

Native Plant Species of Maharashtra for Phytoremediation and Bioremediation: Mechanisms, Performance Evaluation, and Future Prospects

Neha Rajendra Ghole¹, Dipak A. Jadhav², Mali Shivashankar³

¹Research Scholar, JSPM University, Pune, India

²Assistant Professor, JSPM University, Pune, India

³Assistant Professor, Madhav Institute of Technology & Science (Deemed University), Gwalior, India

ABSTRACT

Industrial growth and rapid urbanization in Maharashtra have led to a noticeable increase in soil and water pollution, particularly in rivers that receive untreated sewage, industrial discharge, and agricultural runoff. Although conventional treatment methods are commonly used, their high cost and energy requirements make them difficult to sustain in the long term. In this context, plant-based remediation offers a more practical and environmentally friendly alternative.

This review explores the potential of native plant species in Maharashtra for phytoremediation and bioremediation, with a focus on their mechanisms and suitability to local environmental conditions. Key processes such as phytoextraction, phytostabilization, rhizofiltration, phytodegradation, and plant–microbe interactions are discussed in relation to regional needs. Aquatic plants like *Typha angustifolia*, *Phragmites karka*, and *Lemna minor* are found to be effective in removing nutrients from water, while terrestrial grasses such as *Vetiveria zizanioides* and *Cynodon dactylon* are more suitable for stabilizing heavy metals in soil. Tree species including *Azadirachta indica* and *Terminalia arjuna* play an important role in long-term soil stabilization and overall ecosystem improvement.

The review highlights that aquatic plants are more efficient for short-term nutrient removal, whereas terrestrial species contribute to long-term contaminant stabilization. However, several gaps remain, including limited field-scale studies, insufficient integration of microbial processes, lack of predictive models, and minimal use of geospatial tools.

To overcome these challenges, this study suggests an integrated approach that combines native plants with microbial support, engineered systems, floating wetlands, and remote sensing techniques. Overall, the use of indigenous plant species offers a promising and sustainable solution for improving river and soil quality in Maharashtra.

Keywords: Phytoremediation; Bioremediation; Indigenous plant species; Heavy metal stabilization; Constructed wetlands; Arbuscular mycorrhizal fungi; River restoration; Maharashtra

INTRODUCTION

Environmental degradation has intensified globally as a result of rapid industrialization, expanding urban settlements, and intensified agricultural practices. In India, Maharashtra stands out as one of the most industrially developed states, with major urban centers such as Mumbai, Pune, and Nashik contributing significantly to economic growth. However, this development has also led to considerable pressure on natural resources. Untreated sewage discharge, industrial effluents,

and agricultural runoff have contributed to the deterioration of soil and water quality. Rivers including the Mula–Mutha, Godavari, Krishna, and Ulhas frequently record elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), nutrient enrichment, and heavy metal contamination such as lead (Pb), cadmium (Cd), and chromium (Cr), posing risks to both ecosystems and public health (Pawar et al., 2016; Lokhande & Singare, 2020).

Conventional remediation approaches such as chemical precipitation, membrane filtration, ion exchange, and advanced oxidation are commonly employed for pollution control. While technically effective, these methods often involve high energy consumption, substantial infrastructure costs, and the generation of secondary waste streams (Mahar et al., 2016; Liu et al., 2021). In decentralized riverine systems and peri-urban areas, where contamination sources are diffuse and variable, such centralized technologies may not always be feasible. Consequently, nature-based remediation strategies are receiving increasing attention as sustainable alternatives.

Phytoremediation, which utilizes plants to remove, immobilize, or transform contaminants, represents one such approach (Ali et al., 2013). Its effectiveness relies on multiple mechanisms including phytoextraction, phytostabilization, rhizofiltration, phytodegradation, and phytovolatilization (Sarwar et al., 2017). Aquatic macrophytes such as *Typha angustifolia* and *Phragmites karka* have shown considerable success in nutrient removal within constructed wetland systems (Vymazal, 2018; Sandoval et al., 2019). Similarly, terrestrial grasses such as *Vetiveria zizanioides* exhibit strong root-mediated stabilization of heavy metals (Danh et al., 2009), while *Cynodon dactylon* demonstrates adaptability to contaminated soils (Chen et al., 2022).

Native tree species, including *Azadirachta indica*, further contribute to soil stabilization and enhancement of microbial activity (Hashem et al., 2016). Beyond plant uptake processes, bioremediation incorporates microbial communities capable of transforming pollutants into less harmful forms. The rhizosphere functions as a biologically active interface where plant roots interact with bacteria and fungi. In particular, arbuscular mycorrhizal fungi (AMF) improve nutrient acquisition and enhance plant tolerance to heavy metal stress (Begum et al., 2019; Upadhyaya et al., 2019). The integration of plant-based and microbial processes has therefore emerged as a promising strategy for ecosystem restoration (Chandrasekaran et al., 2019).

The selection of appropriate plant species is central to successful phytoremediation. While globally recognized hyperaccumulator species have been widely investigated, their introduction into non-native ecosystems may lead to ecological imbalance. In contrast, indigenous plant species are better adapted to local climatic conditions, hydrological variability, and soil characteristics. Maharashtra encompasses diverse agro-climatic zones—from the humid Western Ghats to the semi-arid Deccan Plateau and coastal Konkan belt—supporting a rich assemblage of native flora capable of tolerating environmental stress. Utilizing these indigenous species not only enhances survival and performance but also supports biodiversity conservation (Rezania et al., 2016). Despite increasing interest in phytoremediation, comprehensive reviews focusing specifically on Maharashtra's native plant species remain limited. Existing studies often examine individual species under controlled conditions, with fewer investigations addressing field-scale applicability and plant–microbe interactions under dynamic environmental conditions. Furthermore, the integration of phytoremediation with emerging technologies such as remote sensing and floating treatment wetlands remains underexplored.

This review therefore aims to critically evaluate the phytoremediation and bioremediation potential of native plant species in Maharashtra. The objectives are to (i) examine plant- and microbe-mediated remediation mechanisms; (ii) identify indigenous species suitable for soil and water pollution control; (iii) assess their relevance across diverse agro-climatic zones; and (iv) highlight research gaps and future directions. By consolidating available evidence, this study seeks to contribute to the development of region-specific, sustainable remediation strategies aligned with long-term environmental resilience.

2. Mechanisms of Phytoremediation and Bioremediation

Phytoremediation and bioremediation rely on a series of interconnected physiological and microbial processes that regulate contaminant uptake, transformation, stabilization, and removal. These mechanisms operate at the interface of plant roots, soil, water, and associated microbial communities. A comprehensive understanding of these pathways is essential for selecting appropriate plant species and designing efficient remediation systems under diverse environmental conditions. The principal mechanisms discussed below are conceptually represented in Figure 1.

Mechanisms of Phytoremediation

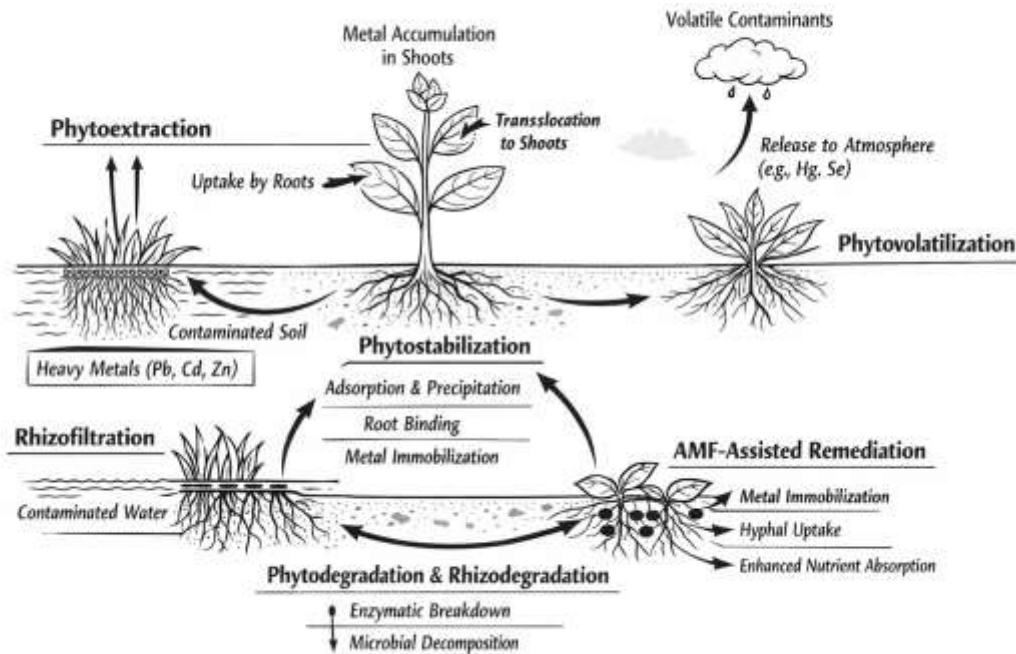


Figure 1: The conceptual framework is synthesized based on established phytoremediation principles described in Ali et al. (2013), Sarwar et al. (2017), Begum et al. (2019), and Upadhyaya et al. (2019).

2.1 Phytoextraction

Phytoextraction involves the uptake of contaminants primarily heavy metals from soil or water into plant tissues, particularly shoots and leaves. Once accumulated in above-ground biomass, contaminants can be removed through harvesting, thereby reducing overall pollutant concentrations in the affected environment (Ali et al., 2013). In certain cases, harvested biomass may also be processed for metal recovery through phytomining techniques. As illustrated in Figure 1, metal ions present in the soil solution are absorbed by plant roots via membrane-bound transport proteins. These ions are subsequently transported upward through the xylem and distributed to aerial tissues. The efficiency of phytoextraction depends on factors such as metal bioavailability, root architecture, transpiration rate, and plant growth dynamics. Species exhibiting high bioaccumulation factors (BAF) and translocation factors (TF) are particularly suitable for this mechanism (Danh et al., 2009; Chen et al., 2022). However, successful application also requires careful biomass management to prevent secondary contamination.

2.2 Phytostabilization

Phytostabilization focuses on immobilizing contaminants within the rhizosphere rather than removing them from the site. This process reduces contaminant mobility, bioavailability, and leaching potential through mechanisms such as adsorption onto root surfaces, precipitation, complexation with organic compounds, and changes in soil pH (Sarwar et al., 2017). Figure 1 depicts this mechanism as root-mediated binding and retention of metals within the contaminated soil matrix. Deep-rooted native species contribute to long-term stabilization by enhancing soil structure and minimizing erosion. For example, species such as *Azadirachta indica* improve soil organic matter content and promote microbial activity, thereby supporting stable contaminant immobilization (Hashem et al., 2016). Phytostabilization is particularly valuable in areas where contaminant removal is impractical but risk reduction is achievable.

2.3 Rhizofiltration

Rhizofiltration is primarily applied in aquatic systems, where plant roots remove dissolved contaminants from water bodies. In this process, pollutants are adsorbed onto root surfaces or absorbed into root tissues, often accompanied by microbial degradation (Rezania et al., 2016). As shown in Figure 1, aquatic macrophytes intercept contaminants directly from contaminated water via extensive and fibrous root systems. These roots provide large surface areas for adsorption and serve

as substrates for microbial biofilms that further enhance degradation. Species such as *Typha angustifolia* and *Phragmites karka* are widely used in constructed wetlands due to their capacity to reduce nutrients, suspended solids, and selected heavy metals (Vymazal, 2018). Rhizofiltration is particularly effective in wastewater polishing and surface water treatment applications.

2.4 Phytodegradation and Rhizodegradation

Phytodegradation refers to the enzymatic breakdown of organic contaminants within plant tissues. Plants produce enzymes such as dehalogenases, peroxidases, and oxygenases that can transform complex organic compounds—including hydrocarbons, pesticides, and certain industrial chemicals—into less harmful forms (Ali et al., 2013). Closely associated with this process is rhizodegradation, which occurs in the rhizosphere. Root exudates—comprising sugars, amino acids, and organic acids—stimulate microbial populations capable of degrading organic pollutants. Figure 1 illustrates this dual process of enzymatic transformation and microbially mediated decomposition occurring in the root zone. This mechanism is especially relevant for hydrocarbon-contaminated soils and agricultural runoff zones.

2.5 Phytovolatilization

Phytovolatilization involves the uptake of certain contaminants followed by their transformation into volatile forms that are released into the atmosphere through transpiration. Elements such as selenium (Se) and mercury (Hg) may undergo biochemical transformation within plant tissues before volatilization (Ali et al., 2013). In Figure 1, this process is represented by upward directional arrows indicating the release of transformed volatile compounds. While phytovolatilization contributes to contaminant reduction in soil or water, its environmental implications must be carefully evaluated, as atmospheric redistribution may occur.

2.6 Role of Rhizosphere Microorganisms

The rhizosphere is a biologically dynamic zone characterized by intense interactions between plant roots and microbial communities. Bacteria, fungi, and actinomycetes participate in processes such as biosorption, redox transformation, nutrient cycling, and enzymatic degradation of contaminants. As summarized in Figure 1, microbial activity enhances remediation efficiency by increasing contaminant solubility for uptake, transforming toxic compounds into less harmful forms, and supporting plant growth under stress conditions. Plant growth-promoting rhizobacteria (PGPR) further contribute by producing siderophores, organic acids, and phytohormones that enhance nutrient availability and stress tolerance.

2.7 Arbuscular Mycorrhizal Fungi (AMF)-Assisted Phytoremediation

Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with plant roots, extending hyphal networks beyond the root zone and increasing the effective absorption area. These fungal hyphae improve nutrient and water uptake while also influencing heavy metal immobilization and sequestration (Begum et al., 2019; Upadhyaya et al., 2019). In Figure 1, AMF-assisted processes are illustrated through hyphal extensions interacting with soil particles and contaminants. AMF can bind metals within fungal structures, reduce oxidative stress in host plants, and enhance overall biomass production. The incorporation of AMF into phytoremediation systems therefore strengthens both plant resilience and remediation efficiency.

2.8 Integrated Phytoremediation–Bioremediation Systems

Contemporary remediation strategies increasingly emphasize integrated systems that combine plant uptake, microbial processes, and engineered substrates. Such hybrid approaches optimize pollutant removal through complementary physical, chemical, and biological pathways (Liu et al., 2021). Figure 1 demonstrates how these interconnected processes operate synergistically. For example, engineered substrates such as sand biofilters enhance adsorption and microbial colonization, while floating treatment wetlands facilitate pollutant interception in surface waters. When combined with microbial inoculation and continuous monitoring, these systems can provide improved efficiency, adaptability, and long-term sustainability.

3. Native Plant Species of Maharashtra for Phytoremediation and Bioremediation

Maharashtra encompasses a wide range of ecological zones, including the humid Western Ghats, the semi-arid Deccan Plateau, the coastal Konkan belt, and densely urbanized river basins. This environmental diversity supports a rich assemblage of indigenous plant species adapted to varied hydrological conditions, soil characteristics, and climatic stresses. The use of native flora for phytoremediation offers several advantages, including ecological compatibility, higher survival rates under local environmental variability, and reduced risk of invasive behavior compared to exotic hyperaccumulator species (Mahar et al., 2016; Sarwar et al., 2017). This section examines major groups of native plants in relation to their habitat preference, pollutant specificity, and dominant remediation mechanisms.

3.1 Wetland and Aquatic Macrophytes

Wetland ecosystems play a central role in nutrient transformation and contaminant attenuation (Vymazal, 2018). In Maharashtra, natural marshlands and river margins host a variety of emergent and floating macrophytes capable of functioning as biological filters. Among these, *Typha angustifolia* is widely distributed along riverbanks and low-lying wetlands. It demonstrates substantial capacity for removing nitrogen (N), phosphorus (P), suspended solids, and certain heavy metals through rhizofiltration and microbially mediated processes (Rezania et al., 2016; Sandoval et al., 2019). Its dense root network facilitates sediment trapping and supports biofilm development, thereby enhancing microbial degradation within constructed wetland systems (Vymazal, 2018). Owing to its tolerance of fluctuating water levels, it is well suited to monsoon-driven river systems such as the Mula–Mutha. Similarly, *Phragmites karka* thrives in nutrient-rich environments and contributes to oxygen transport within the rhizosphere, promoting nitrification–denitrification pathways (Vymazal, 2018). While *Typha* often exhibits higher nutrient uptake efficiency, *Phragmites* provides greater structural stability and long-term sediment retention (Sandoval et al., 2019). Floating species such as *Pistia stratiotes* and *Lemna minor* show rapid biomass production and high nutrient assimilation rates (Rezania et al., 2016). However, their deployment requires controlled biomass management to avoid secondary eutrophication. When properly managed, these species can serve effectively in tertiary wastewater polishing systems (Vymazal, 2018). Collectively, aquatic macrophytes tend to outperform terrestrial species in short-term nutrient removal, making them integral to wetland-based remediation and river restoration efforts in urban Maharashtra.

3.2 Terrestrial Grasses and Herbaceous Species

Native grass species exhibit strong potential for stabilizing contaminated soils, particularly in industrial and peri-urban landscapes. *Vetiveria zizanioides* is notable for its extensive fibrous root system, which penetrates deeply into the soil profile. This characteristic enhances slope stabilization, reduces erosion, and promotes heavy metal immobilization within the rhizosphere (Danh et al., 2009). Evidence suggests that vetiver primarily functions through phytostabilization rather than extensive translocation, thereby limiting contaminant movement into above-ground tissues (Danh et al., 2009; Sarwar et al., 2017). Its tolerance to drought further increases its suitability for semi-arid regions of the Deccan Plateau. *Cynodon dactylon*, widely distributed across Maharashtra, demonstrates adaptability to disturbed and metal-affected soils (Chen et al., 2022). Although its metal uptake capacity is moderate compared to specialized hyperaccumulators, its rapid surface coverage supports soil stabilization and erosion control. Lower translocation factors indicate that it primarily contributes to immobilization rather than metal extraction. *Saccharum spontaneum*, commonly found in floodplain regions, plays a key role in sediment retention and heavy metal stabilization along riverbanks. Its growth cycle aligns with monsoon hydrology, enhancing its effectiveness in riparian restoration. Herbaceous species such as *Alternanthera sessilis* and *Ipomoea aquatica* contribute to nutrient interception in shallow wetlands and drainage channels (Rezania et al., 2016), functioning as transitional buffers between agricultural runoff zones and river systems. Overall, terrestrial grasses are particularly valuable for erosion control and metal stabilization, while herbaceous wetland-edge species enhance nutrient interception across mixed hydrological environments.

3.3 Native Tree Species for Long-Term Stabilization

Tree species contribute to remediation through long-term stabilization, biomass accumulation, and improvement of soil structure (Mahar et al., 2016). *Azadirachta indica* is widely distributed across Maharashtra and demonstrates drought tolerance along with moderate heavy metal retention within root tissues (Hashem et al., 2016). Its contribution to soil organic matter and microbial diversity further enhances stabilization processes. *Pongamia pinnata* is especially relevant for hydrocarbon-contaminated sites due to its association with nitrogen-fixing bacteria and tolerance to petroleum residues (Ali et al., 2013). Its dual ecological and remediation functions make it suitable for industrial landscapes. *Terminalia arjuna*, frequently found along riverbanks, enhances soil cohesion through its deep root system, thereby reducing erosion and sediment-associated pollutant transport. Urban tree species such as *Ficus religiosa* and *Ficus benghalensis* provide complementary ecological services, including air quality improvement and microclimate regulation. Although tree-based systems generally operate more slowly than herbaceous species in terms of contaminant removal, they provide greater ecosystem stability, carbon sequestration, and long-term resilience (Sarwar et al., 2017).

3.4 Shrubs and Hardy Species for Degraded Lands

Shrub species adapted to marginal soils also hold remediation potential. *Calotropis procera* and *Sesbania sesban* tolerate nutrient-deficient and disturbed environments, while *Sesbania* contributes indirectly to soil restoration through nitrogen fixation (Mahar et al., 2016). *Jatropha curcas* has been investigated for its ability to grow in heavy metal-affected soils and offers the added benefit of bioenergy production (Ali et al., 2013). However, careful assessment of contaminant accumulation in biomass is necessary before large-scale application. These hardy species are particularly suited to mine spoils, abandoned industrial sites, and

3.5 Comparative Analytical Assessment

From a functional perspective, native plant species of Maharashtra can be classified according to dominant remediation pathways, as outlined in Table 2 (Ali et al., 2013; Sarwar et al., 2017). Aquatic species such as *Typha angustifolia*, *Phragmites karka*, and *Lemna minor* primarily serve as nutrient removal specialists. Terrestrial grasses and selected tree species—including *Vetiveria zizanioides*, *Cynodon dactylon*, and *Azadirachta indica*—act mainly as heavy metal stabilizers. *Pongamia pinnata* exhibits hydrocarbon degradation potential, whereas riparian species such as *Terminalia arjuna* and *Saccharum spontaneum* contribute significantly to sediment stabilization and erosion control. When interpreted alongside the quantitative comparison presented in Table 2, this classification supports a mechanism-based approach to species selection. Matching plant traits with pollutant type, hydrological conditions, and site-specific objectives can enhance remediation efficiency and ecological sustainability across Maharashtra’s diverse environmental landscapes.

Table 2. Quantitative comparison of phytoremediation performance of selected native plant species relevant to Maharashtra

Plant Species	Habitat Type	Target Pollutant	Removal / Accumulation Efficiency (%)	Bioaccumulation Factor (BAF)	Translocation Factor (TF)	Dominant Mechanism	Suitable Application Zone	Key References
<i>Typha angustifolia</i>	Aquatic	Nitrate	60–85%	—	—	Rhizofiltration	Constructed wetlands	Vymazal (2018); Rezaian et al. (2016)
		Phosphate	55–80%	—	—	Nutrient uptake	River polishing	Sandoval et al. (2019)
		Pb, Cd	40–65%	1.2–2.5	0.6–1.1	Root adsorption	Sewage-fed wetlands	Rezaian et al. (2016)
<i>Phragmites karka</i>	Aquatic	BOD	70–95%	—	—	Microbial-assisted removal	STP polishing	Vymazal (2018)
		Total Nitrogen	50–75%	—	—	Nitrification – denitrification	Marsh systems	Sandoval et al. (2019)
<i>Vetiveria zizanioides</i>	Terrestrial	Pb	45–70%	1.5–3.0	0.4–0.8	Phytostabilization	Industrial soil	Danh et al. (2009)
		Cd	40–65%	1.3–2.4	0.5–0.9	Metal immobilization	Mine spoils	Danh et al. (2009)
<i>Cynodon dactylon</i>	Grass	Zn	35–60%	1.1–1.8	0.6–1.0	Stabilization	Roadside soil	Chen et al. (2022)

		Cr	30–55%	0.9–1.5	0.4–0.7	Root accumulation	Disturbed lands	Chen et al. (2022)
<i>Azadirachta indica</i>	Tree	Pb	25–50% (root dominant)	0.8–1.3	<0.5	Phytostabilization	Riparian buffers	Hashem et al. (2016)
<i>Pongamia pinnata</i>	Tree	Hydrocarbons	50–75% degradation	—	—	Rhizodegradation	Oil-contaminated soil	Ali et al. (2013)
<i>Terminalia arjuna</i>	Tree	Sediment metals	30–55%	0.7–1.2	<0.5	Soil stabilization	Riverbanks	Sarwar et al. (2017)
<i>Saccharum spontaneum</i>	Grass	River sediment metals	40–60%	1.0–1.7	0.5–0.9	Floodplain stabilization	Monsoon zones	Sarwar et al. (2017)
<i>Lemna minor</i>	Floating	Ammonia	65–90%	—	—	Direct uptake	Wastewater ponds	Vymazal (2018)
		Phosphate	60–85%	—	—	Nutrient assimilation	STP polishing	Rezania et al. (2016)

A quantitative comparison of reported removal efficiencies (Table 2) indicates that aquatic macrophytes demonstrate superior nutrient removal efficiencies (60–90%) compared to terrestrial species, which show moderate heavy metal stabilization efficiencies (30–70%). Grasses such as *Vetiveria zizanioides* exhibit higher bioaccumulation factors for lead and cadmium than tree species, suggesting stronger stabilization potential. In contrast, tree species show lower translocation factors (<0.5), indicating reduced risk of contaminant entry into the food chain. Floating species such as *Lemna minor* display the highest nutrient uptake rates, highlighting their suitability for tertiary wastewater polishing systems. These findings emphasize the necessity of habitat-specific plant selection for optimizing remediation performance under Maharashtra’s diverse agro-climatic conditions.

3.6 Relevance to Maharashtra’s Pollution Context

Urban rivers such as the Mula–Mutha experience seasonal variations in pollutant concentration, with elevated contamination during low-flow periods (Pawar et al., 2016). Native macrophytes adapted to monsoonal fluctuations are therefore advantageous. Additionally, industrial corridors and mining regions require species capable of tolerating heavy metal stress under semi-arid conditions (Lokhande & Singare, 2020). The use of native plants ensures ecological resilience, supports biodiversity, and aligns with state-level river restoration initiatives. When combined with microbial inoculation (e.g., AMF-assisted systems), remediation efficiency can be further enhanced (Begum et al., 2019; Upadhyaya et al., 2019).

4. Research Gaps and Future Directions

Although phytoremediation and bioremediation have been widely studied, important knowledge gaps remain, particularly in relation to region-specific applications such as Maharashtra. While foundational studies have clarified the mechanisms underlying plant-based remediation (Ali et al., 2013; Mahar et al., 2016), translation of these insights into consistent field-scale implementation remains limited. The following discussion outlines critical limitations and proposes directions for future investigation.

4.1 Limited Region-Specific Field Validation

A substantial proportion of phytoremediation research has been conducted under laboratory or greenhouse conditions, where environmental variables—including soil pH, moisture, and contaminant concentration are carefully controlled (Sarwar et al., 2017). Although such studies provide valuable mechanistic understanding, they do not fully capture the environmental variability characteristic of Maharashtra’s ecosystems. The state’s hydrology is strongly influenced by seasonal monsoons, leading to marked fluctuations in river flow, sediment transport, and pollutant concentrations. For

example, rivers such as the Mula–Mutha exhibit considerable differences in contaminant loads between monsoon and post-monsoon periods due to variations in dilution and discharge patterns (Pawar et al., 2016). These dynamic conditions directly affect plant growth, contaminant bioavailability, and nutrient removal performance. Nevertheless, long-term field validation of native plant species under such variable conditions remains insufficient. Future research should therefore emphasize multi-season monitoring of remediation efficiency, long-term assessment of biomass accumulation and contaminant partitioning, and evaluation of plant survival under realistic climatic stress. Establishing pilot-scale demonstration projects along contaminated river stretches would help bridge the gap between experimental findings and practical implementation.

4.2 Insufficient Integration of Native Species Databases

Despite Maharashtra's rich indigenous flora, systematic documentation of native species with phytoremediation potential remains fragmented. Existing research often prioritizes globally recognized hyperaccumulators, overlooking regionally adapted species that may perform more effectively under local climatic and soil conditions (Mahar et al., 2016). This lack of consolidated data restricts the development of targeted, context-specific remediation strategies. A structured regional database is therefore essential. Such a repository should compile plant physiological characteristics, bioaccumulation factors (BAF), translocation factors (TF), and pollutant-specific tolerance thresholds. Integrating these quantitative parameters would facilitate mechanism-based species selection and improve decision-making for site-specific applications. Additionally, ecological risk assessment must accompany species evaluation to ensure that large-scale deployment does not compromise native biodiversity or ecosystem balance.

4.3 Limited Understanding of Plant–Microbe Interactions

The importance of arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) in enhancing phytoremediation efficiency is well recognized (Begum et al., 2019; Upadhyaya et al., 2019). However, most studies have focused on agricultural crops under controlled settings, with comparatively limited investigation of native riparian and wetland species under field conditions. As a result, the long-term stability and resilience of plant–microbe interactions in contaminated tropical environments remain insufficiently understood. Future research should prioritize identification of indigenous AMF strains adapted to Maharashtra soils and assess microbial community dynamics during remediation processes. Investigating how heavy metal stress influences rhizosphere diversity and enzymatic activity is particularly important. Advanced molecular techniques, including metagenomic and metatranscriptomic analyses, could provide deeper insight into functional genes involved in contaminant degradation and nutrient cycling. Integrating microbial biotechnology with native plant systems may substantially enhance remediation performance and ecological stability.

4.4 Lack of Predictive Modeling and Quantitative Frameworks

Although many studies report percentage removal efficiencies, predictive modeling of contaminant uptake dynamics remains limited. Mechanistic understanding exists (Ali et al., 2013), yet kinetic and quantitative models are rarely applied to estimate long-term performance or scalability. This restricts the translation of experimental findings into practical planning tools. Future investigations should incorporate first-order and pseudo-second-order kinetic models to describe contaminant uptake behavior under varying environmental conditions. Development of a Remediation Efficiency Index (REI), integrating parameters such as removal rate, biomass productivity, bioaccumulation factor, and ecological adaptability, would enable standardized comparison across species. Coupling such models with GIS-based decision-support systems could enhance site-specific plant selection and facilitate policy adoption.

4.5 Integration with Remote Sensing and Geospatial Technologies

Satellite-based monitoring and geospatial analysis offer promising tools for evaluating vegetation health and water quality at landscape scales. Despite these advances, integration of phytoremediation systems with remote sensing remains limited (Liu et al., 2021). Most remediation assessments rely on localized sampling, restricting spatial and temporal coverage. Future research should explore the use of Sentinel-2–derived indices such as NDVI for vegetation health assessment, NDWI for hydrological monitoring, and NDCI for nutrient and algal detection. GIS-based mapping of pollutant hotspots and geospatial suitability analysis incorporating soil, hydrological, and contaminant data could improve strategic planning. Such approaches are particularly relevant for heterogeneous river systems like the Mula–Mutha.

4.6 Biomass Management and Secondary Contamination Risks

A key challenge of phytoextraction is the management of contaminant-laden biomass (Sarwar et al., 2017). Improper disposal may result in secondary pollution through leaching or uncontrolled decomposition. Sustainable biomass management strategies are therefore essential. Future studies should investigate biomass-to-energy conversion methods such as pyrolysis and gasification, which can immobilize contaminants while generating renewable energy. Phytomining may offer economic benefits in metal-rich contaminated sites. Composting applications should be evaluated through rigorous risk assessment to prevent contaminant remobilization. Developing economically viable biomass utilization frameworks will enhance the feasibility of large-scale implementation.

4.7 Climate Change and System Resilience

Climate variability—including rising temperatures and altered rainfall patterns—may significantly influence plant growth, soil chemistry, and pollutant mobility. Semi-arid and monsoon-dominated regions such as Maharashtra are particularly vulnerable to these fluctuations. Future research should evaluate drought tolerance of native species under contaminant stress and assess the effects of extreme rainfall on pollutant remobilization. Integrating climate projections into plant selection models can strengthen long-term restoration planning, especially for the Deccan Plateau and flood-prone river basins.

4.8 Policy Integration and Community Participation

Despite technical feasibility, phytoremediation adoption in India remains limited. The transition from research to implementation requires economic validation and institutional support. Comprehensive cost–benefit analyses comparing plant-based systems with conventional treatment technologies are needed to inform policy decisions. Community-based wetland restoration initiatives may enhance public participation and decentralized implementation. Integrating phytoremediation with national and state programs including Smart City and river rejuvenation missions—can strengthen funding mechanisms and regulatory backing. Policy-driven integration has the potential to shift phytoremediation from pilot-scale experimentation to mainstream environmental management.

4.9 Future Outlook: Hybrid and Integrated Systems

Sustainable remediation increasingly requires hybrid systems that combine biological and technological components. Native plant-based phytoremediation, AMF-assisted enhancement, engineered substrates, floating treatment wetlands, and remote sensing–based monitoring can function synergistically to improve efficiency and resilience (Liu et al., 2021). For Maharashtra, pilot demonstration projects integrating native macrophytes and AMF within floating wetland systems could provide scalable models for urban river restoration. Addressing gaps in field validation, microbial integration, predictive modeling, geospatial monitoring, biomass management, and policy linkage will be essential. An interdisciplinary, systems-oriented framework is necessary to ensure effective, resilient, and scalable remediation strategies.

CONCLUSION

The growing pressure on soil and water resources in Maharashtra, resulting from sustained industrial activity, expanding urban settlements, and intensified agricultural practices, underscores the need for environmentally sustainable and region-specific remediation approaches. This review demonstrates that native plant species offer considerable potential for phytoremediation and bioremediation within the state’s diverse ecological settings. Aquatic macrophytes such as *Typha angustifolia* and *Phragmites karka* show strong nutrient and organic load reduction in wetland-based systems, supporting their application in constructed wetlands and river polishing units.

In contrast, terrestrial grasses including *Vetiveria zizanioides* and *Cynodon dactylon* are particularly effective in stabilizing heavy metals in contaminated soils, while native tree species such as *Azadirachta indica* and *Terminalia arjuna* contribute to long-term soil stabilization, erosion control, and ecosystem recovery. Comparative assessments suggest that aquatic plants provide rapid nutrient attenuation, whereas grasses and trees offer sustained contaminant immobilization and structural restoration.

The incorporation of plant–microbe interactions, especially through arbuscular mycorrhizal fungi (AMF), further enhances plant resilience under contaminant stress and improves remediation performance. Nevertheless, the transition from controlled experimental studies to large-scale field application in Maharashtra remains limited. Future initiatives should prioritize mechanism-based species selection, site-specific performance evaluation, and integration with geospatial monitoring frameworks. Hybrid systems that combine native vegetation, microbial inoculation, engineered filtration substrates, and floating treatment wetlands hold significant promise for scalable river and soil restoration.

Additionally, considerations related to biomass management, climate variability, and policy integration are critical for ensuring long-term sustainability. Overall, the strategic use of Maharashtra’s indigenous flora represents a practical and ecologically sound pathway toward restoring degraded environments. A coordinated, multidisciplinary approach that integrates biological processes with technological innovation can facilitate sustainable remediation and support ongoing river rejuvenation and land restoration efforts across the region.

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