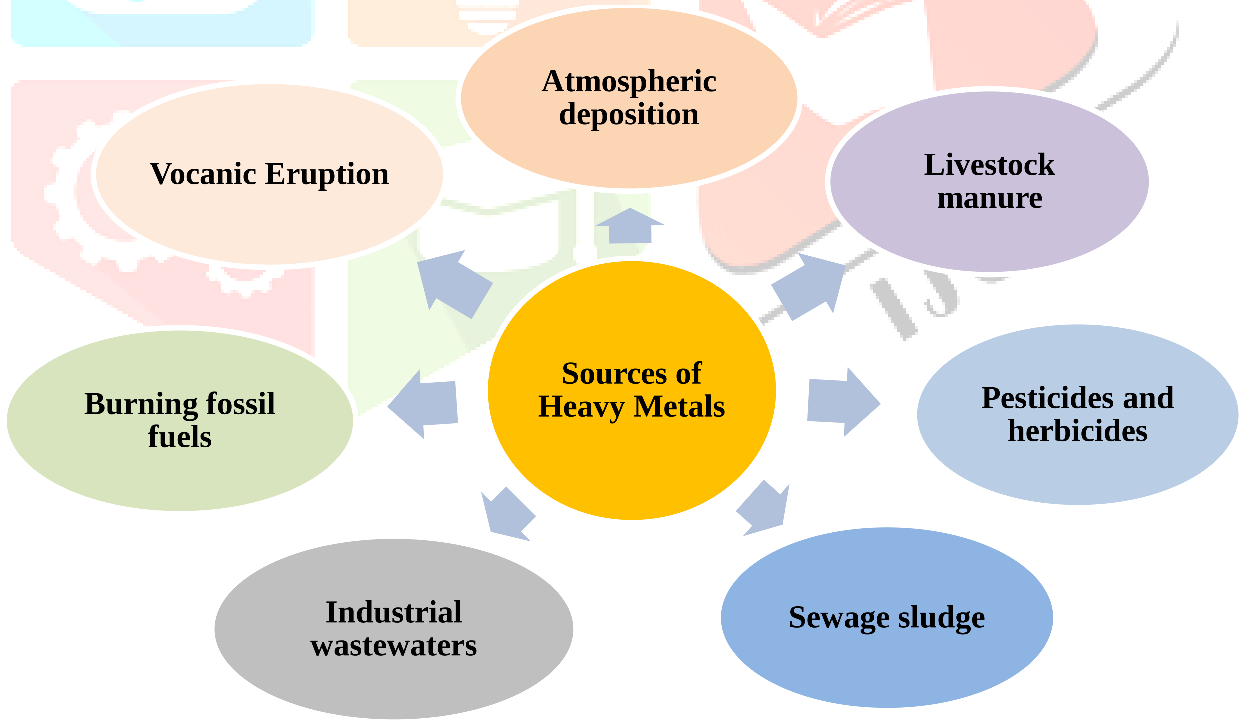

Figure 1. Sources of heavy metals in environment

Types of Plants Used in Various Phytoremediation Techniques

Rhizofiltration:

Water-rooted plants absorb pollutants from surface water, groundwater, and wastewater. Plant roots are used in a process called rhizofiltration to remove toxins from wastewater. HMs can be absorbed by root exudates, changing the rhizosphere's pH (Yan et al., 2020). Rhizofiltration uses roots to trap pollutants found in water, including radionuclides, natural pollutants, and heavy metals (such as lead, mercury, and cadmium). A plant's ability to hold onto pollutants increases with the size of its root system's surface area. Large, fibrous root systems seen in certain sea-going plants make them ideal for rhizofiltration. The following plants work well for the rhizofiltration forms: sunflower, Indian mustard, tobacco, rye, spinach, corn, parrot's plume, iris-leaved surge, cattail, and saltmarsh bulrush. Plant growth and its ability to absorb pollutants can be influenced by elements such as light, water availability, and the presence of other toxins. Furthermore, rhizofiltration system performance may be affected by frequent fluctuations (El-Liethy, M. A., et al. 2022). Rhizofiltration is frequently used to clean wastewater from cities, farms, and industries, especially to remove natural contaminants and heavy metals.

Phytoextraction:

The use of plants to absorb pollutants from soil or water and then move and gather those pollutants in their aboveground biomass is known as phytoextraction (Jacob et al., 2018). Nowadays, the most important phytoremediation technique for recovering heavy metals and metalloids from polluted soil is phytoextraction (Ali et al., 2013; Sarwar et al., 2017). A few stages are included in the procedure of phytoextraction of heavy metals: (i) heavy metal mobilization in the rhizosphere; (ii) heavy metal absorption by plant roots; (iii) heavy metal particle translocation from roots to aerial sections of the plant; and (iv) heavy metal particle sequestration and compartmentation in plant tissues (Ali et al., 2013). Plant selection, plant implementation, heavy metal bioavailability and soil, and rhizosphere characteristics are some of the factors that affect how successful phytoextraction is. A plant's overall health and pace of growth determine its capacity for phytoextraction. Generally speaking, rapidly developing plants with a high biomass have a greater capacity to absorb and accumulate contaminants. A sufficient supply of water and supplements is essential for promoting plant growth and maximizing the extraction process.

The following plants are capable of phytoextration: Chinese Brake Fern (Pteris vittata), Brassica nigra (Black Mustard), Dandelion (Taraxacum officinale), Pennycress (Thlaspi spp.), Coriander (Coriandrum sativum), Red Clover (Trifolium pratense), Sunflower (Helianthus annuus), Willow Trees (Salix spp.), Poplar Trees (Populus spp.), Mustard Greens (Brassica rapa), Water Hyacinth (Eichhornia crassipes), Chinese Brake Fern (Pteris vittata), Dandelion (Taraxacum officinale), and tobacco plants (Patel, K., et al. 2021). Although phytoextraction has limitations in terms of speed, capacity, and toxic quality, when properly handled, it provides a sustainable, economical the arrangement that can be integrated into green remediation methods.

Phytostabilization:

predict their release into the environment and reduce the likelihood that the metals will enter the food chain is known as phytostabilization (Wong, 2003; Marques et al., 2009). Heavy metal precipitation, a decrease in metal valence in the rhizosphere, retention and sequestration within root tissues, or adsorption onto root cell walls are all possible mechanisms for phytostabilization (Kumpiene et al., 2012; Gerhardt et al., 2017). At heavy metal-polluted ranges, plant growth promotes the preservation of soil health. For phytostabilization, the selection of appropriate plant species is important. The plants must be able to tolerate the heavy metal circumstances in order to meet the criteria of very effective phytostabilization. Plants should have robust root systems because they are essential for immobilizing heavy metals, stabilizing soil structure, and preventing soil disintegration. In order to quickly grow a vegetative cover in a specific area, plants should be able to produce a significant quantity of biomass. Under field circumstances, the plant cover should be easy to maintain throughout growth (Marques et al., 2009). For phytostabilization of heavy metal-polluted soils, a variety of plant species that satisfy the above requirements have been identified and used (for a thorough survey, see Burges et al., 2018).

The plants used for phytostabilization include Willow (Salix spp.), Poplar (Populus spp.), Horse feed (Medicago sativa), Indian Mustard (Brassica juncea), Bermuda Grass (Cynodon dactylon), Buffalo Grass (Bouteloua dactyloides), Atriplex (Atriplex spp.), and others. By reducing the portability and bioavailability of poisons, phytostabilization provides an environmentally viable and economical solution for managing contaminated soils (Moreira, H., et al. 2021). While it doesn't entirely remove contaminants, it helps to contain and stabilize them, preventing aid organic contamination.

Phytovolatilization:

The process of phytovolatilization is a phytoremediation method that uses plants to absorb pollutants from the soil, convert them into less toxic unstable forms, and then release them into the atmosphere through plant transpiration through the leaves or foliage system. This method can be linked to the detoxification of natural poisons and certain heavy metals such as Se, Hg, and As (Mehrandish, R., et al. 2019). In phytovolatilization, the plants serve as a filter that absorbs toxins, regularly through the roots, and then releases them into the atmosphere through transpiration or evaporates through their leaves. Usually in the roots or roots, the pollutants undergo a chemical transformation in the plant that transforms them into a form that may be released into the atmosphere as gases or vapors. After being absorbed, the pollutants travel through the vascular system of the plant (from the roots to the shoots), where they are frequently transformed or digested by plant proteins or metabolic pathways into less toxic forms. According to

Mehrandish et al. (2019), some of these pollutants may undergo chemical reactions within the plant and transform into an unstable form that can be released into the atmosphere. Alfalfa (Medicago sativa), Red Clover (Trifolium pratense), Corn (Zea mays), Sunflower (Helianthus annuus), Indian Mustard (Brassica juncea), Cabbage (Brassica oleracea), Tobacco (Nicotiana tabacum), Switchgrass (Panicum virgatum),and Poplar (Populus spp.) A novel and practical approach to managing pollution, phytovolatilization uses plants to transform pollutants into unstable forms that are then released into the environment. The types of contaminants this preparation can manage are limited, and there are possible natural problems with the volatilization of pollutants, even though it is highly effective for some types of natural poisons and can be economical.

Phytofiltration:

Using plant roots (rhizofiltration), shoots (caulofiltration), or seedlings (blastofiltration) to remove toxins from contaminated surface waters or wastewater is known as phytofiltration. Heavy metals can be taken in by their roots or adsorbed onto the root surface during rhizofiltration. In order to prevent the formation of heavy metals in subterranean water, root exudates can change the pH of the rhizosphere, which causes heavy metals to precipitate on plant roots (Javed et al., 2019). The rhizofiltration plants are first grown through hydroponics in clean water to establish a massive root system; the clean water is then replaced with polluted water to allow the plants to adapt. Following adapting, the plants are moved to the contaminated area in order to remove heavy metals.

The roots are collected and placed once they have become wet (Wuana and Okieimen, 2011). Using their roots, organisms like sunflowers, duckweed, which was and water hyacinth are used in phytofiltration to capture and remove heavy metals from both water and soil. Particularly in aquatic settings, phytofiltration is a viable, environmentally beneficial method of removing heavy metals from soil and water. While earthy species like Indian mustard, sunflower, and willows can be used to filter both water and soil, aquatic plants like water hyacinth, duckweed, and cattails are especially well-suited for filtering pollutants in wetlands or lakes.

Phytodegradation

Plants absorb pollutants and convert them into simpler, less dangerous forms through phytodegradation. Breakdown occurs in two ways: 1. Through the plant's internal metabolic process 2. Through plant-produced proteins. The plant uses the pollutants that are broken down into simpler things to develop more quickly. Phytodegradation may break down various inorganic chemicals, pesticides, chlorinated solvents, and other natural substances. Certain plants are thought to have significantly more phytodegrading abilities than a small number of plant species (Khandare and Govindwar 2015).

A study found that when the water hyainth plant is exposed to ethion-free culture conditions, the amount of ethion contained in the stems and roots decreases by 50–90% and 75–80%, respectively. The factors influencing phytodegradation include the effectiveness of the poison's absorption, its concentration in the soil, and the amount of water present in the ground (Awa, S. H., & Hadibarata, T. 2020). The phytochemical characteristics of the plants determine how well contaminants are taken up. For moderately hydrophobic naturally occurring contaminants like as benzene, toluene, ethyl benzene, and xylene, as well as chlorinated solvents and short-chain aliphatic hydrocarbons, the preparation is an effective evacuation tool at shallow depths. Helianthus annuus (sunflower), Salix spp. (willow), Populus spp. (poplar trees), Brassica juncea (Indian mustard), and other plants are included in metal phytodegradation.

Effect of heavy metals on development parameters of plants

The selected plant species with phytoremediation capability have few drawbacks, including slow growth that limits their ability to be applied quickly and extensively (Yan, A., et al. 2020) and adapt to a range of environmental circumstances, such as soils deficient in nutrients (Gerhardt et al., 2017). Terrestrial plants absorb heavy metals from the soil mostly through their roots, while in maritime environments, the entire plant body is accessible to heavy metals and particles. Plant-induced pH variations, chelating specialists produced in the rhizosphere, and a few transport proteins all promote the uptake handle (Tangahu et al. 2011). Wounds, lenticels, stomata, and other structures are further indicators of heavy metal transport (Shahid et al. 2017). Particularly during takeoff, heavy metals are retained because to particles accumulated on the foliar surfaces. Reactive oxygen species (ROS) and free radicals are essentially caused by heavy metals, which results in unchecked oxidation and radical chain reactions that ultimately damage cellular macromolecules such as proteins, lipids, and nucleic acids (Phaniendra et al. 2015). The growth and development of plants can be significantly and oftentimes hampered by heavy metals. These metals, that consist of elements like lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and copper (Cu), can affect a variety of developmental factors, including photosynthesis, biomass accumulation, plant height, root growth, seed germination, and overall health. Damage: By altering protein function and the metabolic processes necessary for seedling growth, heavy metals can prevent seeds from germinating (Dubey, S., et al. 2018). Elevated levels of metals such as lead or cadmium can completely inhibit or delay germination. Heavy metals have the ability to inhibit root growth by reducing root branching and extension. Cadmium, lead, and arsenic are among the metals that can build up in the root structure and prevent the absorption of essential nutrients like calcium, magnesium, and potassium, resulting in deficiencies. A common consequence of heavy metal accumulation in the roots is a reduction in root biomass (Wang, Q., et al. 2016). This helps to impede development by reducing the plant's ability to retain water and nutrients.

Exposure to heavy metals may lead to a reduction in overall biomass output, including both root and shoot mass. This results from the combined effects of cellular damage, reduced photosynthetic ability, and impaired supplement absorption. Depending on the metal and plant type, plants can accumulate heavy metals in a variety of tissues, including roots, stems, and clears out. While some plants can withstand or absorb heavy metals, others may be poisoned by them. These metals can accumulate over time and cause phytotoxicity, which can negatively impact development and perhaps make their way into the food chain (Uddin, M. M., et al. 2021).

Chlorophyll Content and Photosynthesis

Chlorophyll content and the amount of carotenoid in takes reduce negligibly when heavy metals are introduced for phytoremediation nursery testing in general. With increasing concentrations of heavy metals up to the fundamental level, followed by an expansion of the chlorophyll substance, the chlorophyll content showed a consistent declining pattern for chlorophyll a, chlorophyll b, and chlorophyll accumulation (Kondzior, P., & Butarewicz, A. 2018). By disrupting chlorophyll union and preventing photosynthesis, heavy metal poisoning can cause chlorosis, or the yellowing of plants. This occurs as a result of metals like lead and cadmium interfering with the function of proteins involved in the production of chlorophyll.

Reduced Photosynthesis: According to Rai, Agrawal, and Agrawal (2016), heavy metals can damage chloroplasts along with other cellular organelles, making it more difficult for plants to perform photosynthesis in a viable manner. This results in decreased vitality generation, which impacts the growth of plants.

Discussion

Because of industrial development, mining, agricultural practices, and pollution, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and others have become important natural pollutants. These metals' presence in the soil can have detrimental effects on plant growth, development, and the overall health of biological systems (Alengebawy et al. 2021). This talk will examine the ways in which heavy metals affect several aspects of plant growth, illuminating the factors that contribute to their detrimental effects and offering recommendations for plant physiology. Phytoremediation can be used to economically and environmentally address heavy metal pollution, a serious environmental problem caused by mining, machinery usage, and rural hones.

Utilizing plants and the tiny creatures that inhabit them, phytoremediation removes, stabilizes, or degrades pollutants from soil and water. This contrasts with traditional techniques such as chemical precipitation, particle trading, and reverse osmosis, all of which are expensive and produce trash (Saleh et al. 2022). Rhizofiltration, which involves removing metals from water via plant roots; phytoextraction, which involves removing heavy metals through the shoots of hyperaccumulator plants like Brassica juncea and Pteris vittata; phytostabilization, which uses plants like poplar and willow to bind to contaminants in the soil to prevent metal filtering; phytovolatilization, which transforms elements like mercury and Selenium into volatile forms that are released into the surrounding environment; and phytodegradation, which involves plants breaking down toxins enzymatically. Despite its advantages, phytoremediation has drawbacks, such as slowness, selectivity, and the potential for bioaccumulation, which necessitates handling harvested biomass carefully (Singh et al., 2024).

Furthermore, natural elements like temperature, microbial activity, and soil pH have an impact on its sufficiency. In any event, advancements in genetic engineering and microbial-assisted remediation can advance metal absorption and detoxifying capabilities. By using these developments, phytoremediation can be a useful and effective method of reducing heavy metal pollution and restoring polluted biological systems.

Conclusion

Using plants and microorganisms, phytoremediation is a sustainable and economical method of removing heavy metals from soil and water. Improvements in genetic engineering and microbial-assisted remediation increase its efficacy despite obstacles including modest rates and bioaccumulation. With further research, phytoremediation may prove to be an essential technique for cleaning up contaminated areas and advancing environmental sustainability.

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