



A Newer Green Approach of Sustainable Environmental Technology-Phytoremediation

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Abstract

Due to the rising levels of soil pollution, heavy metals have become a threat to the environment through considerable levels of contamination. Remediation techniques are being practiced, which have included excavation, soil flushing, vitrification, and immobilization techniques. Although these techniques are being employed but these processes are expensive with low level of efficiency. These remediation techniques have restricted their application in the efficient eco-friendly remediation of contaminated soils due to heavy metals, which are prevalent all over the world. Phytoremediation is a relatively recent, innovative, cost-effective, eco-friendly, and highly efficient alternative to efficiently remediate heavy metals contaminated soils. Phytoremediation not only provides benefits such as reduced levels of soil erosion, enrichment of organic matter in soils, fertility, and sustainable remediation, among others. Thus, the type of plants to be used, which are efficient in remediation, must be capable of withstanding biodiversity, as well as provide economic, utility, and by-product benefits. Hence, green plants are the most efficient, effective, and feasible options in the phytoremediation as well as Phyto management of heavy metals contaminated soils. The application of green flowering plants also proves to be beneficial and useful in improving landscape aesthetics.

Keywords: Soil pollution, Heavy metals, Phytoremediation, Phytostabilization, Biodiversity

1. Introduction

In the modern age of rapid industrialization, it is not possible to avoid the toxic chemicals and metals in the environment. Heavy metals pollution has grown to be a major risk to the environment primarily due to need of food security of the huge world population in pace with rapid growth in industries, global warming, vehicular pollution, soil degradation, contamination and disturbance of natural ecosystem [1]. Accumulation human health is seriously threatened by the presence of these heavy metals in water sources and agricultural soils due to their potential to infiltrate the food chain [2].

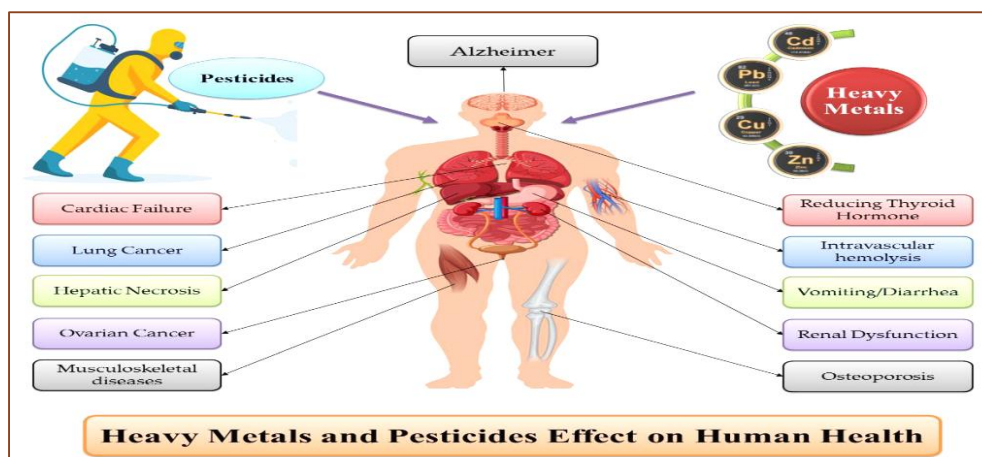


Figure -1 shows effect of rising heavy metals on human health

The components that make up heavy metals are diverse in terms of their chemical characteristics and functions. According to the Periodic Table, heavy metals mostly belong to the transition elements. Elements with a particular weight exceeding 5 grams are considered heavy metal

Natural and manmade processes yield heavy metals. In general, heavy metals are also linked to volcanic explosion, wind erosion, forest burning, and fossil fuel use. The metals from anthropogenic sources, smelters, thermal power plants, are a rising danger to people equally. Sometimes, their chemical coordination and oxidation–reduction properties let them smoothly run the control mechanisms such as homeostasis, transport, compartmentalization and therefore binding to required cell constituents [5]. Several conventional techniques used in curbing the contamination concerning heavy metals are like Sedimentation, Screening, Filtration, Membrane separation, Chemical precipitation, Coagulation and extensive Chemical Methods like Ion exchange, Adsorption, Neutralization, Solvent extraction, microbiological methods etc. Concerns that matter is about these techniques which simultaneously yields huge number of secondary pollutants which adversely affect nature.

“Phyto” means Plant “Remediation” means to restore the balance of various components soil with aid. Among the techniques is phytoremediation of bioremediation where several plants are employed either raw or genetically modified plant species for restoring heavy metal contaminated land and water sources [6]. Phytoremediation has acquired attention over the recent decades, as effective correction method using the natural capabilities of living organisms, an increasing and environmentally friendly green approach to our farming lands [7]. This study mainly focuses on different mechanisms of phytoremediation and application of such mechanisms to rescue the ground (soil), water bodies from hazardous metal pollution.

Heavy metal and their effects

Massive industrialization and urbanization contribute to the attribution of metal contents in the biosphere, resulting in an increase in their status in the ground and aquatic habitats [8].

2. Sources of heavy metal

2.1 Natural Sources

Natural phenomena like volcanic eruption, weathering of rock, forest fire, release small amount of heavy metals Even though they may contribute towards background metal contamination, they are not usually responsible for severe problems. Weathering is a natural phenomenon that allows metals like Pb, Hg, As, Cd, Zn, Cu to contaminate surroundings air, soil, water [11].

2.2 Anthropogenic

Humans have a very major role in heavy metal pollution. These are mining, industrial wastewater, sewage water, pesticide, fertilizers Contamination caused by human are much more than natural limits. If the contaminated water is used then metals get deposited in soil [12].

3. Toxic Effects of Heavy Metals

3.1 Toxic Effects of Heavy Metals on Plants

Plants are adversely affected by heavy metal stress in which the concentration of any metal exceeds its normal physiological level in plant tissues. Lead, cadmium, chromium, mercury, and arsenic are some metals that interfere with the plant growth regulators and metabolism leading to detrimental effect on plants. These heavy metals are essential micronutrients. They are beneficial in lower concentration where as in higher concentration they show severe toxicity. According to chemical reactivity heavy metals are classified into redox active and non-redox active metals. Metals like chromium, copper, iron, manganese act as initiator in redox reaction. These metals (through redox reaction) are prone to produce reactive oxygen Species and free radicals that cause damage in DNA, protein, photosynthetic pigment.[13] Heavy metals that are non-relative (Cd, Hg, Ni, Zn) cause binding with protein sulphahydryl group, decrease glutathione levels, induce free radical generating enzymes that leads to oxidative stress. Heavy metals in higher concentration decrease growth of plants, affects photosynthesis, decrease nutrient absorption, kill root cells, force stop germination, all of these ultimately leads to death of plants.

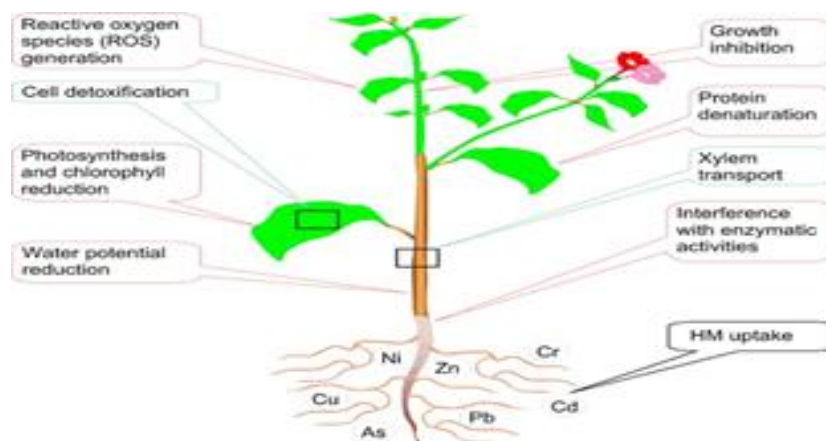


Figure 2.1 -Various cases of heavy metal toxicity in Plants

3.2 Toxic Effects of Heavy Metals on Human

Heavy metals show bioaccumulation in humans and this increase concentration, which leads to more toxicity. Arsenic affect ATP production that leads to decrease in energy production ultimately causing cancer and systemic effects.[14] Mercury after methylation gets easily accumulated in biological system that leads to neurological, respiratory, cardiovascular, immunological disorders. [15] If lead accumulates above a permissible limit in vital organs then it may cause neurological problems and congenital issues.[16] On accumulation of nickel human faces low immunity, hypersensitivity reactions, diabetes, infertility.[17] Cadmium on long duration of bioaccumulation affect kidney, endothelium, nerves that may lead to renal failure.[18] If exposed for longer duration then due to bioaccumulation and toxicity severe side effects are observed in human body.

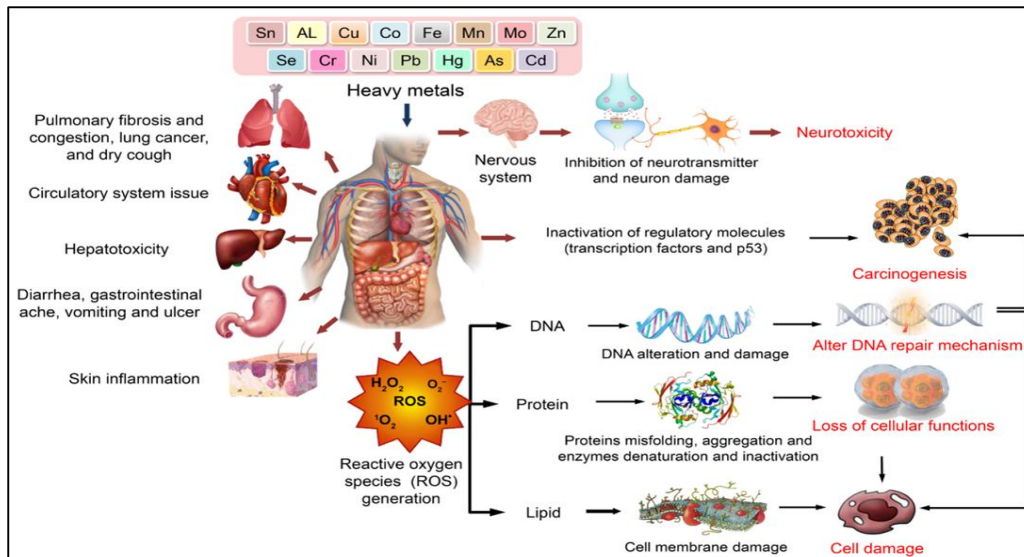


Figure 2.2 - Various cases of heavy metal toxicity in human

4. Several conventional techniques used in heavy metal remediation

a. Chemical Precipitation

Process: When precipitating agents (lime, sulphide) added, soluble heavy metals form insoluble solid particles.

Commonly used for: Treatment of water from metallurgy industry

Limitations: Creates sludge which has to be removed moreover this method cannot completely remove metals.

b. Ion Exchange

Process: The resins bind with toxic metal ions and exchange it with other non-harmful ions.

Applications: Water softening and industrial waste water treatment.

Limitations: Costly, may require modification with respect to chemical changes in water.

c. Adsorption

Process: Heavy metals stick to the exterior of solid adsorbents such as activated carbon, zeolites, or clays.

Advantages: Effective, easy to install and use.

Limitations: due to prolonged adsorption the surface may get saturated then it requires replacement or regeneration.

d. Electrochemical Treatment (Electrolysis)

Process: Electric current is used to precipitate or reduce metal ions from solution.

Applications: Suitable for treating small volumes of highly contaminated wastewater.

Limitations: Expensive and energy-intensive.

e. Membrane Filtration

Techniques: Includes reverse osmosis, ultrafiltration, and nanofiltration.

Process: Separates heavy metals based on size or charge through a semi-permeable membrane.

Limitations: High operating cost and membrane fouling.

5. Phytoremediation: Concept and Principles

Bioremediation refers to the subset that utilizes green plants and their rhizospheric microorganisms for cleaning up polluted soils, water, and air. Based on natural plant processes, phytoremediation includes uptake, translocation, sequestration, and transformation of metals. The technique is suitable for low-to-moderate contamination and large land areas.

5.1 Mechanisms of Phytoremediation

Key mechanisms of Phytoremediation are primarily Phytoextraction, Phytostimulation, Rhizofiltration, Phytostabilization, Phytovolatilization, and Phytotransformation. Phytoextraction involves plants absorbing pollutants through their roots and accumulating them in their tissues, such as sunflowers. Phytotransformation breaks down organic contaminants through enzymatic processes, transforming toxic chemicals into less dangerous materials or integrating them into plant biomass. Rhizofiltration breaks down pollutants found in soil around plant roots by microorganisms, encouraging microbial populations to degrade pollutants. Phytovolatilization absorbs pollutants through roots and releases them in a less hazardous form into the atmosphere.

5.1.1 Phytoextraction

Phytoextraction is a phytoremediation technique where plants or algae absorb pollutants, especially heavy metals, from soil or water and accumulate them in harvestable biomass. Metals taken up by plant roots are translocated to the aerial plant parts such as shoots and leaves, which may be harvested for safe disposal or metal recovery.[19]

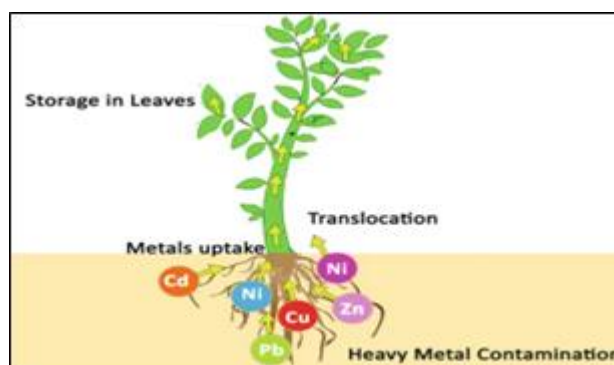


Figure 3 - Phytoextraction

5.1.2 Phytostabilization

Phytostabilization is a phytoremediation technique that reduces the mobility and bioavailability of heavy metals in contaminated soils. Plants immobilize pollutants within the root zone by decreasing metal solubility, limiting wind-blown dust, and reducing soil erosion. Instead of degrading contaminants, plants secrete root exudates that stabilize heavy metals and prevent their migration through soil, water, or the food chain.[20] This method is particularly effective for controlling water-soluble contaminants.

5.1.3 Phytodegradation

Phytodegradation involves the breakdown of organic contaminants absorbed by plants through internal metabolic processes or plant-produced enzymes. These enzymes catalyze the degradation of complex organic pollutants into

simpler, less toxic compounds. The degraded products are then incorporated into plant tissues and utilized for plant growth, making phytodegradation effective for the remediation of organic pollutants.[21]

5.1.4 Phytostimulation

Phytostimulation increases microbial populations around the roots, which degrade organic pollutants. Plants release substances like sugars, alcohol, organic acids into the soil, which increase the growth of microbes like bacteria and fungi.[22] These microbes degrade toxic substances like fuel and solvents into other less harmful substances. Transgenic plants, which improve the association of microbes and plants, improve the effectiveness of the technique.[23]

5.1.5 Phytovolatilization

Phytovolatilization is a process whereby plants remove contaminants from soil or water and then release them as vapours. In this respect, contaminants gain access to plant roots, find their way to plant leaves, and then get volatilized. There can be a direct phytovolatilization of contaminants or be mediated

interaction in increasing metal uptake and mitigation of metal toxicity. Induced phytoextraction is carried out indirectly via effects on soil. Plants also help in soil stabilization.[24]

5.1.6 Rhizofiltration

Rhizofiltration is the process of removing contaminants from water, such as groundwater, wastewater, or surface water, using plant roots. In this process, plants are grown in a hydroponic system with their roots immersed in water, allowing the contaminants to be absorbed, adsorbed, or precipitated out around the plant's roots. Once the plant's roots are loaded with impurities, they are removed and disposed of properly to remediate the polluted water. The process is commonly used to clean water of heavy metals.[25]

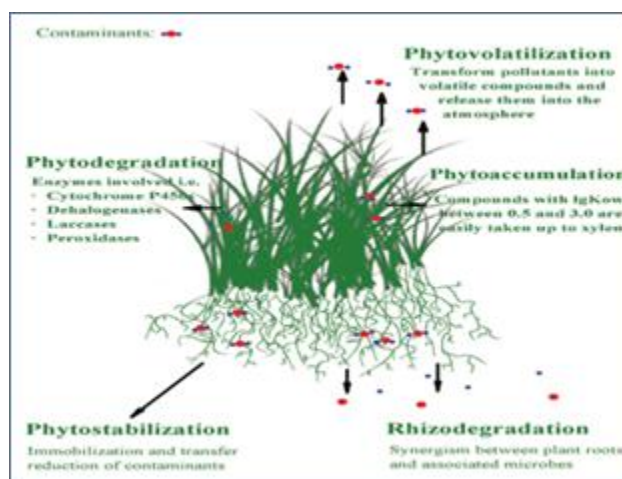


Figure 4 – Mechanism of Phytoremediation

6. Literature Review

Almost in the year of 2005 heavy metal contamination became an alarming problem as per scientists. Then the idea of phytoremediation was introduced as an eco-friendly solution. In the year of 2007 and 2008 scientific research focused on mechanisms like phytoextraction and phytostabilization. In 2009-2011 some plants were shown to absorb metals like lead, cadmium, zinc etc. Around 2012-13 researchers suggest that treating plants with soil microbes can escalate the process of cleaning. In 2014-15 researches conducted on application of chelating agents. From 2017 to 2019 ecological aspects of phytoremediation was studied. In 2021 research was done on phytoremediation and genetic engineering. In 2023-25 nanotechnology was introduced into phytoremediation methods.

7. Genetically Modified Plants Used in Bioremediation

Plants that are genetically modified are designed to increase the phytoremediation potential by incorporating genes that are integral to the metal uptake, transportation, and immobilization processes. This helps in the increased absorption, transportation, and accumulation of the metals in the plant parts that are harvestable. The genetic engineering of the synthesis of metal chelators such as phytochelatins and metallothioneins further increases the plant's potential in tolerating heavy metals.

Research has indicated that there are only a few genes involved in metal tolerance, enabling genes from hyperaccumulators and other organisms to be introduced into suitable plants. Metallothionein genes derived from humans, yeast, mice, and plants have been successfully introduced into several organisms, such as *Nicotiana tabacum*, *Brassica* spp., and *Arabidopsis thaliana*, in relation to increased tolerance to cadmium and copper. Transgenic plants engineered to overexpress genes for interaction in increasing metal uptake and mitigation of metal toxicity.

Cysteine synthase and yeast CUP1 genes have shown a marked improvement in cadmium tolerance and uptake even in the absence of a significant impact on metal uptake mechanisms. This indicates that genetically engineered organisms possess a high capacity for metal tolerance and removal, hence effective in bioremediation strategies.

Table 1: List of some of the plants for phytoremediation

Plant Name	Biological Sources	Uses
Indian mustard	Scientific Name: <i>Brassica juncea</i> Family: Brassicaceae Heavy Metal: Root > Shot > Leaves Highest Concentration in 60-90 days	Cadmium and Chromium absorption
Willow	Scientific Name: <i>Salix viminalis</i> Family: Salicaceae Fast growing so helpful in contaminated sites Leaves and twigs store Cd, Zn	Stabilizes heavy metal contaminated sites
Alpine Pennycress	Scientific Name: <i>Noccaea caerluscens</i> Family: Brassicaceae Absorbed by root and stored in leaf vacuole Zn (30,000- 40,000ppm), Ni (10,000- 20,000), Cd	A model hyper accumulator for zinc and nickel
Vetiver Grass	Scientific Name: <i>Chrysopogon zizanioides</i> Family: Poaceae Absorb and accumulate Pb, Cd, Zn, Cu, Ni	Strong root system helps remediate multiple heavy metals

	Root system store and prevent from groundwater or root system	
Sunflower	<p>Scientific name: <i>Helianthus annuus</i></p> <p>Family: Asteraceae</p> <p>Stored in root, stem, leaves</p> <p>Store Pb, Cd, As</p> <p>In root in early stage and in stem and leaves in later stage</p>	Efficient at extracting lead and arsenic from soil.
Marigold	<p>Scientific Name: <i>Tagetes erecta</i>, <i>Tagetes patula</i></p> <p>Family: Asteraceae</p> <p>NPK fertilizers improve Cd accumulation</p> <p>Improve soil quality</p> <p>Absorb Cd, Pb, Zn, Cr</p>	Enhances soil health by accumulating heavy metals
Reed Grass	<p>Scientific Name: <i>Phragmites australis</i></p> <p>Family: Poaceae</p> <p>Storage in roots and rhizomes and low mobility upwards</p> <p>Absorbs Cd, Hg, Pb, Zn</p>	Water and soil remediation by multiple heavy metals
Poplar	<p>Scientific Name: <i>Populus</i> sp (<i>P. deltoids</i>, <i>P. niagra</i>, <i>P. tremula</i>, <i>P. alba</i>, <i>P. trichocarpa</i>)</p> <p>Family: Saliceae</p> <p>Roots store Cr, Pb, Cu. Leaves store Cd, Zn.</p> <p>High biomass and transpiration pull cause phytoextraction and phytostabilization</p>	Fast growing tree with high biomass for heavy metal uptake and soil stabilization
Paulownia	<p>Scientific name: <i>Paulownia</i> sp (<i>P. tomentosa</i>, <i>P. elongata</i>, <i>P. fortunei</i>)</p> <p>Roots absorb soil pollutants (Cr, Cu) and leaves absorb air pollutants (Zn); Cd remains at lower stem</p>	Both air and water pollutants are absorbed
Four O' Clock Flowers	<p>Scientific name: <i>Mirabilis jalapa</i></p> <p>Family: Nyctaginaceae</p> <p>Maximum accumulation found in day 45</p>	Highly effective for phytoremediation of petroleum contaminate soil

	Absorb Pb, Cd, Cr Heavy metal removal is ph dependent	
Chinese ladder Brake	Scientific name: <i>Pteris vittata</i> Family: Pteridaceae Storage in fonds. Zn, Cr, As Absorbed. Younger leaves store more elements than mature. In younger fonds 85% arsenic stored(3100ppm)	Used for phytoremediation of arsenic contaminated soil

8. Advantages of Phytoremediation

Phytoremediation is a green technology that can be used in both in situ and ex situ applications to address various organic and inorganic pollutants. It is both ecologically sustainable and visually appealing to the public, providing aesthetic benefits through tree use and green areas. Phytoremediation is ideal for expansive spaces where other approaches would be expensive and ineffective. It is reasonably simple to implement and doesn't call for costly equipment or highly skilled workers. The fact that a wide range of organic and inorganic substances can be treated by phytoremediation is a major benefit process [26]. Both in situ and ex situ applications of phytoremediation are possible. Because in situ treatments decrease disturbance of the soil and surrounding ecosystem and lessen the spread of contamination through airborne and waterborne wastes, they are often taken into consideration. It is a green technology that, when used correctly, benefits the environment and the general public's aesthetics. Phytoremediation is comparatively simple to perform and doesn't require costly equipment or highly skilled workers. In a variety of settings, it can permanently treat a broad range of pollutants. The main benefit of phytoremediation is its low cost compared to conventional clean-up technologies [27].

9. Limitations

Phytoremediation, while eco-friendly and cost-effective, has several limitations: -----

1. Slow Process: It often takes months or even years to significantly reduce contamination levels.
2. Shallow Root Zone: Most phytoremediation plants can only access contaminants in the topsoil, limiting effectiveness for deeper pollution.
3. Metal-Specific: Plants may only accumulate certain heavy metals and not others, reducing versatility.
4. Biomass Disposal: Contaminated plant material must be harvested and properly disposed of or treated to prevent secondary pollution.
5. Climate and Soil Constraints: Effectiveness depends on suitable climate, soil type, and nutrient availability, which may not be optimal at all sites.
6. Limited to Low-to-Moderate Contamination: Highly toxic or heavily polluted sites may inhibit plant growth, making phytoremediation impractical.

7. Risk of Food Chain Contamination: If edible or grazing plants are used, there is a risk that metals could enter the food chain.

Despite these limitations, phytoremediation remains a promising green technology for certain types of heavy metal contamination.

10. Future prospect of Phytoremediation

Metal transporter manipulation and cellular targeting to particular cell types, including vacuoles, to enable the safe segregation of heavy metals in certain areas that do not disturb other cellular functions. Genetic Chloroplast genome manipulation may be, for some plants, an alternative approach to achieve higher gene expression while avoiding the risk of transgene escape via pollen. Identification Developing potential plants with compounds that would discourage herbivores from consuming them, followed by the development of such plants with modified or enhanced metal tolerance capacities; this method will assist in preventing the entry of metals into the food chain. Creation of Transgenic Plants with enhanced plant-microbe interaction or rhizosphere microbial activity; it may be possible either in order to create transgenic plants that can secrete metal-selective ligands capable of solubilizing elements for phytoremediation or to find simple molecules with selective chelation ability which plants can make and secrete into the rhizosphere. Transgenic research in phytoremediation should also address the problem of mixed contamination occurring in many of the polluted sites. A multigene approach involving the simultaneous transfer of several genes into suitable candidate plants that may help to remove contaminants of mixed or complex nature. Identification of cropping system with the target (heavy metals) and site (environmental condition) specific phytoremediation and establishment of management practices for maximum efficiency of heavy metal accumulation along with the additive is the future of phytoremediation.

11. Conclusion

Heavy metals are one of the most critical threats to the soil and water resources, as well as to human health. The concentrations of heavy metals increasing in the environment from year to year. Phytoremediation is a new cleanup concept that involves the use of plants to clean or stabilize contaminated environments. Phytoremediation of metals is the most effective plant-based method to remove pollutants from contaminated areas. This green technology can be applied to remediate the polluted soils without creating any destructive effect of soil structure. Some specific plants, such as herbs and woody species, have been proven to have noticeable potential to absorb toxic metals and are known as hyperaccumulators. Phytoremediation is regarded as a sustainable technology due to its low cost and use of environmentally friendly methods to clean up soil, water, and air pollutants. Using a range of techniques, such as rhizofiltration, phytoextraction, phytostabilization, and phytovolatilization, phytodegradation, the future of greener environment depends on Phytoremediation together with other sustainable ways.

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