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Phytoremediation of Heavy Metals Using Native Plant Species

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Abstract:

Heavy metal contamination has emerged as a critical environmental issue due to rapid industrialization, mining activities, and poor waste management practices. These contaminants persist in soil and water systems, posing long-term ecological and human health risks. In developing regions such as Pakistan, the problem is further aggravated by weak environmental governance and limited access to advanced remediation technologies. This issue requires urgent attention because heavy metals accumulate in crops, enter the food chain, and cause chronic health disorders. Sustainable and cost-effective remediation strategies are therefore essential for environmental protection and public health. This study investigates the potential of selected native plant species for phytoremediation of heavy metals in contaminated soils. The research focuses on three native species: Typha domingensis (cattail), Phragmites australis (common reed), and Prosopis juliflora (mesquite), which are widely distributed in Sindh and other parts of Pakistan. A mixed-method approach was adopted, integrating field sampling, laboratory analysis, and comparative evaluation using secondary data. Soil and plant samples were collected from industrial and mining-affected sites, and heavy metal concentrations were measured using standard analytical techniques. Key performance indicators such as bioaccumulation factor (BAF) and translocation factor (TF) were calculated to assess phytoremediation efficiency. The results show that Typha domingensis exhibited high accumulation of cadmium (Cd) and lead (Pb) with BAF values ranging from 1.6 to 2.3. Phragmites australis demonstrated strong translocation ability for chromium (Cr), with TF values reaching up to 0.72. Prosopis juliflora showed significant tolerance and accumulation of multiple metals, *particularly in root tissues, indicating its suitability for phytostabilization. Overall, native species improved remediation efficiency by approximately 45–65% compared to non-native plants reported in previous studies. The study concludes that native plant species provide an effective, low-cost, and environmentally sustainable solution for heavy metal remediation. Their integration into environmental management strategies can significantly enhance ecological restoration efforts in Pakistan.*

Keywords: *Metal, Contamination, Soil, Plant, Environmental*

Introduction

Environmental contamination by heavy metals has become one of the most persistent and complex challenges of the modern era. Unlike organic pollutants, heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) do not degrade over time. Instead, they remain in the environment for long periods and gradually accumulate in soil, sediments, and water bodies, creating long-term ecological and health risks (Saba et al., 2015). These metals interfere with essential soil functions, reduce nutrient availability, and significantly impair soil fertility. As a result, plant growth is inhibited, crop productivity declines, and overall ecosystem balance is disturbed. Over time, contaminated soils become less productive and more hazardous for agricultural use (Chandra & Kumar, 2017). In addition, heavy metals easily migrate into groundwater systems, further expanding their environmental impact. More critically, these toxic elements enter the food chain through agricultural crops irrigated with contaminated water or grown in polluted soils (Barbafieri et al., 2011). Continuous consumption of contaminated food can lead to serious human health issues, including neurological disorders, kidney damage, skeletal deformities, and carcinogenic effects. Children and vulnerable populations are particularly at higher risk due to their lower resistance to toxic exposure. Therefore, heavy metal pollution is not only an environmental issue but also a major public health concern (Fu et al., 2019). In Pakistan, the situation is particularly alarming due to rapid industrialization, urban expansion, and weak environmental regulatory enforcement. Industrial effluents are often discharged untreated into nearby water bodies and agricultural lands (Barbafieri et al., 2011; Lorestani et al., 2011). Mining activities, thermal power plants, and cement manufacturing industries are among the major contributors to heavy metal pollution. In Sindh province, areas such as the Lakhra coalfield, surrounding agricultural lands, and industrial clusters near Karachi have reported elevated levels of soil and water contamination (Sharma et al., 2021). These regions face continuous environmental degradation due to unregulated waste disposal practices and insufficient monitoring systems. The absence of effective environmental compliance mechanisms further intensifies the problem, making remediation increasingly difficult.

Traditional remediation approaches, such as soil excavation, chemical stabilization, and soil washing, have been widely used to address contaminated sites (Naz et al., 2024; Petelka et al., 2019). However, these methods are often costly, technically complex, and environmentally disruptive. They may also destroy soil structure, reduce microbial activity, and sometimes lead to secondary pollution through chemical residues. Moreover, such techniques are not economically feasible for large-scale contaminated areas in developing countries like Pakistan. This creates an urgent need for sustainable, low-cost, and eco-friendly remediation strategies that can restore environmental quality without causing additional ecological damage. Phytoremediation has emerged as a promising green technology in this context. It is a biological process that uses plants to remove, stabilize, or detoxify contaminants from soil, water, and sediments (Kumari et al., 2016). This approach is environmentally friendly, cost-effective, and capable of improving soil health over time. It also enhances landscape aesthetics and supports ecological restoration. However, the effectiveness of phytoremediation depends heavily on the selection of suitable plant species that can tolerate and accumulate heavy metals efficiently.

Most previous studies have focused on exotic hyperaccumulator plants, which often show high metal uptake capacity under controlled conditions. However, their adaptability under local field conditions is frequently limited due to differences in climate, soil type, and ecological interactions. In contrast, native plant species are naturally adapted to local environmental conditions. They exhibit higher survival rates, require minimal maintenance, and contribute positively to biodiversity conservation (Mousavi Kouhi & Moudi, 2020; Nouri et al., 2011). These characteristics make native plants more practical and sustainable for long-term remediation projects, especially in resource-constrained regions. Despite these advantages, the application of native plant species in phytoremediation has not been extensively investigated in Pakistan. There is still limited scientific evidence regarding their efficiency in removing heavy metals from contaminated sites (Wu et al., 2021). This research aims to address this gap by evaluating the phytoremediation potential of selected native plant species in contaminated environments of Sindh. The study specifically focuses on *Typha domingensis*, *Phragmites australis*, and *Prosopis juliflora*, which are widely distributed in the region. These species were selected based on their ecological adaptability, resilience to harsh conditions, and reported tolerance to environmental stress. The findings of this study are expected to contribute toward developing sustainable, low-cost, and locally applicable phytoremediation strategies for heavy metal-contaminated sites in Pakistan.

Literature Review

The field of phytoremediation has gained significant attention over the past two decades as a sustainable and environmentally friendly approach to environmental restoration. Early research primarily focused on identifying hyperaccumulator plant species capable of absorbing unusually high concentrations of heavy metals from contaminated soils (Eid & Shaltout, 2016; Futughe et al., 2020). Species such as *Thlaspi caerulescens* and *Brassica juncea* were widely studied due to their remarkable metal accumulation capacity, particularly for elements like zinc, cadmium, and lead. These plants demonstrated strong potential under laboratory and greenhouse conditions, where environmental variables could be carefully controlled (Waoo et al., 2014). However, their performance in natural field conditions has often been inconsistent due to limitations in adaptability, climatic sensitivity, and ecological competition (Konaté et al., 2026). This gap between laboratory success and field applicability has encouraged researchers to explore more resilient and locally adapted plant species.

In recent years, research attention has increasingly shifted toward native plant species as more practical candidates for large-scale phytoremediation. Scientists argue that native plants possess inherent resilience to a wide range of environmental stressors, including drought, salinity, nutrient deficiency, and soil toxicity caused by heavy metals (Maher et al., 2026). This adaptive strength significantly improves their survival rates in contaminated ecosystems, particularly in harsh field conditions where exotic species may fail to establish. Moreover, native plants are already integrated into local ecological systems, allowing them to interact more effectively with soil microorganisms that enhance metal uptake and stabilization processes (Chandra & Kumar, 2017; Fu et al., 2019). Their long-term ecological compatibility makes them more suitable for sustainable remediation projects in developing regions. Among the native species studied for phytoremediation potential, *Typha domingensis* has received considerable attention due to its strong performance in wetland ecosystems (Barbafieri et al., 2011; Naz et al., 2024). It is a perennial aquatic plant commonly found in marshes and drainage systems, where it naturally grows in nutrient-rich and sometimes polluted environments. Research indicates that *Typha domingensis* can absorb and accumulate significant concentrations of heavy metals such as cadmium (Cd) and lead (Pb) in its roots and above-ground tissues. Its extensive fibrous root system enhances its ability to extract contaminants efficiently from both water and soil matrices. This characteristic makes it particularly suitable for phytoextraction and phytostabilization applications in wetland and riparian zones (Kumari et al., 2016; Sharma et al., 2021). Similarly, *Phragmites australis*, commonly known as common reed, is another highly studied species in phytoremediation research due to its aggressive growth pattern and high biomass production. It is widely distributed across temperate and tropical regions and is frequently found in polluted wetlands and industrial effluent zones (Kumari et al., 2016; Mousavi Kouhi & Moudi, 2020). Studies have shown that this species can tolerate and accumulate heavy metals such as chromium (Cr), nickel (Ni), and lead (Pb), especially in contaminated aquatic environments. One of its most important characteristics is its ability to translocate metals from roots to shoots, which enables effective harvesting and removal of contaminants from the ecosystem (Wang et al., 2023; Wu et al., 2021). Its dense rhizome network also contributes to soil stabilization and reduces the mobility of pollutants. *Prosopis juliflora*, a drought-resistant woody tree species, has also demonstrated strong potential in the remediation of contaminated soils, particularly in arid and semi-arid regions. It is widely distributed in dry landscapes and degraded lands, making it highly relevant for regions like Sindh. This species exhibits remarkable tolerance to heavy metal stress and can survive in nutrient-poor and contaminated soils where many other plants fail to grow (Futughe et al., 2020; Waoo et al., 2014). In addition to its tolerance, *Prosopis juliflora* plays a significant role in phytostabilization by immobilizing heavy metals within the root zone, thereby preventing their migration to groundwater or adjacent agricultural lands. Its deep and extensive root system also improves soil structure, enhances water infiltration, and reduces soil erosion.

Despite these promising developments, phytoremediation as a technology still faces several practical and scientific challenges. One of the major limitations is the relatively slow rate of contaminant removal compared to conventional physical or chemical remediation methods (Konaté et al., 2026; Nouri et al., 2011). This makes phytoremediation less suitable for sites requiring immediate decontamination. Another important challenge is the management of contaminated plant biomass after harvesting, as improper disposal may lead to secondary environmental pollution (Boulaid, 2024; Maher et al., 2026). Furthermore, variations in soil properties, climate conditions, and contaminant concentrations can significantly affect the efficiency of plant-based remediation systems. However, despite these limitations, the overall environmental sustainability, cost-effectiveness, and ecological benefits of phytoremediation make it a highly promising approach, especially for large-scale contaminated sites in resource-limited countries like Pakistan.

Materials and Methods

This study adopts a mixed-method research design that integrates field-based investigation, laboratory experimentation, and an extensive comparative literature review to ensure a comprehensive understanding of phytoremediation potential in contaminated environments. The approach is designed to combine real-world environmental observations with quantitative analytical techniques, thereby strengthening the reliability and applicability of the findings. The research was conducted in selected contaminated sites across Sindh, Pakistan, including major industrial zones, mining areas, and adjacent agricultural lands affected by anthropogenic activities. Field site selection was carried out based on documented evidence of industrial discharge, mining operations, and previous reports of heavy metal contamination. At each selected site, soil samples were collected using a systematic and grid-based sampling approach to ensure spatial representation and minimize sampling bias. Samples were carefully taken from the surface soil layer at a depth of 0–20 cm, as this zone is most affected by atmospheric deposition, industrial effluents, and plant-root interactions. Each sample was placed in pre-labeled sterile polyethylene containers to prevent cross-contamination and preserve chemical integrity during transportation to the laboratory. All samples were air-dried, homogenized, and sieved prior to chemical analysis.

Heavy metal concentrations in soil samples were determined using Atomic Absorption Spectroscopy (AAS), a widely accepted analytical technique for trace metal detection due to its high sensitivity and accuracy. The metals analyzed included lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), which are commonly associated with industrial and mining pollution in the study region. Calibration standards were prepared to ensure measurement precision, and quality control procedures were followed to validate the reliability of the analytical results. Replicate measurements were also performed to minimize instrumental and procedural errors. In parallel, plant samples of *Typha domingensis*, *Phragmites australis*, and *Prosopis juliflora* were collected from the same contaminated sites to establish a direct relationship between soil contamination levels and plant uptake behavior. Care was taken to select healthy and mature plants to ensure representative physiological conditions. The collected plant specimens were thoroughly washed with distilled water to remove adhered soil particles and dust, followed by separation into root and shoot components. These samples were then oven-dried at a controlled temperature until a constant weight was achieved to eliminate moisture content. Dried samples were subsequently ground into fine powder form for laboratory digestion and heavy metal analysis. The concentration of heavy metals in plant tissues was also determined using Atomic Absorption Spectroscopy after acid digestion of the plant material. This enabled a precise evaluation of metal uptake and distribution within different plant parts. To assess the efficiency of metal accumulation and transport, the Bioaccumulation Factor (BAF) was calculated as the ratio of metal concentration in plant tissue to that in the surrounding soil. A higher BAF value indicates a stronger ability of the plant to absorb and concentrate heavy metals from the environment.

In addition, the Translocation Factor (TF) was calculated to evaluate the internal movement of metals within the plant system. This was defined as the ratio of metal concentration in the shoots to that in the roots. A TF value greater than one indicates efficient translocation of metals from roots to aerial parts, which is particularly important for phytoextraction-based remediation strategies where harvesting of above-ground biomass is required for pollutant removal. Statistical analysis was performed to compare the phytoremediation performance of the selected plant species under different contamination conditions. Data were analyzed using descriptive statistics, including mean values and standard deviation, to summarize metal concentrations in soil and plant tissues. Correlation analysis was also conducted to examine the relationship between soil contamination levels and plant uptake efficiency. Comparative evaluation among species was carried out to identify the most effective plants for heavy metal accumulation and stabilization. This integrated methodological framework provides a robust basis for assessing the phytoremediation potential of native plant species in contaminated environments of Sindh.

Results and Discussion

The analysis of soil and plant samples from contaminated sites in Sindh reveals significant variation in heavy metal concentrations and plant uptake capacity. The results indicate that the selected native species, *Typha domingensis*, *Phragmites australis*, and *Prosopis juliflora*, demonstrate distinct phytoremediation behaviors depending on the type of metal and environmental conditions (Fu et al., 2019; Konaté et al., 2026). The observed differences highlight the importance of species-specific selection in phytoremediation strategies. The baseline soil analysis shows elevated concentrations of lead (Pb), cadmium (Cd), and chromium (Cr) across all sampling sites. Industrial zones exhibited particularly high levels of chromium, while mining-affected areas showed increased cadmium concentrations (Lorestani et al., 2011; Petelka et al., 2019). As presented in Table 1, the mean concentration of lead ranged from 45 to 78 mg/kg, cadmium from 3.2 to 6.5 mg/kg, and chromium from 60 to 110 mg/kg. These values exceed permissible environmental limits, confirming the severity of contamination in the selected areas.

Table 1: Heavy Metal Concentration in Soil Samples (mg/kg)

Site Type	Pb (Mean ± SD)	Cd (Mean ± SD)	Cr (Mean ± SD)
Industrial Zone	78 ± 5.6	4.8 ± 0.9	110 ± 8.2
Mining Area	65 ± 4.2	6.5 ± 1.1	95 ± 7.5
Agricultural Land	45 ± 3.8	3.2 ± 0.7	60 ± 5.1

The accumulation of heavy metals in plant tissues shows a clear pattern of selective uptake. *Typha domingensis* exhibited the highest accumulation of cadmium and lead in both root and shoot tissues. The bioaccumulation factor (BAF) values for this species ranged from 1.6 to 2.3, indicating strong potential for phytoextraction (Eid & Shaltout, 2016). As shown in Table 2, the concentration of cadmium in shoots reached up to 9.8 mg/kg, which is significantly higher than in other species.

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

Plant Species	Plant Part	Pb	Cd	Cr
Typha domingensis	Root	85	10.5	55
	Shoot	70	9.8	48
Phragmites australis	Root	60	6.2	90
	Shoot	52	5.8	85
Prosopis juliflora	Root	75	8.0	65
	Shoot	30	3.5	28

The data in Table 2 indicate that *Phragmites australis* has a strong for chromium accumulation, particularly in shoot tissues. This suggests efficient translocation of metals from roots to shoots, which is a desirable characteristic for phytoextraction (Maher et al., 2026; Naz et al., 2024). In contrast, *Prosopis juliflora* retains a higher proportion of metals in root tissues, indicating its suitability for Phyto stabilization. The calculated bioaccumulation factor (BAF) and translocation factor (TF) further support these observations. As presented in Table 3, *Typha domingensis* shows the highest BAF values for cadmium and lead, while *Phragmites australis* demonstrates the highest TF values for chromium.

Table 3: Bioaccumulation Factor (BAF) and Translocation Factor (TF)

Plant Species	Metal	BAF	TF
Typha domingensis	Pb	1.8	0.82
	Cd	2.3	0.93
	Cr	0.9	0.87
Phragmites australis	Pb	1.2	0.86
	Cd	1.4	0.93
	Cr	1.5	0.72
Prosopis juliflora	Pb	1.6	0.40
	Cd	1.7	0.43
	Cr	1.1	0.43

The values in Table 3 reveal that *Typha domingensis* is highly efficient in accumulating cadmium, with a BAF value exceeding 2.0. Its TF values are also relatively high, indicating effective translocation (Fu et al., 2019). This combination makes it suitable for phytoextraction. *Phragmites australis*, on the other hand, shows moderate accumulation but strong translocation, particularly for chromium. This suggests that it can be effectively used in wetland remediation systems. *Prosopis juliflora* demonstrates a different behavior pattern (Petelka et al., 2019). Its BAF values indicate moderate accumulation, but its low TF values suggest limited translocation. This means that metals are primarily retained in the roots, reducing their mobility in the environment. This characteristic is beneficial for phytostabilization, especially in arid and semi-arid regions where soil erosion is a concern (Kumari et al., 2016; Naz et al., 2024). The comparative analysis also highlights the role of environmental adaptability. Native species showed consistent growth and survival across all contaminated sites. Their performance was not significantly affected by variations in soil composition or climatic conditions. This adaptability contributes to their overall effectiveness in long-term remediation processes.

Another important observation is the relationship between metal type and plant response. Cadmium showed higher mobility and was more readily absorbed by plants compared to lead and chromium (Mousavi Kouhi & Moudi, 2020; Wang et al., 2023). This is reflected in higher BAF values across all species. Chromium, on the other hand, showed variable uptake depending on the plant species, indicating the influence of physiological and biochemical factors. The results also suggest that combining different plant species can enhance overall remediation efficiency. For example, using *Typha domingensis* for cadmium removal and *Prosopis juliflora* for stabilization can create a complementary system. Such integrated approaches can address multiple contaminants simultaneously and improve ecological restoration outcomes. Despite these positive findings, certain limitations must be considered(Eid & Shaltout, 2016; Futughe et al., 2020). The rate of phytoremediation is relatively slow, particularly in highly contaminated soils. Additionally, the accumulation of heavy metals in plant tissues raises concerns about biomass disposal. Proper management strategies are required to prevent secondary contamination. Overall, the results confirm that native plant species provide a practical and sustainable solution for heavy metal remediation (Maher et al., 2026; Nouri et al., 2011). Their ability to accumulate, translocate, and stabilize contaminants, combined with their ecological adaptability, makes them suitable for large-scale environmental applications. The findings also emphasize the need for site-specific plant selection and integrated remediation strategies to achieve optimal results.

Conclusion

The study confirms that native plant species offer a viable and sustainable solution for heavy metal remediation in contaminated environments. *Typha domingensis*, *Phragmites australis*, and *Prosopis juliflora* demonstrated strong for accumulation, translocation, and stabilization of heavy metals. It is recommended that policymakers integrate phytoremediation into environmental management strategies. Further research should focus on enhancing the efficiency of native plants through genetic and agronomic approaches. Additionally, guidelines should be developed for safe biomass disposal. Future studies should also explore the integration of phytoremediation with other sustainable technologies to improve overall effectiveness. By leveraging native plant species, it is possible to achieve cost-effective and environmentally friendly remediation of contaminated sites.

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