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Phytoremediation Techniques for Heavy Metal Contaminated Soils: Advances and Challenges

Madhulika Krishan Yadav[1], Purva Rajendra Yeram[2], Mrunmayi Vijay Vartak [3], Sneha Arunkumar Dubey[4], Devesh Avinash Machhi[5], Pratik Uttam Gangavane[6]

[1]*HOD, Assistant Professor, Department of Botany, VIVA College of Arts Commerce and Science, Virar West*

[2]*M.Sc. Biotechnology, VIVA College of Arts Commerce and Science, Virar West*

[3]*M.Sc. Biotechnology, VIVA College of Arts Commerce and Science, Virar West*

[4]*M.Sc. Biotechnology, VIVA College of Arts Commerce and Science, Virar West*

[5]*Assistant Professor, Department of Biotechnologyy, VIVA College of Arts Commerce and Science, Virar West*

[6]*Programme Development Officer, VIVA College of Arts Commerce and Science, Virar West*

Abstract

Soil contamination with heavy metals, such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), presents severe ecological and health risks due to their persistence and bioaccumulation in the food chain. These contaminants can cause irreversible damage, including neurotoxic effects, renal injury, and cancer. Phytoremediation, an eco-friendly bioremediation technique, utilizes plants to uptake, immobilize, or detoxify heavy metals from contaminated soils. Methods such as phytoextraction, phytostabilization, and phytodegradation have shown potential in mitigating heavy metal pollution. This process offers a sustainable and efficient alternative to traditional remediation techniques like excavation and chemical treatments, providing environmental benefits and improving public health.

Keywords *Soil contamination, heavy metals, phytoremediation, phytoextraction, environmental remediation.,*

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I. Introduction

A. Introduction to Soil Contamination with Heavy Metals

Soil heavy metal contamination is now a prominent environmental issue for its rather adverse health impact on the ecosystem and human beings. Heavy metals pollution occurs from the point of industrial discharges, agricultural practices as well as mining and urban runoff (Alloway, 1995). For example, Metals like lead (Pb), cadmium (Cd), arsenic (As) mercury (Hg.) are the most detrimental since they are non-biodegradable and bioaccumulate in the food chain, thus posing a great risk for irreversible damage caused by neurotoxic effects, renal injury, cancers etc.;(Hodge & Channon, 2020). Because these contaminants are still persistent, proper remediation of these contaminations is vital not only for the restoration of healthy soil but also to safeguard public health.

B. Phytoremediation: remediation strategy

Phytoremediation is a novel and eco-friendly bioremediating technique that employs plants to uptake, immobilize or detoxify contaminants from the soil (Raskin et al., 1997). Phytoremediation is a bioremediation process that utilises the natural capacity of some plant species to uptake, translocate and accumulate heavy metals in aboveground tissues as source of nutrients, thus providing an environmentally benign alternative to classical remediation techniques like excavation or chemical treatment (Meharg & Hartley-Whitaker, 2002). Several good phytoremediation methods such as phytoextraction, phytostabilization, and phytodegradation have been constructed and improved in several soil types contaminated with heavy metals (Cunningham et al., 1996).

The Review – Why it Matters and What it Hopes to Achieve

This review focuses on recent progress and problems in metal contaminative soils phytoremediation wise. Through a review of recent advances in employed plant species, methodologies and research in the area of phytoremediation, this paper aims to highlight efficient ways of working with metal uptake and soil restoration. It will also cover the disadvantages and threats of phytoremediation which demands integrated methods with inclusion of biological and biomechanical processes for obtaining optimal remediation (Zhang et al., 2015). This will pave the way towards informed research and application to phytoremediation for future sustainability in soil decontamination.

II. Phytoremediation Mechanisms for Heavy Metals

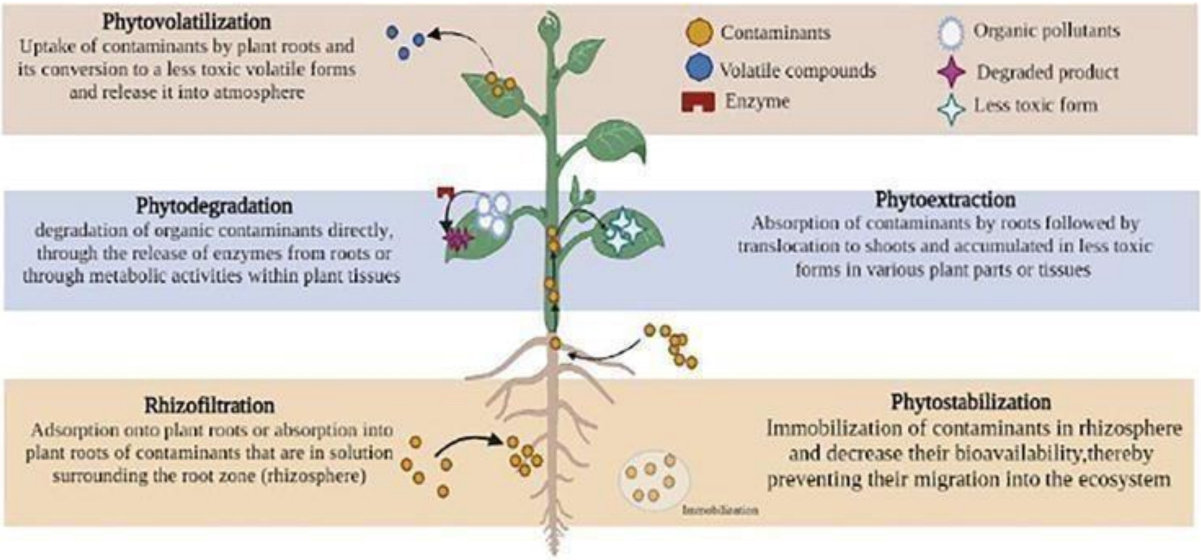


Fig 1: Diagram of Phytoremediation Mechanisms (Phytovolatilization, Rhizofiltration, etc.)

Different phytoremediation mechanisms are used to mitigate soil heavy metal pollution utilising specific plant potentials against environmental stresses. The major mechanisms are known as phytoextraction, phytostabilization, phytovolatilization and rhizofiltration. Knowledge of these processes is important for plant species selection and remediation efficiency.

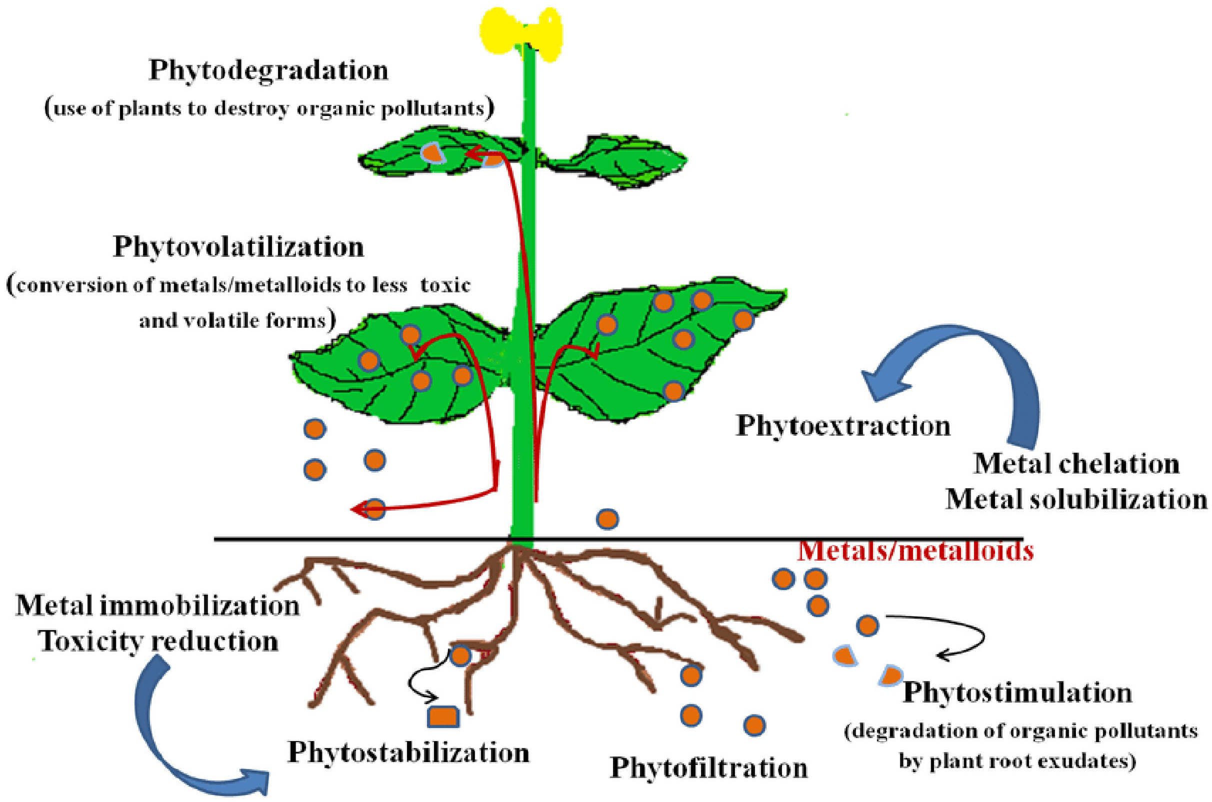


Fig 2: Overview of Phytoremediation Processes (Phytoextraction, Phytostabilization, Phytodegradation, etc.)

A. Phytoextraction

This phenomenon is known as phytoextraction, whereby the plants absorb heavy metals from the soil via their roots and then translocate them to shoots and leaves (Salt et al., 1998). Such a mechanism appears to work especially well for metals like lead, cadmium, and zinc. Some of the hyperaccumulator plants such as Thlaspi caerulescens and Alyssum murale can withstand high tissue concentrations of metals, thus facilitating a detoxification process to evolve (Baker et al., 2000). After the metals accumulate in their aboveground biomass, they can be harvested and either disposed of or recycled to ensure the metal contaminants are removed from the soil (Chaney et al. 1997). Various physicochemical constituents including the properties of the soil, metal bioavailability and plant physiology influence the efficiency of phytoextraction (Rascio & Navari-Izzo, 2011).

B. Phytostabilization

Phytostabilization is a process that uses plants to immobilize heavy metals within the soil system and translates metal reduction into decreased bioavailability by either reducing leaching potential through increasing ground solution retention (Kumar et al., 1995). This mechanism is especially relevant for stabilization of contaminated sites, because it reduces metal mobility and bioavailability. Plants improve soil structure and stimulate microbial activity, which also plays an important role in metal stabilization (secretion of root exudates promoting metal sorption on soil particles) (González-Mendoza et al., 2017). It includes the use of grasses and legumes species that can grow in polluted soils which helps to improve the physical or chemical properties of contaminated soil (Shaheen et al., 2021).

C. Phytovolatilization

Phytovolatilization refers to a mechanism where volatile heavy metals are absorbed by plants and transported into the atmosphere through transpiration (Liu et al. 2015). This mechanism is less common and it also exists in certain plant species, whereby heavy metal compounds are converted into a non-toxic/non-semi-volatile form prior to excretion. To elaborate, there are plants that can absorb mercury and allow it to become methylmercury before volatiling into the atmosphere (Baker & Raskin, 2003). Phytovolatilization is a process where higher plants uptake heavy metals and subsequently releases them in the gaseous state [4], but this method has limited application in that specific heavy metal species are needed, and certain specific plants are necessary to mediate such processes efficiently [2-4].

D. Rhizofiltration

Rhizofiltration (Vogel et al., 2008) is a type of phytoremediation that uses plant roots to absorb and concentrate heavy metals from water. It is particularly useful in the regeneration for water from metals such as arsenic, cadmium and lead. For optimum uptake this species is generally cultivated for rhizofiltration under hydroponic conditions, as rapid germination and direct contact with liquid growth media maximises uptake [55]. The contaminants are retained by the roots serving as biofilter, hence to separate them at harvesting step is easier (Shah et al., 2018). Speciality of rhizofiltration performance is species of plants, type of root and chemical nature of contaminant.

III. Recent Developments in Phytoremediation Methods

AbstractIn past years, there have been many developments in the area of phytoremediation due to increased human activity that resulted in higher concentrations of toxic metals heavy-contaminated soils [1]. The following section deals with milestone researches generalized as hyperaccumulators identification, genetic engineering methods, microbial-assisted efforts, chelate-assisted_phytoextractions method and novel phytomining and agromining strategies.

A. Hyperaccumulator Plants Identification And Characterization

Studies on hyperaccumulator plants which can be absolutely developed in heavy steel polluted areas are performed. Phytoremediation is the process of bringing down pollution using plants and these can absorb metals at extremely high concentrations, which makes them excellent candidates for this as well (Yoon et al., 2006). With the development of molecular techniques, including transcriptomics and proteomics, it has become posible to understand how metal uptake and tolerance works in hyperaccumulators such as Alyssum or Thlaspi species (Pilon-Smits et al., 2009) Moreover, recommended field trials and various agronomic practices have been laid down to yield plants that would exhibit enhanced growth and biomass for remediation (McGrath & Zhao, 2003).

B. Genetically Modified Plants to Improve Phytoremediation

Phytoremediation Potential of Specific Plant Species Can Be Enhanced with the Help of Genetic Engineering For example, through methods like transgenesis and gene editing (CRISPR/Cas9) plants can currently be modified for enhanced metal uptake, translocation, and tolerance respectively (Kumar et al., 2019). Such as overexpressing genes orchestrating metal transport or detoxification pathways to stimulate the capacity of plants for accumulating metals in tissues. Advancements have also been made in engineering plant species resistant to heavy metals such as arsenic and cadmium (Hussain et al., 2020) which indicate the biotechnological prospects of phytoremediation.

C. Phytoremediation with Microbial Assistance

Microbial-assisted phytoremediation (MAP) is a technique that combines the features of plants and soil microorganisms to improve microbial degradation and plant uptake of heavy metals (Glick et al., 2007). Certain soil bacteria possess the ability to promote plant growth via the synthesis of growth components while also improving metal bioavailability by secreting siderophores and organic acids (Pérez-de-Mora et al., 2015). However, recently studies have shown positive plant-microbe interactions related to metal uptake and detoxification mechanisms which need a systematic approach in phytoremediation methodologies (Singh et al., 2020).

D. Phytoremediation with the Help of Chelating Agents

In chelate-assisted phytoremediation, chelating agents are used to improve the bioavailability of heavy metals in soil so that plants can take them up (Huang et al., 2019). Chelators like EDTA (ethylenediaminetetraacetic acid) and citric acid bind metal ions to form resistant complexes that carry higher solubility units of heavy metals, causing their uptake through roots. Various significant chelators have been applied to several greenness species, and the acquisition in heavy metals has shown considerable potential in enhancing remediation capabilities (Chen et al., 2021). Nonetheless, the environmental consequences of using chelator should be closely considered to prevent any negative effects on soil and water environments.

E. Phytomining & Agromining Strategies

Phytomining and agromining are novel technologies that employ hy- peraccumulator plants in the production of valuable metals from polluted soils (van der Ent et al, 2013). Phytomining is an agricultural strategy for sustainable metal sourcing, where plants are grown on metal-contaminated substrates, harvested plant material accumulated in metals is recovered through metal recovery processes (Reeves & Baker 2000). Agromining, which is another form of phyto-extraction, aims to plant metal-accumulating plants in agricultural contexts to remediate soils while also producing biomass for bioenergy or other purposes (Baker et al. 2013). Furthermore, with additional economic benefits from the agroforesry practices some of these approaches bring, they depict how integrated resource management can mitigate soil contamination while bringing in more value.

IV. Determining the Efficiency of Phytoremediation

Multiple factors that affect the uptake as well as accumulation of heavy metals from contaminated soils by plants determine the phytoremediation efficiency. Therefore, the determination of these factors is essential to optimize the phytoremediation strategy and to achieve successful bioremediation. Some of them include soil type, plant types and climate factors and agriculture characteristics.

A. Soil Characteristics and Metal Availability

Soil characteristics play an important role because they govern the bioavailability of heavy metals as well as the efficiency of phytoremediation (Ghosh et al. 2016). Soil characteristics such as pH, organic matter and texture control the solubility and mobility of metals (McBride, 1994). This is because acidic soils increase metals solubility and in turn plant uptake of metals, unlike alkaline soils that can precipitate metals decreasing their bioavailability (Ranjbar et al., 2018). The fact that organic matter generally increases metal

binding and stabilization and modifies the ability of metals to be absorbed by plant roots (Huang et al., 2019). It is necessary to assess soil properties to select appropriate remediation strategies and plant species.

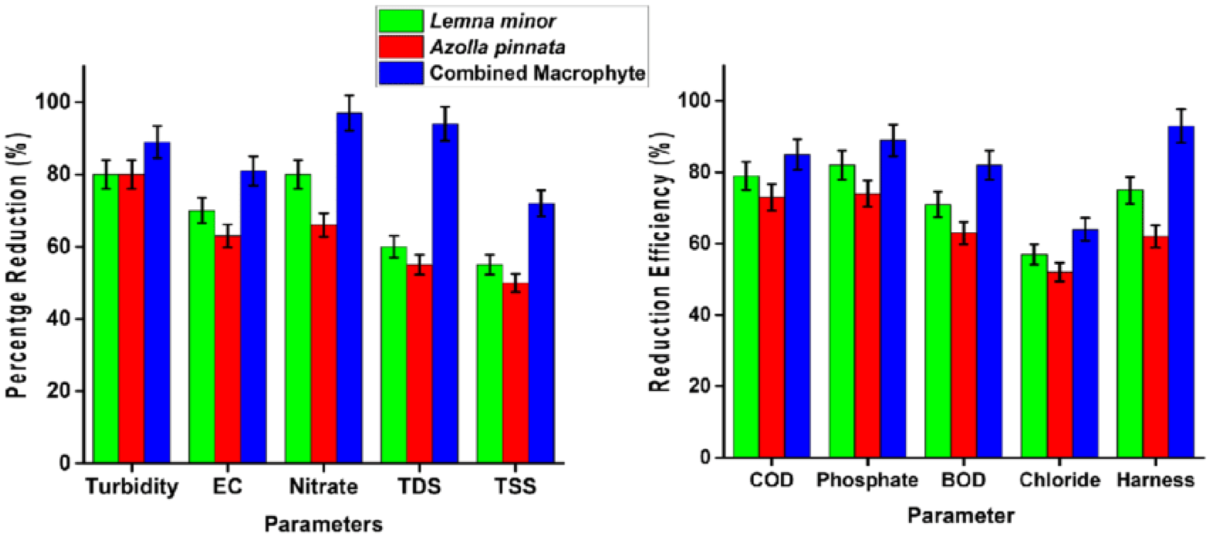


Fig 3: Percentage Reduction of Water Parameters by Macrophytes (Lemna minor, Azolla pinnata, and Combined Macrophytes)

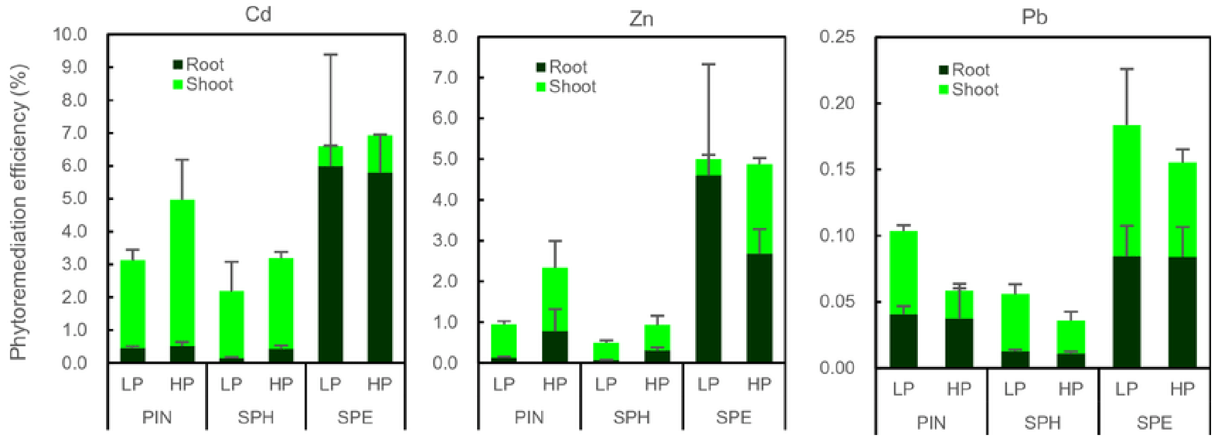
B. Choice and description of the plant species

A successful phytoremediation is based on the selection of suitable plant species. Different plant species differ in tolerance and accumulation of heavy metals due to diverse root structure, biomass production and physiological traits (Kumar et al., 2019). Plants known as hyperaccumulators, such as Helianthus annuus (sunflower), and Brassica juncea (Indian mustard) have developed specific mechanisms for improved metal uptake from soil compartments, which are far more efficient overall (Baker et al., 2000). In addition, growth rate, biomass yield and rooting depth are key characteristics that greatly affect the efficiency of phytoremediation (Ghosh & Singh, 2005). Thus, selecting the right plant species in any given site will favor better metal accumulation and remediation outcomes (Ouzounidou et al., 2018; Wambuguh et al., 2022).

C. Climatic Elements and Environmental Conditions

The success of phytoremediation is strongly influenced by environmental conditions such as climate, precipitation and light availability. Although specific temperature ranges can mitigate or enhance plant development and metal absorption, extremes, high, or low lead to physiological strain on the plants (Rascio & Navari-Izzo, 2011).

Further, moisture availability affects plant physiological processes such as transpiration and nutrient uptake that are crucial for metal accumulation (Zhao et al., 2010). In addition, light could have an impact on the determination of photosynthesis then overall plant health and indirectly performance of phytoremediation. So knowledge of local climate conditions is critical for effective design and implementation of phytoremediation solutions.



E. Research and development of agronomic practices and management strategies

Combination of effective agronomic practices and management strategies can help improve the efficiency of phytoremediation. The amendment of soil with organic matter and/or fertilization can improve both structure and nutrient availability in soils, thus improving plant growth as well as metal uptake (Kumar et al., 2019). Alternatively, crop rotation and intercropping are JPA advances that may enhance the biodiversity, soil quality and thus the stability of a phytoremediation system (Mena et al., 2019). The phytoremediation site must be assessed frequently, and instrumentation to measure plant metal concentrations may be needed to ensure successful remediation. There are several best management practices that could also increase the overall efficiency of phytoremediation.

Fewer biomass production of hyperaccumulator plants is one of the most serious limiting factor on phytoremediation [11]. Although these plants are able to take in and store heavy metals, they only have a small biomass yield so the fraction of metals that can be cleansed from polluted soils remains low (Ali et al., 2013). This is due to several reasons such as sluggish growth rates, poor soil conditions, and lack of nourishment. Consequently, a large number of plants may need to be planted in order for meaningful remediation results to occur, which is unrealistic at larger scales (Yoon et al., 2006).

V. Limitations in Heavy Metal Phytoremediation

Phytoremediation seems a sustainable remediation strategy, but it contains many obstacles that limit its performance for heavy metal-contaminated soil management. We summarize the principal challenges such as low biomass yields, time to remediate, shallow rooting systems and potential food chain contamination and contaminated plant waste disposal.

A. Small Scale Production of Biomass by Hyperaccumulators

However, phydoremediation still has some major limitations regarding slow biomass production of hyperaccumulator plants. Although these plants have ability to uptake and accumulate heavy metals, their biomass yield is often too low to remove the total amount of metals from contaminated soils (Ali et al., 2013). Several reasons could be behind this restriction, like stagnant growth rates, lack of soil conditions and nutrient deficiencies. Consequently, it may be necessary to use large numbers of plants if appreciable remediation is to take place so that these herbaceous techniques are infeasible for large areas (Yoon et al., **2006).**

B. Extended Timeframes for Remediation

One limitation of phytoremediation is the lengthy remedial times that often are needed to achieve desired results. It may take many growing seasons to years until a significant reduction in metal concentrations can be achieved, depending on the degree of contamination and plant species (McGrath & Zhao 2003). The long timeframe from application to activation is a potential disadvantage, particularly in urgent remediation situations where the need for rapid decontamination is necessary. In turn, long time periods of remediation process by the phytoremediation species may cause a postponement of site recycling or agricultural utilisation and reflect an expensive economic burden (Kumar et al. 2019)

C. Root Depth is Restricted and Contaminants are Accessible

Phytoremediation also depends on the root depth of the plant species chosen. The effectiveness of unionized root systems lowers for many hyperaccumulators, since this cannot reach heavy metals in deeper layers of soil because they have shallow roots (Zhao et al., 2010). Such limited root penetration may be especially detrimental when contaminants are not homogeneously distributed in the soil profile as it causes a non-uniform uptake of metals and an incomplete remediation (Rascio & Navari-Izzo, 2011). To overcome this limitation, (i.e., contaminants and/or pollutants are not easily accessible), one could use deep-rooted plant species or other remediation approaches to facilitate the accessibility of contaminant.

D. Issue with Contaminating Food Chains

The other major issue related to phytoremediation is food chain contamination (WWC). However, if herbivores or humans consume hyperaccumulator plants, the metals can enter into the food chain (Meharg et al., 2009). In agricultural scene this bio-accumulation can cause severe health hazards as the contaminated plants may be harvested and consumed inadvertently (Shahid et al., 2017). This means that monitoring of the metal concentrations in plant tissues and standards for safe recycling through phytoremediation crops are necessary to address this risk.

E. Contaminated plant biomasses destruction

As the major drawback of phytoremediation, disposing plant biomass contaminate is a challenge. However, heavy metals will be firmly bound in the plant biomass, which has to be properly disposed of further down stream to make sure that no contaminants entered back into the environment (Hussain et al., 2020). Your disposal options are to incinerate, landfill or further process it for metal recovery – each with its own environmental costs and implications. Moreover, it is still formidable to dispose contaminated biomass under safe and sustainable way without taking considerable risk to the environment (Vangronsveld et al., 2009).

VI. New Techs & Looking Ahead

Phytoremediation is in an expanding area, the technologies and strategies here are emerged to develop this truly sustainable high performance remediation technology. This section discusses the advancements such as screening of integrated phytoremediation with other technologies for remediation option, nano scale materials; biosystems biology approaches, environmental biotechnology and gene editing techniques.

A. Compatability with Other Remediation Technologies

Those new emerging guidelines focus on combining phytoremediation with other remediation technologies which could have synergies. As an example, phytoremediation can remove organics along with heavy metals when used in conjunction with bioremediation (Kumar et al., 2019). Phytoremediation can also be coupled with other technologies such as soil washing, electrokinetic remediation or thermal treatment to increase metal bioavailability or reduce contaminant concentration in soil (Zhao et al. 2010). This composure allows for a more comprehensive corrective approach that can address multiple pollutants while also providing site-specific standards to help facilitate a speedy and effective cleanup solution.

B. Phytoremediation assisted by Narromaterial

The use of nanomaterials on phytoremediation is a new perspective which appears to be the next generation with potential for soil metal absorption and detoxification. For this purpose, various nanoparticles like metal oxides, carbon-based materials and nanosilica can be used which may either apply on the contaminated soil or feed them in the plant system to promote metal solubility that ensures its uptake (Khan et al., 2018). Nano fertilizer have been shown to accelerate growth of the plant, increase root contact area, and augment heavy metal bioavailability which leads to higher phytoremediation efficacy (Deng et al., 2020). However, the risk and environmental impacts of nanomaterials should also be included in the apples-to-apples comparison that expresses both sides of the trade-off.

C. Other methods from the frontlines of biotechnology and genomics

The most recent developments in biotechnological methods like the CRISPR / Cas9 gene editing procedures provides a very powerful tool to enhance plant phytoremediation potential. With these techniques, researchers allow precise construction of plant genomes with modified traits for metal tolerance and accumulation (Hussain et al., 2020). Contamination of soils and plants with heavy metals can be reduced by restructuring the metabolic pathways, targeting few genes involved in metal transport, and detoxification pathways on those associated with chemical distortion (Baker et al., 2013). Furthermore, the synthetic biology approaches can be used to generate plant novel traits tailored for their optimal phytoremediation that may yield further major advances in this area.

F. Phytoremediation Modelling and Prediction Tools

AbstractWhile a number of predictive and modeling tools have been developed for phytoremediation, these approaches are still emerging at the field scale and enhanced development of such tools is warranted as they are increasingly recognised to be required for optimisation of remediation and prediction. They are capable of simulating the complex interaction between phytoremediator plant, contaminant and environmental conditions, allowing insights in phytoremediation efficiency under varying parameter values (Garcia et al., 2017). On the other hand, for instance process-based models predict potential metal uptake rates directly from some soil properties, plant physiology characteristics and climatic conditions thus helping researchers and practitioners to consider proper choices of plants and adequate management practices (Kumar et al., 2020). In addition, machine learning and artificial intelligence (AI) techniques are investigated for their possibilities in analysing extensive data sets to find patterns as well as increasing the accuracy of predictions regarding phytoremediation efficacy (Miller et al., 2021; Rodrigues GdF et al., 2021). Combining predictive modeling to determine site-specific potentials with experimental data can refine the future planning and implementation of phytoremediation by stakeholders.

E. Design and optimization of phytoremediation systems

Phytoremediation is a suitable technique and due to its setting up and optimization, are critical factors for achieving success in remediation. Other components of a reliable design include the selection of plant species, soil amendments for increasing nutrient and moisture contents in contaminated media, irrigation strategies, and arrangement of the remediation plant (Zhang et al. 2016). Recently developed systems are aimed at enhancing metal uptake and ecosystem tolerance with a wide range of benefits through (new) types of plant species, capable of addressing the limitations outlined above (Zhao et al., 2018). Along similar lines, hydroponics or aquaponics may be applied to provide more controlled growth conditions in order to optimize the uptake of contaminants and plant growth (Hassan et al., 2020). This strategy requires real-time monitoring and adaptive management that must be carried out based on performance data and variation of biotic (e.g., dominant species) and abiotic factors peculiar to the environment [88]. An integrated design framework of this nature may be a promising way forward for enhancing the effectiveness of phytoremediation.

VII. Use Cases: Applications in The Field

Phytoremediation under field circumstances has offered an practical expertise of actual capacity along side the dangers of such method. Topics in this section include large-scale examples of successful implementation, lessons learned and phytoremediation economics.

A. Realeffective Examples Of Phytoremediation

We can refer to dozens of examples around the world of successful phytoremediation where plants have decontaminated heavy metals polluted sites. Brassica juncea (L.) Czern (Indian mustard) has been shown to tolerate lead- and cadmium-contaminated soils in sites ranging from urban gardens to industrial settings, and is an effective phyto-remediator of these metals (Kumar et al., 2019). The second one is the most familiar Helianthus annuus (sunflower), which has been utilized for in place lead polluted soils in USA, where the metal content was decreased significantly after a few cropping seasons (Ravindran et al., 2016). They are among the best ammunition in the case studies for how certain plant species prove to be effective capabilities at taking up heavy metals and healing soil.

B. Lessons from Big Project Experience

During the past decades, a number of large-scale tree-based phytoremediation programs have developed which are contributing important lessons for the future. The highest level takeaway has been to prioritize immediate site characterization and an understanding of the related local environmental logistical considerations ahead of project implementations. For example, in Italy, mixed soil salinity and nutrient deficiencies resulted from a projectfocused on remediating a chromium-contaminated site and impaired plant growth,potentially inhibiting metal uptake (Morrison et al., 2020). It underlines the need for comprehensive site specific site investigations to create remediation based on local ecology. However beyond this, combining other disciplines such as ecologist, soil scientist and agricultural expert has also contributed to the outgoing success of phytoremediation practices with establishment of sustainability of remediation over time (Ghosh et al.

C: Cost-Benefit, Economic Feasibility

Economic feasibility is the mostcontributing parameters for utilization and implementation of phytoremediation as a remediation approach. Although more cost-effective than traditional methods like excavation and landfilling, its feasibility should be evaluated through an integrated approach of cost-benefit analysis (Ali et al., 2013). Phytoremediation expenses can include the costs of planting, tending/monitoring plants and, if necessary, hazardous waste disposal. However, the estimates should also reflect the gains like soil restoration, enhancement of biodiversity and ecosystem (Kumar et al., 2019). The results of specific case studies suggest that phytoremediation may facilitate considerable cost savings and ongoing benefits when present at the site in future relied on as a remedial option by stakeholders (clients and managers).

VIII. Environmental and Ecological Issues

Phytoremediation is a more sustainable approach but brings with it some environmental and ecological challenges. It takes on the consequences for soil ecosystems and biodiversity, risk of introducing invasive species, and the long-term impact on soil quality and fertility.

A. Effect on soil ecosystems and biodiversity

Soil ecosystem and biodiversity can be positively or negatively affected by phytoremediation. On one hand, hyperaccumulator plants increased biodiversity by providing habitats for other organisms, such as beneficial soil microbes and insects (Nedunchezhiyan et al., 2017). Such plants can help restore the ecosystem by creating a soil structure, organic matter content, and nutrient cycling. In contrast, the all-dominating plant species in a certain phytoremediation may destroy originally established plants communities and therefore reduce biodiversity–especially when these plants outcompete autotrophically mixed flora (Vangronsveld et al., 2009). Thus, the selection of plant species and local ecological considerations are essential to mitigate biodiversity loss.

B. Introduction of Invasive Species

Plant Introductions: Hyperaccumulator plants are emerging for phytoremediation but their introduction into native ecosystems may lead to new invasive species. An inappropriate choice could be invasive hyperaccumulators competing with local vegetation and changing ecosystem dynamics if they are not carefully selected in accordance to their ecological behaviour (González et al., 2020). More specifically some metal-accumulating species from Euphorbia and Alyssum have been shown to be invasive in certain areas. To minimize this risk, non-indigenous species should be used in phyto-extraction only after proper ecological risk analysis and native or well-adapted species should normally take precedence [20].

C. Soil Quality and Fertility- Perpetual Impacts

Soil quality and fertility are an important aspect of sustainability of land use system in the long-run which need attention, especially considering the fallacy that phytoremediation is not affecting soil quality. Although the phytoremediation process may decrease metal levels in contaminated soils, it does not necessarily ensure soil restoration (Rascio & Navari-Izzo, 2011). It requires longer-term monitoring of any shifts in soil physicochemical properties, microbial communities, and nutrient dynamics. For instance, the drama remains one of humus-prone from dying plant parts can increase soil fertility, or on the other hand taking too many metals up can cause soil degradation (Huang et al., 2019). This way, continuous investigations along with field

IX. Regulatory and Policy Implications

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Understanding the policy and regulatory framework is crucial to ensuring that phytoremediation can be implemented successfully as a viable tool for remediating heavy metal contamination. Keywords Current regulations and guidelines Conclusion Introduction Phytoremediation is a versatile bioremediation technique that utilizes plants to remediate contaminated soil or water, specifically targeting the pollution associated with organic solvents and heavy metals.

A. Existing regulations and guidelines

Currently, regulations and guidelines addressing phytoremediation vary by region and are largely based on domestic environmental policies and International Treaties. Existing regulatory frameworks for contaminated sites in many countries are generally the foundation of requirements for risk assessments, remediation goals and monitoring protocols (EPA 2020). For instance, the phytoremediation potential is incorporated in U.S. Environmental Protection Agency (U.S. EPA) guidelines for selecting remediation technologies as part of CERCLA [11]). Similarly, the Soil Framework Directive in Europe strengthens soil management and remediation strategies (including phytoremediation) as part of broader environmental protection goals (European Commission 2014). While regulations on the subfield of phytoremediation would allow for more widespread application and acceptance, they are currently nonexistent.

B. Challenges in Standardisation and Implementation

Histories: Preface: The absence of widely accepted guidelines and acceptance criteria for phytoremediation in different jurisdictions is one of the major barriers to its implementation. The challenge is exacerbated by divergent regulation from region to region causing confusion and uncertainty for practitioners, stakeholders and investors alike (McCarthy et al., 2019). Additionally, it has been found difficult to create uniform performance criteria due to the diversity of phytoremediation technologies and its biological characteristics leading not only to hindrance in effectiveness proving but also regulatory approvals (Pilon-Smits et al., 2009). Phytoremediation way too is thought of as less reliable and/or slower than conventional remediation technologies that could reduce acceptance, either among decision-makers or landowners. The need to overcome these hurdles will require coordinated efforts to develop standardized procedures and benchmarks that can facilitate the integration of phytoremediation into existing regulatory frameworks.

C. Policy Directions to Enable Phytoremediation in the Future

Policy directions for the future should focus on the provision of appropriate regulations, development incentives as well as awareness and education initiatives to enable broader adoption of phytoremediation as a remediation technology. It will also assist policymakers in reflecting phytoremediation advantages in national and regional environmental policies by providing a specific guidance on phytotechnologies that could be used (Zhang et al., 2016; Zhang et al., 2017). Grants or tax breaks for projects that employ this phytoremediation method may spur landowners and businesses to incorporate it into their plans. Furthermore, increasing the public awareness about both ecological and economic benefits of phytoremediation can also contribute to better acceptance لهز implementation [3]. Spanning both academic and industry background, partnerships at government level may likewise assist the incentives of knowledge transfer and new applications to facilitate broader buy-in surrounding phytoremediation projects.

X. Conclusion

A: Overview of the Work Done and Questions Left Open

Phytoremediation is a sustainable and effective remedial technology for plant uptake to extract, stabilize or detoxify heavy metal from soils. Phytoremediation has reached high efficiency and practical application level due to rapid progress in molecular genetic bases, understanding of the mechanisms specified for heavy metal tolerant and accumulating traits, hyperaccumulator species development, genetic engineering, microbial assisted phytoremediation and elements delivery system including nanomaterials (Shahvazi et al., 2020). However, there are some challenges with such an approach: limited biomass production of hyperaccumulators, the time-consuming remediation process (which may take decades), low depth of root for access to one or mix of contaminants and food chain contamination risk. In addition, logistical and environmental problems with disposal of the biomass of contaminated plant materials must be addressed.

B. Perspectives on Phytoremediation of Soils Contaminated with Heavy Metals

In the next future, phytoremediation has great opportunities to be applied in a larger range of contaminated sites. Phytoremediation holds a crucial position in the path towards achieving environmental remediation goals as more advanced, and pragmatic regulatory frameworks come into play to accommodate for sustainable remediation practices. The effectiveness and applicability of phytoremediation will be further improved by the integration of phytoremediation with other remediation technologies, mainly in reference to other biological treatment systems, continuous advancement on predictive modeling and system optimization. Additionally, the promotion of awareness and policy support for phytoremediation will be important in aiding its selection as a viable mechanism to reduce heavy metal contamination.

C. Research Needs and Priorities

We conclude by identifying the remaining challenges to implementing phytoremediation and suggesting research aimed at unlocking its full potential as an effective technology. It highlights priorities for future research, notably on the identification and functional characterization of novel hyperaccumulator species, standardized protocols and performance indicators as well as emerging technologies including gene editing and nanomaterials. Needless to say, long-term studies on the ecological effects and sustainability of phytoremediation practices are necessary to support policy decisions and future implementations. These research needs can guide stakeholders to promote phytoremediation as an integral part of sustainable soil management and environmental restoration.

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