DISCOVERY

58(319), July 2022

Phytoremediation of Heavy Metals and its Application: A comprehensive study

Sosale SM, Raju NS*

To Cite:
Sosale SM, Raju NS. Phytoremediation of Heavy Metals and its Application: A comprehensive study. *Discovery*, 2022, 58(319), 807-816

Author Affiliation:
Department of Studies in Environmental Science, University of Mysore, Manasagangotri, Mysore -570 006, Karnataka, India

***Corresponding Author:**
Department of Studies in Environmental Science, University of Mysore, Manasagangotri, Mysore -570 006, Karnataka, India
E-mail: nsr@envsci.uni-mysore.ac.in

Peer-Review History
Received: 14 May 2022
Reviewed & Revised: 15/May/2022 to 20/June/2022
Accepted: 21 June 2022
Published: July 2022

Peer-Review Model
External peer-review was done through double-blind method.

ABSTRACT

Year after year, heavy metal concentrations in the environment are increasing. As a result, heavy metal-contaminated soils must be decontaminated to safeguard the environment and restore the ecosystem. Phytoremediation is a technique for cleaning up toxins in the environment that relies on natural processes. Plants aid in the removal of pollutants through several mechanisms, including absorption and concentration, pollutant transformation, stabilization, and rhizosphere degradation, in which plants promote the growth of bacteria that break down toxins underground in the root zone. While the use of phytoremediation is on the rise, little. There has been focus on the ecological features of the plants used. This research investigated the possibility of using native plants to clean up soil while simultaneously providing benefits above ground, such as wildlife habitat. A relatively new technology is phytoremediation. With several advantages over traditional site clean-up methods. Some of the applications have only been tested in the lab or a greenhouse, while others have been field-tested to the point that they may be employed on a large scale. Phytoremediation was recently produced by engineers and scientists as a cost-effective and environmentally acceptable method of treating polluted areas using biomass/microorganisms or live plants. Only a few of the applications include Phytofiltration, phytostabilization, phytoextraction, and phytodegradation.

Keywords: Phytoremediation, bioaccumulation factor, Translocation factor, and Heavy Metals.

INTRODUCTION

When plants are employed to partially or remove toxins from polluted soil, sludge, sediment, groundwater, surface water, and wastewater, this is known as phytoremediation. It makes use of a variety of plant biological activities as well as physical features to aid in site clean-up. Phytoremediation is also known as green remediation, botana remediation, agroremediation, and vegetative remediation. Phytoremediation is a set of actions that vary in intensity based on the environment, media, contaminants, and plants involved. In the literature, these various processes have been referred to by a variety of terms. This section introduces and uses a variety of terms as a handy means of introducing and comprehending the processes that occur during phytoremediation. [1] Various xenobiotic organic substances (herbicides, insecticides, miticides, and hydrocarbons, among others) have been produced, disseminated, and mistakenly spilled, resulting in direct or indirect environmental damage to soil, water, and air. Bioremediation is defined as the chemical modification of pollutants using microorganisms that meet their nutritional needs while also contributing energy to the environment's detoxification or mineralization. [2, 44, 46]

To remediate contaminated soils and residues, many processes such as removal, isolation, incineration, solidification/stabilization, vitrification, thermal treatment, solvent extraction, chemical oxidation, and others can be utilized. These treatments have the drawback of being very expensive, and in some cases, they necessitate transporting contaminated materials to treatment sites, which increases the risk of secondary contamination.[3, 47]

As a result, in situ technologies that are both environmentally friendly and cost-effective are becoming increasingly popular. In this case, biotechnology offers phytoremediation techniques as a feasible alternative. Phytoremediation is the process of removing, degrading, or isolating dangerous compounds from the environment using plants (including trees, shrubs, grasses, and aquatic plants) and the accompanying microbes.[4, 45]

The name "phytoremediation" is derived from the Greek words "phyton" (plant) and "remedium," which means "to correct" or "to remedy." Metals (Pb, Zn, Cd, Cu, Ni, Hg), metalloids (As, Sb), inorganic compounds (NO3-, NH4+, PO43-), Petroleum hydrocarbons (BTEX), pesticides (atrazine, bentazone, chlorinated and nitroaromatic compounds), explosives (TNT, DNT), chlorinated solvents (TCE, PCE), radioactive chemical elements (U, Cs, Sr), and petroleum hydrocarbons (BTEX) (PCPs, PAHs). [5] Metal contamination is a serious concern in the mining areas under examination, as evidenced by the presence of heavy metals and metalloids in both soils and native wild plants. The native flora's ability to withstand high concentrations of heavy metals/metalloids in the soil has been demonstrated It has been shown that the soil is capable of withstanding high soil concentrations of heavy metals/metalloids. [6]

In 1986, the Chornobyl Nuclear Power Plant Reactor 4 in Ukraine contaminated the environment severely, requiring phytoremediation with Brassica juncea and Brassica carinata.

Phytoremediation of explosives contaminated groundwater in US Army sites (Superfund sites) using Gujarat's Pariyej Reservoir, home to aquatic life- "Wetland of International Importance" - to determine the degree of heavy metal contamination using aquatic macrophytes as Bio-monitors. [7, 8].

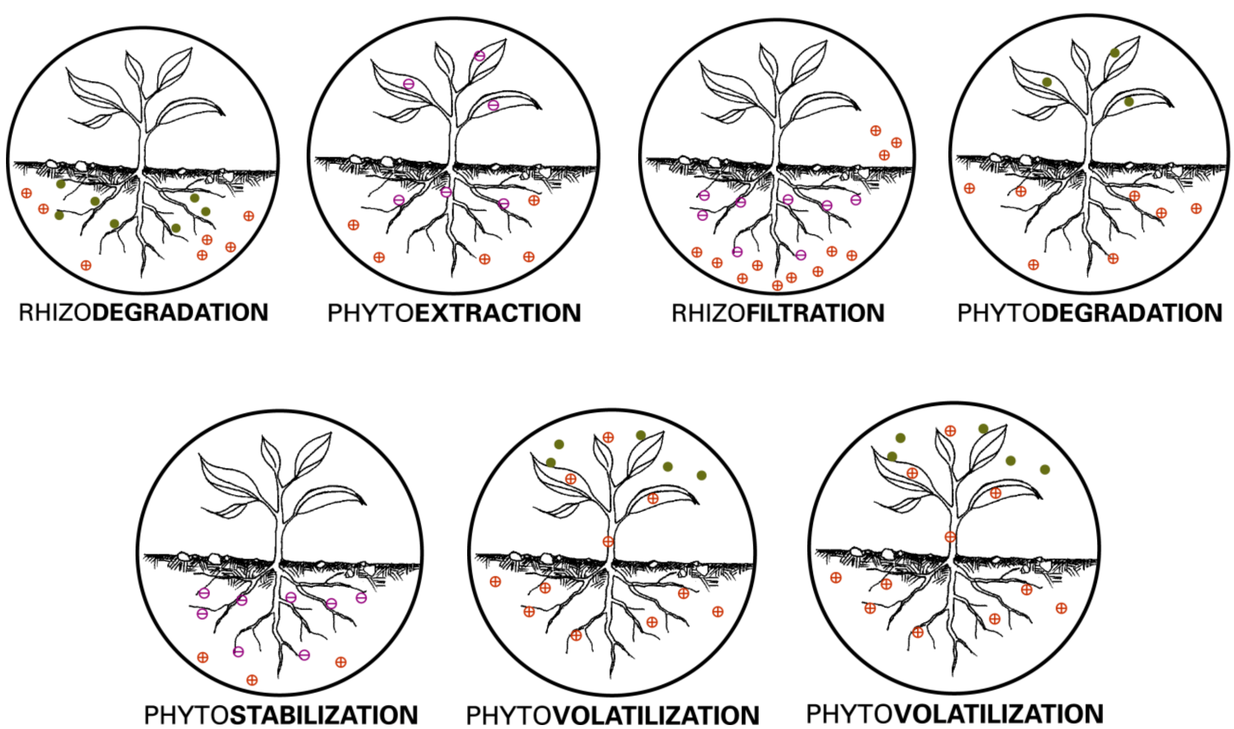
Table 1:

Technique	**Description**
Phytoextraction	Accumulation of pollutants in harvestable biomass i.e., shoots
Phyto filtration	Sequestration of pollutants from contaminated waters by plants
Phyto stabilization	Plant roots reducing the bioavailability and mobility of contaminants in soil
Phytovolatilization	Pollutants being converted to a volatile state before being released into the atmosphere
Phytodegradation	Plant enzymes within plant tissues break down organic xenobiotics.
Rhizodegradation	**Removal of excess salts from saline soils by halophytes**
Phytodesalination	Degradation of organic xenobiotics in the rhizosphere-by-rhizosphere microorganisms

Table 2: Heavy Metals (HM) sources of specific heavy metals in the environment Harmful effects on human health

Heavy Metals (HM)	**Anthropogenic sources of specific heavy metals in the environment**	**Harmful effects of specific heavy metals (HM) on human health**
As	Pesticides and wood preservatives	Since as (as arsenate) is an analogue of phosphate, it prevents the production of ATP and other vital cellular activities including oxidative phosphorylation.
Cd	pigments and paints. stablers made of plastic. electroplating. burning of plastics, phosphate fertilisers, and cadmium-containing materials	Renal failure and chronic anaemia are caused by the endocrine disruptor Cd, which is also carcinogenic, mutagenic, and teratogenic. It also interferes with calcium

		regulation in biological systems.,
Cr	Tanneries. steel industries. fly ash	Cr - Cause hair loss
Cu	Pesticides. fertilizers	Cu -Elevated levels have been found to cause brain and kidney damage, liver cirrhosis and chronic anemia, stomach and intestinal irritation
Hg	Release from Au—Ag mining and coal combustion, medical waste	Hg -Anxiety. autoimmune diseases, depression, difficulty with balance, drowsiness, fatigue, and hair loss. insomnia. irritability, memory recurrent restlessness. vision disturbances, tremors, temper outbursts. ulcers and damage to the brain, kidney, and lungs
Ni	Industrial effluents. kitchen appliances, surgical instruments, and steel alloys. Automobile batteries	Ni -Allergic dermatitis is known as nickel itch: inhalation can cause cancer of the lungs. nose, and sinuses; cancers of the throat and stomach have also been attributed to its inhalation: hematotoxin, immunotoxin, neurotoxic. genotoxic, reproductive toxic. pulmonary toxic, nephrotoxic, and hepatotoxic; causes hair loss
Pb	Aerial emission from combustion of leaded petrol, battery manufacture, Herbicides, and Insecticides	Pb - Children who consume it are harmed, suffering from lower IQ and delayed growth. Renal failure and an increased risk of cardiovascular disease are caused by short-term memory loss, learning difficulties, and coordination issues.
Zn	Mining and Industrial and Agricultural activities	Zn - Overdosage can cause dizziness and fatigue.



Phyto filtration:

Phyto filtration is the removal of pollutants from contaminated surface waters or wastewaters by plants. Phyto filtration

1. Rhizofiltration (use of plant roots)
2. Last filtration (use of seedlings)
3. Utilizing cut plant shoots (caulofiltration; from the Latin for "shoot").

Hydroponics used for metal remediation 75% of Metal removed from mine drainage Rhizofiltration is equal to phytoextraction and phytostabilization. [9]

Rhizodegradation:

Rhizodegradation is the breakdown of organic contaminants in the soil by rhizosphere bacteria. The plant influences the rhizosphere, which spans about 1 mm around the root. Exudates including carbohydrates, amino acids, and flavonoids secreted by plants can boost the rhizosphere's microbial population by 10 to 100 times. Plant roots release nutrient-rich exudates, which give carbon and nitrogen supplies to soil microorganisms and generate a nutrient-rich environment conducive to microbial activity. [10]

Rhizofiltration:

Pollutants are removed from water by plant roots in a hydroponic system for inorganics Metals, Metalloids, and Radionuclides. Plant roots and shoots are harvestable (may be used to mine metals) or disposed of after minimizing volume Rhizofiltration ('rhizo' means 'root') is the adsorption or precipitation onto plant roots (or absorption into the roots) of contaminants that are in the root zone's immediate solution. Like phytoextraction, rhizofiltration also uses plants as a solvent to clean up contaminated groundwater rather than the soil can be used for Pb, Cd, Cu Zn. and Cr. which are primarily retained within the roots.[11-13]

Phytodegradation

Plants use enzymes like dehalogenase and oxygenase to break down organic pollutants during the process known as phytodegradation, which is independent of rhizospheric bacteria. Organic xenobiotics can be accumulated by plants in contaminated settings and detoxified by their metabolic processes ("Green Liver" for the biosphere”). Heavy metals are toxic and non-biodegradable.[14, 15] Phytodegradation. Pollutant degradation by plants, with or without absorption, and translocation Nitro reductase, for example, is oxygenated by enzymes. TCE, TNT, and atrazine in tissues and root exudate, for example. Some metal (loid)s some volatile organics, phytovolatilization: pollutant discharged in volatile form into the air.[16]

Disadvantage: Because it does not entirely remove the pollutant, it can only be moved from one segment (soil) to another (atmosphere), where it can be redeposited. Phytovolatilization is the process of plants absorbing pollutants from the soil, converting them to a volatile state, and then letting them go into the air.[17] This method can be used to detect organic contaminants as well as heavy metals like mercury and Se. Selenium was eliminated from wetland construction at a rate of 75%. It entails phytoextraction.

- Phytovolatilization
- Phytostabilization
- Rhizofiltration
- Phytostimulation

Phytoremediation vs. Mechanical/chemical treatment Advantages of phytoremediation

- Cheaper w10 100x - Excavation cc reburial: up to $1 million/acre Revegetation: 20,000/acre
- Biological remediation localised solar power Energy from fossil fuels Ex-situ Mechanical and chemical processing
- Soil cleaning
- Excavation and reinterment *Chemical clean-up of soil water • Combustion
- Plant tolerance to pollutant/conditions - bigger problem with metals than organics - Can be alleviated using amendments, or treating hot spots by another method
- Bioavailability of contaminant

Phytodesalination

Phytodesalination is the process of using halophytic plants to remove salts from salt-affected soils, allowing them to support normal plant growth. A summary of the many phytoremediation approaches. [6]

Natural attenuation: with/without adding clean topsoil

- polluted site left alone but monitored
- Vegetative cap: polluted site revegetated, then left alone, monitored

Hydraulic barrier

Capillary fringe

Contaminated plume

Clay (aquitard)

Water flow redirected

Pollutants intercepted

Water

Monitoring organic molecules and heavy metals

- The extraction of ores and processing lead to the production of heavy metals.
- Heavy metals are non-biodegradable,
- They accumulate in the environment
- Subsequently contaminate the food chain.
- Heavy metals cause toxicological effects on soil microbes, which may lead to a decrease in their numbers and activities. Both the environment and human health are at risk from this contamination.

Essential HM: Fe, Mn, Cu, Zn, and Ni

Non-essential HM: Cd, Pb, As, Hg, and Cr.

Sources of heavy metals in the environment

1. Natural sources- weathering of minerals, erosion, and volcanic activity
2. Anthropogenic sources: mining, smelting, electroplating, use of pesticides and (phosphate) fertilizers as well as biosolids in agriculture, sludge dumping, industrial discharge, atmospheric deposition, etc.[18]

Phytoremediation

A sustainable solution to the HM issue "Phytoremediation" is defined as "the use of plants and associated soil microorganisms to lower the concentrations of pollutants in the environment or their hazardous effects. [6]" Heavy metals and radionuclides can be removed, as well as organic contaminants including polynuclear aromatic hydrocarbons, polychlorinated biphenyls, and pesticides [19]. It is an innovative, cost-effective, efficient, environmentally, and eco-friendly, solar-driven remediation technique that may be used in situ. Plants, for the most part, handle toxins without harming the topsoil and take pollutants from the environment. Costs of installation and upkeep are inexpensive. Planting vegetation on polluted soils also aids in the prevention of erosion and metal leaching.[20]

Purpose of phytoremediation

Phytoextraction of metals of market value, such as Ni, Tl, and Au; risk containment (phytostabilization). Long-term land management in which phytoextraction gradually improves soil quality in preparation for the cultivation of higher-value crops in the future. Plants that grow quickly and produce a lot of biomass, such as willow, poplar, and Jatropha, could be used for both phytoremediation and energy production.[21, 22]

Phytoextraction of heavy metals

The most common and effective phytoremediation method for removing heavy metals and metalloids from polluted soils, sediments, and water. Many factors influence efficiency, including heavy metal bioavailability in soil, soil characteristics, heavy metal speciation, and plant type. The following properties should be present in plants that are suitable for phytoextraction: High pace of growth, production of greater above-ground biomass, and a root system that is widely spread and highly branched. [23]

Phytoextraction:

Two crucial elements the two most crucial factors affecting a plant's potential for phytoextraction are shoot metal content and shoot biomass. Heavy metal phytoextraction has been tested using two alternative techniques.:[24] Hyperaccumulators are being used because they produce less aboveground biomass but more target heavy metals.[25] The use of alternative plants, such as Brassica juncea (Indian mustard), that produce more aboveground biomass and accumulate target heavy metals at a lower rate than hyperaccumulators, resulting in an overall accumulation that is comparable to hyperaccumulators.[26]

Bioavailability of Heavy Metals in soils

Metal mobility and bioavailability are influenced by the chemical composition and sorption characteristics of the soil. Low bioavailability is a major stumbling block to contaminant phytoextraction. Strong heavy metal binding to soil particles or precipitation renders a major portion of soil heavy metals insoluble, rendering them mostly inaccessible for plant absorption. Heavy metal/metalloids bioavailability in soil: The elements that are most readily accessible are Cd, Ni, Zn, As, Se, and Cu, whereas Co, Mn, and Fe are the least readily bioavailable (Pb, Cr, U). Conversely, plants have developed mechanisms for saturating soil with heavy metals. [27] Phyto siderophores are metal-mobilizing compounds secreted by plant roots in the rhizosphere. Roots can acidify the rhizosphere and promote metal solubility by secreting H+ ions. Heavy metal cations adsorbed on soil particles can be displaced by H+ ions. [28, 29]

Phytoextraction

Natural conditions: no soil amendment, two modes Different chelating agents such as EDTA (ethylene diamine tetra acetic acid), citric acid, elemental sulfur, and (NH4)2S04 are added to soil to increase the bioavailability of heavy metals in the soil for plant uptake (induced or chelate-assisted phytoextraction).[30] Because metal salts are soluble in acidic media rather than basic media, soil pH can be reduced to promote heavy metal bioavailability. Chemical treatments, on the other hand, can result in additional environmental issues. Citric acid, which has a natural origin and is easily biodegradable in soil, could be a promising chelating agent.[31]

Metallophytes

Plants known as "metallophytes" have evolved specifically to grow in soils high in heavy metals.

Metallophytes are divided into three categories:

1. Heavy metals from the ground are accumulated by metal excluders into their roots, but their movement and admission into their aerial parts are constrained. Such plants may be effective for phytostabilization but have a low potential for metal extraction.[32]
2. Metal indicators reflect heavy metal concentrations in the substrate by accumulating heavy metals in its aerial sections.[33]
3. Plants that can concentrate heavy metals in their above-ground tissues to levels significantly higher than those found in the soil or in non-accumulating plants are known as metal hyperaccumulators.[34]
4. The Brassicaceae plant family contains the majority of these species. It is a desirable concept to use them, especially in mining regions, either by themselves or in conjunction with microbes to perform phytoremediation on soils that have been poisoned with heavy metals.[35]

Hyperaccumulators

The one that is most frequently proposed. Hypothesis about the cause or. Metal has an advantage. Hyperaccumulation in plants is fundamentally opposed. Herbivores (by creating leaves) are herbivores. pathogens (unpalatable or toxic) Hyperaccumulators can be utilized for both phytoremediation and Phyto mining of poisonous and dangerous heavy metals (such as Au, Pd, and Pt).[36] Some plants have an inherent hyperaccumulation propensity for certain heavy metals. Plant hyperaccumulation. The following is a list of the concentration requirements for various metals and metalloids in dried leaves from plants that were growing in their natural environment.

Habitats are suggested.

•100 mg/kg for Cd, Se, and Tl.

•300 mg/kg for Co, Cu, and Cr.

•1000 mg/kg for Ni, Pb and As.

•3000 mg/kg for Zn.

•10000 mg/kg for Mn

Hyperaccumulators, on average, attain a 100-fold increase in shot. Metal concentration vs. crop (without yield reduction). Plants or non-accumulator plants in general Hyperaccumulators achieve a metal concentration from the shoot to the root. Greater than one ratio also known as the translocation factor, or TF.[37]

Quantification of phytoextraction efficiency

The accumulation factor (A) can alternatively be expressed in percent using the equation below: AF = Accumulation Factor, where A stands for accumulation factor. Metal content in plant tissue is expressed as percent C, while the metal concentration in soil is expressed as. Similarly, the translocation factor can be expressed in percent using the equation below.[38]

Accumulation factor (A) can also be represented in percent according to the following equation

$$\text{Accumulation factor } A = \frac{C\ plant\ tissue}{C\ soil} \times 100$$

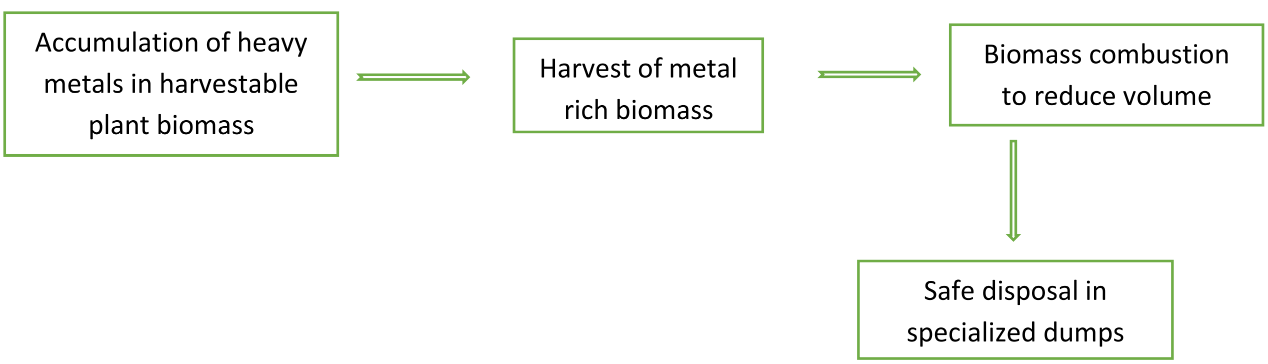
Where Ais accumulation factor %, $C_{\text{plant tissue}}$ is metal concentration in plant tissue and C_{Soil} is metal concentration in soil.

The following equation can be used to express the translocation factor in percent.

$$\text{Translocation factor } TF = \frac{C\ areal\ part}{C\ roots} \times 100$$

The fate of plants used for phytoextraction

Heavy metal accumulation in biomass from harvestable plants. To minimize the concentration, metal-rich biomass is harvested. Disposal in specialized dumps is safe. The most common method of phytoremediator plant post-harvest treatment Advantages of Phytomining Biomass combustion is a way of obtaining energy from biomass, with the residual ash being referred to as "bio-ore." Phyto-mining is the selling of energy generated by biomass combustion; -bio-ore can be processed to recover or extract heavy metals. Bio-ores are processed in a way that emits less SOX into the sky. Commercially, Phytomining has been used to extract Ni, and it is thought to be less expensive than traditional extraction procedures. [39]



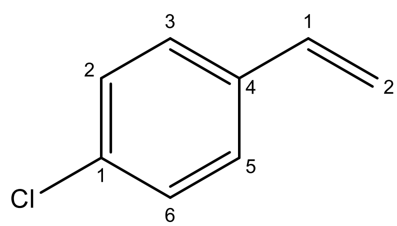
The main route of post-harvest treatment of phytoremediation plants.

Use of constructed wetlands for phytoremediation.

Effluents and drainage streams are cleaned in constructed wetlands. Aquatic macrophytes are better for wastewater treatment than terrestrial plants because they grow quicker, produce more biomass, and have a higher potential to absorb pollutants. On the margin, poplar and willow can be employed. Heavy metals have been removed from manmade wetlands using water hyacinth (Eichhornia crassipes). Water lettuce (Pistia stratiotes) has been identified as a potential Mn phytoremediator plant. Azolla (short doubling time 2—3 days) can fix nitrogen and is resistant to and accumulates a variety of heavy metals. Heavy metal absorption, translocation, and tolerance mechanisms, Heavy metals are absorbed by plants through their roots from the soil solution. Heavy metal ions can be stored in roots or translocated to shoots predominantly through xylem vessels, where they are mostly deposited in vacuoles after entering roots.[40] The mechanism of heavy metal phytoextraction involves five main aspects: heavy metal mobilization in soil, Plant roots absorbing metal ions, metal ion translocation from roots to aerial tissues, metal ion sequestration in plant tissues, and metal tolerance. Mechanisms that affect heavy metal tolerance in plant cells include cell wall binding, active transport of ions into the vacuole, chelation via activation of metal-binding peptides, and creation of metal complexes. Organic acids are acids that are made up of carbon atoms because their molecules contain donor atoms (S, N, and O), amino acids have been proposed as ligands for the chelation of heavy metal ions. [41]

Role of phytochelatins and metallothioneins in phytoextraction.

Phytochelatins (PCs) and metallothioneins are the most critical peptides/proteins involved in metal build-up and tolerance (MTS). Cysteine sulfhydryl groups in plant PCs and MTS adsorb and bind heavy metal ions in highly stable complexes. PCs are tiny glutathione-derived, enzyme-synthesized peptides that bind metals and are an important part of plants' metal detoxification system. They have a general structure of (c-glutamyl-cysteinyl) n -glycine, with NH2 from MTS. Low molecular weight metal-binding proteins that are gene-encoded can shield plants from the negative impacts of toxic metal ions. [6]



PCs

Limitations of phytoremediation

It will take a long time. The sluggish development rate and low biomass of hyperaccumulators are frequently limiting factors. The densely bound fraction of metal ions in soil has a low bioavailability. It can be used in locations that have low to moderate levels of metal pollution. Contamination of the food chain is a possibility. Heavy metal-contaminated soils must be cleaned up as soon as possible to reduce their influence on ecosystems. soil washing, soil flushing, solidification, excavation and landfilling, in situ vitrification, and stability of electrokinetic systems are examples of traditional remediation processes. High expenses, demanding labour, irreversible changes in soil parameters and disruption of natural soil microorganisms, secondary contamination, and so on are some of the disadvantages. It has the potential to be slower. The rate of biological processes is a constraint. -Accumulation in plant tissue is sluggish, for example, metals take an average of 15 years to clean up. - Plant-based filtering: quick (days) - Metabolic breakdown (organics): rather quick (less than a year)[6, 42, 43]

CONCLUSIONS

Physical and chemical approaches for cleaning and restoring heavy metal-contaminated soils have significant drawbacks, such as high costs, irreversible changes in soil properties, extinction of native soil microflora, and the emergence of secondary pollution issues. Phytoremediation on the other hand, is a solar-powered, environmentally friendly, and ecologically responsible technology that has widespread acceptability. Phytomining is a plant-based, environmentally friendly method of extracting QI metals. This method can be used to recover metals from low-grade ores. Heavy metal phytoextraction is predicted to become a commercially viable method for phytoremediation and heavy metal mining in the future. This approach works best when there is enough time available, the pollution is shallow enough, and the pollutant concentrations are not phytotoxic. For very large volumes of the mildly contaminated substrate, phytoremediation may be employed in conjunction with other remediation methods: phytoremediation is the only cost-effective choice. Root depth is limited. Prairie grasses > forbs, other grasses > trees 5 m is the maximum depth. With deep planting, the height can be grown to 20 meters.

Future trends in phytoremediation:

Phytoremediation is a relatively new study subject. Results in the field may differ from those obtained in the lab or in a greenhouse (different factors simultaneously play their role). Variations in temperature, nutrients, precipitation, and moisture can all affect phytoremediation in the field.

Recommendations

1. Researchers from different backgrounds should be welcomed and encouraged to use their talent and knowledge in this subject because phytoremediation research is really interdisciplinary.
2. Existing plant diversity should be explored for a hyperaccumulation of various heavy metals to find new effective metal hyperaccumulators.
3. Before using transgenic plants for phytoremediation in the field, thorough and trustworthy risk assessment studies should be carried out.
4. It is important to undertake more phytoremediation studies on the ground with unbiased cost-benefit analyses, keeping in mind how environmentally friendly the method is.
5. More studies should be conducted to better understand interactions among the four players in the rhizosphere that is among metals, soil, microbes, and plant roots.
6. The destiny of metal ions in plant tissues should be better understood, which would increase knowledge of metal hyperaccumulation and tolerance in plants. Advances in spectroscopic and chromatographic techniques should be taken advantage of.

Acknowledgement

Mr. Santhosh M Sosale, would like to acknowledge funding support from Special Cell for SC/ST, University of Mysore, Centenary Building Mysore 5700051.

Funding

This study has not received any external funding.

Conflicts of interests

The authors declare that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

REFERENCES AND NOTES

1. Vangronsveld, J., et al., Phytoremediation of contaminated soils and groundwater: lessons from the field. 2009. 16(7): p. 765-794.
2. Peters, E.C., et al., Ecotoxicology of tropical marine ecosystems. 1997. 16(1): p. 12-40.
3. Mulligan, C., R. Yong, and B.J.E.g. Gibbs, Remediation technologies for metal-contaminated soils and groundwater: an evaluation. 2001. 60(1-4): p. 193-207.
4. Garbisu, C. and I.J.B.t. Alkorta, Phytoextraction: a cost-effective plant-based technology for the removal of metals from the environment. 2001. 77(3): p. 229-236.
5. Favas, P.J., et al., Phytoremediation of soils contaminated with metals and metalloids at mining areas: potential of native flora. 2014. 3: p. 485-516.
6. Ali, H., E. Khan, and M.A.J.C. Sajad, Phytoremediation of heavy metals—concepts and applications. 2013. 91(7): p. 869-881.
7. Schwitzguébel, J.-P., et al., Phytoremediation: European and American trends successes, obstacles and needs. 2002. 2(2): p. 91-99.
8. Dhir, B., Phytoremediation: role of aquatic plants in environmental clean-up. Vol. 14. 2013: Springer.
9. Gardea-Torresdey, J., et al., Use of phytofiltration technologies in the removal of heavy metals: A review. 2004. 76(4): p. 801-813.
10. Wenzel, W.W.J.P. and Soil, Rhizosphere processes and management in plant-assisted bioremediation (phytoremediation) of soils. 2009. 321(1): p. 385-408.
11. McGrath, S.P. and F.-J.J.C.o.i.b. Zhao, Phytoextraction of metals and metalloids from contaminated soils. 2003. 14(3): p. 277-282.
12. Rai, P.K.J.C.R.i.E.S. and Technology, Heavy metal phytoremediation from aquatic ecosystems with special reference to macrophytes. 2009. 39(9): p. 697-753.
13. Moosavi, S.G., M.J.J.A.i.A. Seghatoleslami, and Biology, Phytoremediation: a review. 2013. 1(1): p. 5-11.
14. Vishnoi, S.R. and P. Srivastava. Phytoremediation–green for environmental clean. in Proceedings of Taal2007: the 12th World lake conference. 2007.
15. Yadav, R., et al., Perspectives for genetic engineering of poplars for enhanced phytoremediation abilities. 2010. 19(8): p. 1574-1588.
16. Cluis, C.J.B.J., Junk-greedy greens: phytoremediation as a new option for soil decontamination. 2004. 2(6): p. 1-67.

17. Limmer, M., J.J.E.s. Burken, and technology, Phytovolatilization of organic contaminants. 2016. 50(13): p. 6632-6643.
18. Sumiahadi, A. and R. Acar. A review of phytoremediation technology: heavy metals uptake by plants. in IOP conference series: earth and environmental science. 2018. IOP Publishing.
19. Lee, J.H.J.B. and B. Engineering, An overview of phytoremediation as a potentially promising technology for environmental pollution control. 2013. 18(3): p. 431-439.
20. Glick, B.R.J.B.a., Phytoremediation: synergistic use of plants and bacteria to clean up the environment. 2003. 21(5): p. 383-393.
21. Whiting, S., et al., Research priorities for conservation of metallophyte biodiversity and their potential for restoration and site remediation. 2004. 12(1): p. 106-116.
22. Witters, N., et al., Phytoremediation, a sustainable remediation technology? Conclusions from a case study. I: Energy production and carbon dioxide abatement. 2012. 39: p. 454-469.
23. Ashraf, S., et al., Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. 2019. 174: p. 714-727.
24. Shen, Z.G., et al., Lead phytoextraction from contaminated soil with high-biomass plant species. 2002. 31(6): p. 1893-1900.
25. Wu, G., et al., A critical review on the bio-removal of hazardous heavy metals from contaminated soils: issues, progress, eco-environmental concerns and opportunities. 2010. 174(1-3): p. 1-8.
26. Ghosh, M. and S.J.E.p. Singh, A comparative study of cadmium phytoextraction by accumulator and weed species. 2005. 133(2): p. 365-371.
27. Bolan, N., et al., Remediation of heavy metal (loid) s contaminated soils–to mobilize or to immobilize? 2014. 266: p. 141-166.
28. Violante, A., et al., Mobility and bioavailability of heavy metals and metalloids in soil environments. 2010. 10(3): p. 268-292.
29. Smith, S.R.J.E.i., A critical review of the bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. 2009. 35(1): p. 142-156.
30. Evangelou, M.W.H., Biochelators as an alternative to EDTA and other synthetic chelators for the phytoextraction of heavy metals (Cu, Cd, Pb) from soil. 2007, Aachen, Techn. Hochsch., Diss., 2007.
31. McLaughlin, M.J., et al., Soil testing for heavy metals. 2000. 31(11-14): p. 1661-1700.
32. Yadav, K.K., et al., Mechanistic understanding and holistic approach of phytoremediation: a review on application and future prospects. 2018. 120: p. 274-298.
33. Gisbert, C., et al., Tolerance and accumulation of heavy metals by Brassicaceae species grown in contaminated soils from Mediterranean regions of Spain. 2006. 56(1): p. 19-27.
34. Baker, A., et al., The possibility of in situ heavy metal decontamination of polluted soils using crops of metal-accumulating plants. 1994. 11(1-4): p. 41-49.
35. McGrath, S., J. Zhao, and E. Lombi, Phytoremediation of metals, metalloids, and radionuclides. 2002.
36. Boyd, R.S.J.P. and Soil, The defense hypothesis of elemental hyperaccumulation: status, challenges and new directions. 2007. 293(1): p. 153-176.
37. Chaney, R.L., et al., Improved understanding of hyperaccumulation yields commercial phytoextraction and phytomining technologies. 2007. 36(5): p. 1429-1443.
38. Li, Y., et al., Heavy metal pollution in vegetables grown in the vicinity of a multi-metal mining area in Gejiu, China: total concentrations, speciation analysis, and health risk. 2014. 21(21): p. 12569-12582.
39. Laidlaw, W., et al., Phytoextraction of heavy metals by willows growing in biosolids under field conditions. 2012. 41(1): p. 134-143.
40. Denny, P.J.W.S. and Technology, Implementation of constructed wetlands in developing countries. 1997. 35(5): p. 27-34.
41. Rascio, N. and F.J.P.s. Navari-Izzo, Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? 2011. 180(2): p. 169-181.
42. Lasat, M.J.J.o.H.S.R., Phytoextraction of metals from contaminated soil: a review of plant/soil/metal interaction and assessment of pertinent agronomic issues. 1999. 2(1): p. 5.
43. Gavrilescu, M., L.V. Pavel, and I.J.J.o.h.m. Cretescu, Characterization and remediation of soils contaminated with uranium. 2009. 163(2-3): p. 475-510.
44. Promise NU, Ukpaka CP, Puyate YT. Biokinetics of Crude Oil Remediation using Dogoyaro (Azadirachta indica) Stem. Indian Journal of Engineering, 2020, 17(47), 250-260
45. Pradnya R Ingle, Ramling S Saler. Bioremediation of Toxic Cr- VI from Effluent of Electroplating Industries by Immobilized Microbes. Discovery, 2021, 57(305), 416-421
46. Akpan EN, Edem, CA. Phytotoxicity assessment of the effects of unused and spent engine oil on the germination and seedling growth of Zea Mays L. Discovery, 2022, 58(316), 299-309
47. Wanjohi L, Mwamburi L, Mwasi S, Meso D, Isaboke J. Use of multistage phytoremediation technique in wastewater treatment. Discovery, 2022, 58(316), 252-263