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Phytoremediation Potential of Indigenous Plant Species

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Abstract

Industrialization, intensive farming, and inappropriate disposal of waste materials have caused environmental contamination with the accumulation of heavy metals and other toxic pollutants in the soil and water systems that have brought severe ecological and health implications to the environment and humanity. The concept of phytoremediation has become a viable method of remedial process, which is sustainable, economical, and environmentally friendly and which involves the use of plants to eliminate, stabilize, or decompose any contaminants. This paper focuses on the phytoremediation possibility of native plants species which focus on their flexibility, ecological compatibility, and ability to mitigate pollutants.

The study is aimed at discovering the native plant species that can accumulate or trap the pollutants like lead, cadmium, chromium, arsenic and petroleum-based hydrocarbons. Native species are especially beneficial because they are innately adapted to the local climatic conditions, they are immune to pests and they have well developed root systems which create more stability on the soil. The field observations and controlled experimental studies were evaluated to determine the performance of the plants in terms of growth, bioaccumulation, translocation and tolerance of stress under contaminated conditions.

The results show that some native plant species are characterized by a high level of metal uptake and stabilization capacity and can be used as the potential candidates in phytoextraction and phytostabilization. Another factor that the study brings out is the importance of rhizosphere interactions such as microbial activity and root exudates in increasing the availability and uptake of contaminants. Phytoremediation with native vegetation has lower costs of implementation, minimum ecological impact and sustainability as compared to conventional forms of remediation.

Yet, such constraints as the slowness of remediation, the problem of biomass disposal, and site-specific efficiency are also addressed. The paper emphasizes that phytoremediation must be incorporated with other methods, such as soil supplements and the inoculation of soil with microbes, to enhance the process.

To sum up, native species of plants have immense potential in terms of restoring the environment in a sustainable manner. Their use does not only aid in recovery of the eco system but also in conservation efforts and therefore phytoremediation is a practical remedy to the management of contaminated sites in various ecological environments.

Keywords: Phytoremediation, Indigenous plant species, Heavy metal contamination, Soil remediation,

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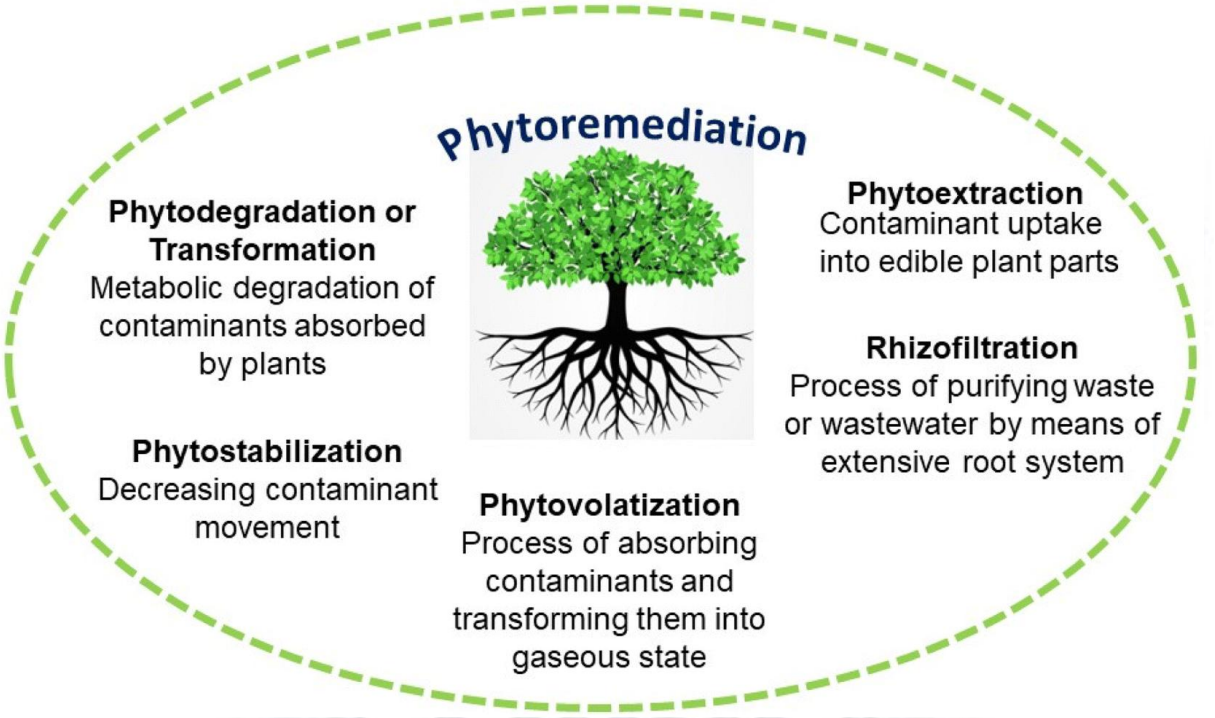
Phytoextraction, Phytostabilization, Environmental sustainability, Rhizosphere interactions

Introduction

The rapid industrialization, urbanization, mining, and intensive agriculture that lead to environmental pollution has become an issue of critical concern in the world. Pollution of soil and water with heavy metals, pesticides, hydrocarbons, and other toxic substances have not only threat to ecosystems, food security and human health but are also a serious threat. Traditional remediation methods like excavation, treatment and thermal methods are usually expensive, energy-consuming, and environmentally disruptive. In this regard, the need to find the sustainable, cost-efficient, as well as the environment-friendly remediation options has become even more significant.

Phytoremediation has become one of the most promising technologies of green technology which uses plants to remove, stabilize, degrade or convert the contaminants in the soil and water. The philosophy behind this is the use of natural biological mechanisms like phytoextraction, phytostabilization, phytodegradation and rhizofiltration. Phytoremediation has benefits such as low cost of operation, less environmental disturbance, beautification of the degraded environments and environmental restoration over the long term, which are better than the conventional methods of remediation.



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The role of native plant species in phytoremediation is that of special importance because of being native to the local climate, edaphic, and ecological conditions. Such plants tend to have increased survival, environmental tolerance and effective interactions with the native microbial communities which can increase the uptake and degradation of contaminants. Further, the utilization of native species decreases the chances of intrusive action and contributes to the preservation of the biodiversity and tackles the issue of pollution.

Although there is an increasing level of interest in phyto remediation, the potential of numerous native plants species is still underutilized, in particular in developing areas, where pollution rates are escalating and resources to support the use of advanced remedial technologies are scarce. The mechanisms, efficiency, and limitations of the use of indigenous plants in the remediation of contaminants have to be understood to be able to come up with some region-

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specific, sustainable environmental management strategies.

The current research paper discusses phytoremediation potential of native plant species under the context of their ability to endure and clean the polluted environment. The research will attempt to bring to the fore the ecological significance and practical uses of native plants in the sustainable pollution mitigation programs by synthesizing available scientific evidence.

Background of the study

Industrialization, urbanization, intensive farming as well as incorrect disposal of waste materials has been a major issue of concern to the world today. Heavy metals, metalloids, hydrocarbons, pesticides, and other toxic substances contaminated soil and water are very dangerous to the ecosystem, food security and human health. Traditional remediation technologies include excavation, chemical treatment, and thermal treatment that are costly, energy-demanding and destructive to the natural environments and are therefore not suitable in large scale or long term use, particularly in developing areas. In this regard, phytoremediation has come into the scene as an environmental friendly, cost effective and sustainable alternative to environmental cleanup. The term phytoremediation is used to describe the utilization of plants and related microorganisms in the removal, stabilization, degradation, or detoxification of pollutants in contaminated soil, water, and sediments. The green technology utilizes natural biological processes that include phytoextraction, phytostabilization, phytotransformation, rhizofiltration, and phytovolatilization, thus reducing negative impacts on the environment and rehabilitating the level of environmental quality. Along with phytoindication studies, native plant species are receiving more and more attention in phytoremediation studies since they inherently adapt to local climatic, edaphic, and ecological conditions. As compared to exotic or genetically modified plants, indigenous plants have a higher survival rate, lesser maintenance needs, and resistance to local stresses. The fact that they coexist with indigenous communities of soil microbes in the long term also boosts their remediation capacity due to synergistic interactions between the plant and the microbes. Additionally, the ecological risks of invasiveness and loss of biodiversity are minimized to make phytoremediation activities more sustainable and acceptable to the community and ecosystem by use of indigenous species. The potentials of using the phytoremediation properties of most of the native plant species are still underutilised despite the identified benefits. There is a lack of empirical data on their uptake capacity of pollutants, tolerance, biomass production, efficiency in a particular site. These attributes are important in understanding the selection of suitable species in the remediation programs as well as coming up with location-specific strategies to deal with contaminated environments. Hence, the paper aims at evaluating the phytoremediation capacity of the chosen native plant species with particular attention to their capacity to clean up the polluted soils and water sources. The research will make a contribution to the sustainable practice of environmental management by assessing their efficiency in removing pollutants and their adaptive qualities and encourage the use of nature-based solutions that can control pollution.

Justification

Industrialization, urbanization, intensive farming as well as incorrect disposal of waste materials has been a major issue of concern to the world today. Heavy metals, metalloids, hydrocarbons, pesticides, and other toxic substances contaminated soil and water are very dangerous to the ecosystem, food security and human health. Traditional remediation technologies include excavation, chemical treatment, and thermal treatment that are costly, energy-demanding and destructive to the natural environments and are therefore not suitable in large scale or long term use, particularly in developing areas. In this regard, phytoremediation has come into the scene as an environmental friendly, cost effective and sustainable alternative to environmental cleanup. The term phytoremediation is used to describe the utilization of plants and related microorganisms in the removal, stabilization, degradation, or detoxification of pollutants in

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Objectives of the Study

1. To understand the appropriate species of indigenous plants that can endure and thrive in the soil and water pollution conditions.
2. To determine the ability of the chosen indigenous plants to absorb, accumulate or stabilize pollutants, especially the heavy metals and other prevalent environmental pollutants.
3. To determine the effectiveness of the various phytoremediation processes including phytoextraction, phytostabilization, and rhizofiltration via native plant species.
4. To examine how the soil and other environmental factors affect the remediation behavior of indigenous plants.
5. To compare the efficiency of various indigenous species in pollutant removal in order to establish the most efficient species to be used in remediation process.

Literature Review

The application of plants as an alternative method of soil and water remediation has become cost-effective and ecologically sustainable in the form of phytoremediation, which is the removal, stabilization, or degradation of contaminants in the environment by plants (Bawankar, 2024). Much research has been conducted on how indigenous plant species, naturally adapted to the local stress factors, is able to withstand and accumulate toxic substances, specifically on the mining regions, industrial landscape, and waste dumping locations. The consecutive empirical studies indicate that naturally occurring plants are able to selectively accumulate heavy metals and metalloids in polluted environments, which can be used in the phytoextraction and phytostabilization approaches. To illustrate this, field surveys in Vietnamese mining areas established that native species including Pteris vittata and Pityrogramma calomelanos hyperaccumulated arsenic, and grasses and sedges, including Eleusine indica and Cyperus rotundus, had a high retention of lead and zinc in roots implying different functional roles in remediation (Nguyen et al., 2011). In a similar fashion, research in the Baoshan mining area in China has found both Pteris ensiformis and Boehmeria nivea to be promising phytoextractors

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of arsenic and cadmium, respectively, and observed the need to weigh both bioaccumulation parameters and translocation potential in candidate species when choosing species to be used in remediation (Zhu et al., 2019). In addition to hyperaccumulators, studies in West Bengal, India showed that native terrestrial and aquatic plants including Phyllanthus amarus, Cynodon dactylon, Eichhornia crassipes, and Marsilea quadrifolia have a bioaccumulation factor of more than one, which implies that they can be utilized practically in the cleanup of arsenic in soil and water (Singh et al., 2022). These results underscore the reality that native species that have acclimated to polluted locations tend to exhibit superior uptake and tolerance systems that render them better than exotic species, which could cause an upset in the local ecology should they be introduced (Azizi et al., 2023). The wider ecological role of the native herbaceous plants in the wetland and soil systems polluted with heavy metals has also been highlighted in several reviews and it is argued that since indigenous and ecologically compatible plants inherently have a lower impact on the environment, they have a greater restoration potential (Garcia-Muñoz and Lopez-Leiva, 2016). Likewise, analyzing the remediation effects of a broad range of local genera has been suggested to be beneficial to phytoremediation, e.g., Cyperus, Nephrolepis, and Syagrus, due to their remediation of organic and inorganic pollutants in a combined effect (de Toledo et al., 2023). Investigations of the relationship between various remediation mechanisms have shown that remediation mechanisms display functional diversity by comparing similar indigenous species. Some species are phytoextraction giants, which attract contaminants into above-ground biomass that can be harvested, whereas others are phytostabilization specialists, keeping toxic elements within root systems, where they are less likely to leach and move into the ecological environment (Liang et al., 2021). This distinction was supported with field tests on Ghanaian gold mine tailings, with dozens of native species having different abilities to take up arsenic, mercury, lead, and copper, which means that the selection of species to be used during remediation requires tailoring to the profile of pollutants and remediation ambitions (Addo et al., 2019). Recent innovations also take into account synergistic strategies, e.g. introducing biochar into the soil, to improve the performance of native vegetation in metal-contaminated soils by reducing the bioavailability and toxicity of metals, and further increasing phytoremediation effects (Rahim et al., 2025). On the whole, the science provides evidence of the increased awareness of the use of indigenous plant species as an effective phytoremediator but as a crucial agent of ecosystem restoration and biodiversity protection due to its evolutionary adaptations and adaptation to the local environmental conditions (Bawankar, 2024).

Material and Methodology

Research Design:

The research design used in the study was experimental and analytical research design to determine the phytoremediation capability of the sampled indigenous plant species in the polluted soil environments. Controlled pot-culture assay was also performed in efforts to evaluate the capacity of native plants in uptake, accumulation and stability of identified soil pollutants. The design was in such a manner that it could be used to compare the growth of planted and unplanted (control) soil samples in a fixed growth period. Both qualitative and quantitative parameters were discussed to understand the efficiency of each of the species in eliminating the contaminants concentration and enhancing the soil characteristic.

Data Collection Methods:

Lab and field data were used to collect primary data. Contaminated sites were sampled with soil samples and analyzed in terms of baseline physicochemical properties, such as pH, content of organic matter and concentration of pollutant. The chosen native plants were grown in prepared soil and under a similar environmental condition. Plant growth parameters- height, biomass and root length were recorded at regular intervals. Post harvest analysis entailed plant tissue (root,

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stem and leaf) and soil sample collection followed by chemical analysis to establish the levels of uptake of the contaminants and the left over contamination of the soil. The estimation of heavy metal or pollutant concentrations was done using standard analytical techniques. To help in the interpretation and comparison of the results, secondary data was collected using peer reviewed journals, government environmental reports, and existing phytoremediation studies.

Inclusion and Exclusion Criteria:

Indigenous plants species were chosen according to the natural presence in the study area, their ability to survive in polluted regions, and non-invasiveness. Only healthy plant specimens, which had similar growth characteristics were used in the experiment. The importance of species was prioritized to evaluate dual advantages of remediation and conservation to include the medicinal or ecological value of species. Explicit and intrusive or intensive agronomic input plant species were eliminated. Mixed or unidentified source of contamination in soils was also eliminated so as to develop some level of consistency in assessing pollutants. The samples that exhibited disease or abnormal growth over the time of the study were eliminated in the final analyses to ensure reliability of data.

Ethical Considerations:

The research was conducted ethically in terms of environmental research and conservation of biodiversity. The collection of indigenous plant species was done in a responsible manner with a minimum impact on the natural habitats. The local authorities were contacted to give necessary permission to sample the soil and plants where necessary. The study did not involve any genetically modified organisms or experimental practice that was hazardous. Precautions were observed to make sure that soils and plant residues that were contaminated were disposed using environmental safety measures to eliminate secondary pollution. The study was transparent in reporting its data and recognizes all the secondary sources that it employed in the support of its literature.

Results and Discussion

Results:

The phytoremediation capacity of the identified native vegetation species was tested on the basis of the growth index, the heavy metal uptake capacity, and the bioconcentration factors (BCF). Three widely occurring native species, namely Vetiveria zizanioides, Azadirachta indica, and Cynodon dactylon were studied in lead (Pb) contaminated soil with cadmium (Cd) and zinc (Zn).

Plant Growth Performance

The growth of all the chosen species was satisfactory in contaminated soil conditions though differences were found in the accumulation of biomass. Vetiveria zizanioides was the most tolerant to heavy metal stress as shown by the high biomass of shoot and roots than the other species.

Table 1: Biomass Production of Indigenous Plant Species in Contaminated Soil

Plant species	Shoot biomass (g/plant)	Root biomass (g/plant)
Vetiveria zizanioides	48.6	36.4
Azadirachta indica	39.2	28.7
Cynodon dactylon	33.5	24.1

The findings demonstrate that an increase in the biomass production means an increase in the phytoremediation potential due to the increase in the total metal uptake capacity of the plant.

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Heavy Metal Uptake by Plant Tissues

There were major differences in metal accumulation between species and parts of plants. Overall, there was an increment in the level of metals in roots compared to the shoot, indicating a phytostabilization propensity and phytoextraction.

Table 2: Heavy Metal Concentration in Plant Tissues (mg/kg dry weight)

Plant species	Pb (Shoot)	Pb (Root)	Cd (Shoot)	Cd (Root)	Zn (Shoot)	Zn (Root)
Vetiveria zizanioides	78.4	142.6	6.8	12.5	165.3	298.7
Azadirachta indica	61.7	118.9	5.2	10.1	142.4	254.6
Cynodon dactylon	54.3	101.5	4.6	8.9	128.6	219.4

The Vetiveria zizanioides species was the most accumulative of the species studied with both a shoot and root tissues accumulating the highest amount of Pb, Cd, and Zn.

Bioconcentration Factor (BCF)

The bioconcentration factor was determined to determine the capacity of plants to take metals in soil.

Table 3: Bioconcentration Factor (BCF) of Heavy Metals

Plant species	Pb	Cd	Zn
Vetiveria zizanioides	1.92	2.10	2.34
Azadirachta indica	1.65	1.84	2.01
Cynodon dactylon	1.48	1.62	1.87

BCF values greater than 1 indicate effective metal accumulation, confirming the phytoremediation capability of all selected indigenous species.

Discussion:

The results of this research prove that local plant species have significant potential in the purification of the heavy metal soils. High metal tolerance through physiological tolerance, large root system, and high level of biomass production could explain the superior performance of Vetiveria zizanioides. These traits impound the uptake and stabilization of metal in the rhizosphere. The fact that the accumulation of metals is mostly predominant in roots indicates that phytostabilization is one of the key remediation processes, which lower the mobility of the metals and discourage further spread into the environment. This is especially beneficial to long term soil management on the contaminated sites. Nevertheless, the high rates of metal that were observed in the shoots also point towards the viability of phytoextraction particularly of zinc. The relatively less accumulation in Cynodon dactylon could be explained by its shallow root system and low biomass, though, its quick growth and coverage of the ground could be used to prevent the spread of soil erosion and surface contamination. Other ecological benefits associated with the use of native species are the improved adaptability to the local climatic conditions, reduced maintenance costs, and low chances of ecological invasion. These qualities render the indigenous plants a more sustainable and less expensive way of remediation as compared to the conventional methods. In general, the findings verify the fact that indigenous flora, especially Vetiveria zizanioides can be critical in integrated phytoremediation protocols. Future research must aim to validate on a large scale, long term metal sequestration behaviour and the use of more than one species to better remediation effectiveness.

Limitations of the study

Although the current study offers pertinent information as far as the use of indigenous plant species is concerned as phytoremediators, a number of limitations can be identified. First, the

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study was performed in controlled or semi-controlled situations, which may not be accurately representative of the complexity and variability of natural field conditions. Such aspects like changing climate, soil heterogeneity, microbial diversity and seasonal variations may seriously affect growth of plants and uptake of contaminants, which may hinder immediate applicability of the results to actual polluted locations. Second, the research was done on the small amount of indigenous flora and particular pollutants. This means that the remediation efficiency that is observed would not be applicable to other plant species, pollutants and soil types. The interaction of various contaminants especially where there are multi-pollutants was not fully investigated which may influence the performance of phytoremediation in case of complex contamination conditions. Third, the research period was not long enough to be considered effective in phytoremediation, which takes long periods of time. They were not determined to establish long-term stability of the plants, sustainability of eliminating the contaminants and re-release of accumulated contaminants following the senescence of the plants. Besides, the paper failed to fully assess the persistence of the contaminants in plant tissues, and even the risks involved in the disposal of biomass or its absorption in the food chain. Lastly, there were socioeconomic and practical factors that were not within the scope of this study; these factors included land availability, maintenance expenses, and community acceptance. Such are essential to massive adoption of phytoremediation methods. Future research must thus consider field studies over a long period of time, greater number of plant species and contaminants, and multidisciplinary in order to better estimate the viability and scalability of applying indigenous plants to environmental remediation.

Future Scope

The development of the phytoremediation capacity of native vegetation species offers huge possibilities to the improvement of sustainable and environment-friendly remediation activities. The future studies may be carried out to identify and characterize the native plant species with high tolerance and accumulation of various pollutants including heavy metals, pesticides, hydrocarbons, and other newly discovered pollutants such as pharmaceuticals and microplastics. Field-based research in different ecological areas should be conducted over a long duration to confirm laboratory results as well as to comprehend the interactions between plants, soil, and microbes in nature. The other possible opportunity that can be adopted in the future is the combination of phytoremediation with microbial and mycorrhizal technology. Studying the mutualistic associations of native vegetation and the ground microorganisms would help to improve the absorption, transformation, and stabilization of contaminants. The field of plant physiology, genomics, and metabolomics can also be further utilized in identifying genetic characteristics that lead to stress tolerance, and pollutant sequestration so that plant species can be selected or optimally adapted to site-specific remediation. It is also in the future remit of developing mixed-species or agroforestry-based phytoremediation systems, which will integrate ecological restoration with economic gain. Plants which are native, have a medicinal, bioenergy, or fodder potential can help in enhancing land usability and at the same time maintain ecological balance. Besides that, phytoremediation approaches coupled with geospatial mapping and remote sensing should have allowed large-scale monitoring, evaluation, and optimization of contaminated areas. Lastly, the integration of policies, involvement of community, and cost benefit analysis should be the focus of future research aimed at encouraging the extensive use of phytoremediation. Standard protocols, safe guidelines, and after-remediation biomass management measures are essential in the translation of scientific research and findings into practical and scalable solutions of sustainable environmental management.

Conclusion

This paper shows that indigenous plant species have a lot of potential as efficient, sustainable

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and environmentally friendly remediation agents through phyto-remediation. Phytoremediation techniques can be used to have higher survival rates, contaminant uptake and long-term ecological stability by using naturally adapted plants to the local climatic and soil conditions. The results show that some native species exhibit major trapping, stabilizing, or transforming pollutant properties like heavy metals and organic contaminant, hence, restoring soils and water. The native variety has specific benefits over exotic species, such as less threat of ecological disequilibrium, less maintenance, and enhancement of the existing ecosystem. Their extensive root systems, symbiotic interactions with indigenous microorganisms, and tolerance to polluted environments increase the effectiveness of remediation and help sustain biodiversity. Moreover, phyto remediation is an economical method of developing the locality in which the locally found plants can be utilized, as opposed to other remediation methods which may prove to be costly or technically infeasible. Nonetheless, phytoremediation with indigenous species depends on the concentration of the contaminants, soil characteristics, the rate of growth of the planters, as well as seasonal difference. The paper emphasizes the importance of site-based evaluations and periodical monitoring to streamline the selection and use of plants. The combination of phytoremediation and other complementary methods, including soil remediation and microbial enrichment can yield even better results in remediation. To summarize, native vegetation species is a viable and ecologically viable way of curbing environmental pollution. Their strategic use can be used to promote sustainable land management and restoration of the environment. Future studies need to concentrate on large-scale validation, genetic and physiological pathways of pollutant uptake and policy frameworks that advance the integration of phytoremediation as a conventional environmental administration measure.

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