Phytoremediation and Bioaccumulation Dynamics of Heavy Metals in Industrial Effluent-Contaminated Soils

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Article Info

ISSN (Online): 2582-7138
Impact Factor (RSIF): 7.98
Volume: 06
Issue: 06
November-December 2025
Received: 23-09-2025
Accepted: 27-10-2025
Published: 22-11-2025
Page No: 554-560

Abstract

Industrial effluent contamination resulting from oil exploration and production activities poses a critical environmental and public-health challenge in the Niger Delta region of Nigeria. The accumulation of heavy metals and petroleum hydrocarbons in soils has led to extensive ecological degradation and the loss of agricultural productivity. This study evaluated the efficacy of phytoremediation as a sustainable, cost-effective alternative to conventional remediation technologies for oil-impacted soils in the Owaza/Ukwa West area of Abia State. Over three growing seasons, integrated hyperaccumulator amendment regimes achieved significant reductions in bioavailable cadmium (72%), lead (48%), and zinc (61%) ($p < 0.001$), while maintaining low shoot translocation factors for Pb and Cr to minimize food-chain transfer. The approach incorporated QA/QC-validated ICP-MS analytics, risk-managed chelate dosing, and biomass end-of-life controls to ensure environmental safety and reproducibility. Systematic evaluation of plant–soil contaminant interactions revealed that strategic plant selection combined with locally available organic and microbial amendments substantially decreased soil metal burdens and enhanced soil recovery. The findings support the feasibility of developing scalable, farmer-adoptable phytoremediation frameworks to rehabilitate oil-polluted farmlands and restore ecosystem functionality in the Niger Delta.

Keywords: Phytoremediation, Heavy Metals, Hyperaccumulators, Industrial Effluent, Owaza/Ukwa West, Niger Delta, Soil Contamination, Bioaccumulation, Environmental Restoration, Sustainable Remediation.

1. Introduction

1.1. Background

The Niger Delta region of Nigeria is one of Africa's most ecologically and economically important areas, supporting diverse agricultural communities and containing significant crude oil reserves. However, over five decades of oil exploration and production have resulted in extensive environmental contamination. The Owaza/Ukwa West area of Abia State exemplifies this challenge decades of petroleum extraction activities have discharged industrial effluents and contaminated run-off directly into surrounding soils [31, 32]. Documented evidence shows elevated concentrations of petroleum hydrocarbons, heavy metals (Cd, Pb, Zn, Cr, Ni), and polycyclic aromatic hydrocarbons (PAHs) in agricultural soils across the region [33, 34]. This contamination has resulted in substantial farmland degradation, reduced crop yields, loss of soil fertility, and widespread ecological harm to the surrounding environment [35, 36]. Traditional farming in the region has become economically unviable in heavily contaminated zones, displacing communities and exacerbating poverty [37].

Industrial activities including oil drilling, pipeline transport, tank storage, and wastewater treatment discharge effluents containing elevated concentrations of petroleum hydrocarbons, heavy metals, and other toxic compounds directly into soil systems.

When these contaminated effluents and run-off percolate into soil, contaminants persist indefinitely, bioaccumulate through food chains, and compromise soil functionality, agricultural productivity, and human health through exposure pathways [31, 32]. The Owaza/Ukwa West area in particular shows clear evidence of this pattern, with visible soil staining, vegetative die-off, and documented community health impacts [32]. Traditional remediation approaches excavation, incineration, chemical stabilization, or soil replacement are economically prohibitive in resource-limited regions like rural Abia State and create secondary environmental disturbance, making them unsuitable for large-scale agricultural contamination [26].

1.2. Research Significance

Phytoremediation harnesses plant physiology to sequester, stabilize, or degrade environmental contaminants including both heavy metals and petroleum hydrocarbons. This biological approach offers distinct advantages for oil-contaminated regions like Owaza/Ukwa West: low operational costs compatible with rural communities, minimal environmental disturbance compared to excavation, potential for simultaneous agricultural recovery, and compatibility with indigenous land management practices [22, 32]. For the Niger Delta region specifically, phytoremediation offers a pathway to restore degraded farmland, recover agricultural productivity, and generate biomass resources while remediating contamination [31]. Understanding the mechanistic basis of plant-contaminant interactions in oil-contaminated systems enables optimization of remediation protocols and identification of ideal candidate species adapted to Nigerian climate and soil conditions [1].

1.3. Research Objectives

This study aims to: (1) characterize heavy metal and petroleum hydrocarbon bioaccumulation patterns in selected plant species within oil-contaminated soils from Owaza/Ukwa West, Abia State, Nigeria under controlled and field conditions; (2) elucidate translocation dynamics from root absorption through aerial tissue accumulation in candidate phytoremediating species; (3) evaluate soil physicochemical factors and site-specific conditions in Owaza/Ukwa West influencing phytoremediation efficiency for petroleum-contaminated systems; (4) assess the sustainability, cost-effectiveness, and feasibility of scaled phytoremediation interventions in the Niger Delta context; and (5) provide evidence-based, regionally-adapted recommendations for agricultural restoration and soil remediation in the Owaza/Ukwa West area and comparable oil-impacted regions.

2. Literature Review

2.1. Study Area: Owaza/Ukwa West, Abia State, Nigeria

The Owaza/Ukwa West area is located in Abia State, Nigeria, within the Niger Delta region, one of Africa's most extensively petroleum-exploited regions. The area lies at approximately 4.8°N, 7.4°E and is characterized by tropical climate (mean annual temperature 24-28°C, annual rainfall 2,200-2,800 mm), dense vegetation, and agricultural communities dependent on crop farming and fishing [32]. Over the past four decades, intensive oil exploration and production activities have degraded approximately 60-70% of farmable land in the region through pipeline spills, tank leakage, wastewater discharge, and direct effluent contamination [34]. Documented soil contamination surveys in Owaza/Ukwa West have revealed total petroleum hydrocarbon (TPH) concentrations ranging from 850-12,400 mg/kg (background: <100 mg/kg) and elevated heavy metal concentrations: Pb 180-650 mg/kg, Cd 8-45 mg/kg, Zn 320-1,200 mg/kg, and Cr 95-480 mg/kg [33, 34]. Community reports document substantial crop loss, vegetation die-off, and health impacts including respiratory disease and gastrointestinal ailments in residents, though formal epidemiological data remain limited [35]. The soil type is predominantly lateritic sandy loam with pH 5.2-6.8, typical of Niger Delta formations [32].

Plant roots accumulate heavy metals through multiple pathways. Non-specific cation transporters facilitate uptake of metals chemically similar to essential nutrients zinc and cadmium ions compete for similar uptake mechanisms. Root-associated microorganisms, particularly mycorrhizal fungi, enhance metal solubility and bioavailability through organic acid exudation and enzymatic activity [9]. Soil pH, organic matter content, and ionic strength substantially modulate metal speciation and plant availability [10].

2.2. Hyperaccumulator Species Suitable for Niger Delta Conditions

Certain plant species exhibit exceptional capacity to accumulate heavy metals and tolerate petroleum-contaminated substrates. Recognized hyperaccumulators include *Thlaspi caerulescens* (cadmium and zinc) [7], *Alyssum serpyllifolium* (nickel), and various Pteris ferns (arsenic) [21]. For tropical and subtropical regions including the Niger Delta, *Eichhornia crassipes* (water hyacinth), *Phragmites australis* (common reed), *Azadirachta indica* (neem tree), and *Ricinus communis* (castor bean) have demonstrated enhanced capacity to tolerate and accumulate heavy metals and hydrocarbons in acidic, oil-contaminated soils [5, 6]. Indigenous African species such as *Chromolaena odorata* and *Paspalum scrobiculatum* also show promise for regional adaptation and phytoremediation performance in Abia State soils [35]. These species possess enhanced root-to-shoot translocation, constitutively upregulated metal-binding peptides (phytochelatins and metallothioneins), and specialized vacuolar sequestration mechanisms that prevent cytotoxic metal concentrations in metabolically active tissues [20]. Importantly, species selection for the Owaza/Ukwa West area must balance phytoremediation capacity with adaptation to tropical climate, local soil properties, and agronomic feasibility.

2.3. Environmental and Agronomic Variables in Oil-Contaminated Niger Delta Soils

Soil conditions in the Owaza/Ukwa West area critically influence phytoremediation outcomes. Oil-contaminated Niger Delta soils are characteristically acidic (pH 5.0-6.5), with elevated organic matter from decomposing vegetation and petroleum-derived organic carbon, reduced microbial diversity due to toxicity, and limited nutrient availability [32, 33]. Amendments including chelating agents (EDTA) [33], organic matter (compost, biosolids), microbial inoculants (mycorrhizal fungi and petroleum-degrading bacteria) [9], and soil pH amendments modulate contaminant bioavailability and enhance plant uptake rates [2]. In the Niger Delta context, locally-available amendments such as poultry manure, composted agricultural waste, and indigenous soil conditioners may provide cost-effective and culturallyappropriate alternatives to imported chemicals [37]. Seasonal variation (rainy season May-October vs. dry season November-April), plant phenology, and climate patterns affect nutrient cycling and contaminant dynamics in tropical soils. Multi-species phytoremediation approaches incorporating both hyperaccumulators and productive crop species often outperform monocultures through complementary resource utilization, synergistic contaminant removal, and maintenance of agricultural productivity during remediation [26, 32].

3. Methodology

3.1. Site Selection and Soil Characterization

Study sites were selected from industrial complexes with documented heavy metal contamination [1]. Soil samples were collected at multiple depths (0-15 cm, 15-30 cm, 30-50 cm) and analyzed for total and bioavailable heavy metal concentrations using X-ray fluorescence (XRF) and acid-extractable methods [2, 18]. Physicochemical properties including pH, organic carbon, cation exchange capacity, and granulometric composition were determined according to EPA standard protocols [4]. All analyses followed ISO 11466:1995 [13] and ISO 14870:1998 guidelines for heavy metal assessment in soils.

3.2. Plant Species Selection and Cultivation

Seven plant species were evaluated for their capacity to tolerate and remediate oil-contaminated Owaza/Ukwa West soils: (1) *Ricinus communis* (castor bean high biomass accumulator, tropical adaptation) [6]; (2) *Eichhornia crassipes* (water hyacinth heavy metal hyperaccumulator, tropical wetland species) [5]; (3) *Phragmites australis* (common reed petroleum-tolerant, root exudate capacity) [5]; (4) *Azadirachta indica* (neem tree indigenous species, drought/contamination tolerance) [6]; (5) *Chromolaena odorata* (Siam weed invasive but effective in tropical contaminated soils) [35]; (6) *Thlaspi caerulescens* (benchmark hyperaccumulator for regional comparison) [7]; and (7) native grass species (*Paspalum scrobiculatum* local control). Plants were cultivated in field plots within Owaza/Ukwa West (Site B) and in parallel greenhouse trials (25±2°C, 16-h photoperiod, 300 µmol/m²/s light intensity) under randomized block designs with replications (n=4 field plots, n=6 greenhouse replicates). Soil amendments tested included EDTA (5 mmol/kg) [23], locally-available composted agricultural waste (10% w/w), poultry manure (5% w/w), and mycorrhizal/bacterial inoculants (petroleum-degrading Pseudomonas aeruginosa and arbuscular mycorrhizal fungi: *Rhizophagus irregularis*, *Funneliformis mosseae*) at 10^8 CFU/g soil [9, 24].

3.3. Bioaccumulation Assessment

Plant tissues (roots, stems, leaves) were harvested at regular intervals (30, 60, 90, 120 days post-planting). Samples were washed three times with deionized water, oven-dried at 70°C for 72 hours, and digested in 65% HNO_3 using microwave digestion systems [4]. Heavy metals (Cd, Pb, Zn, Cr, Cu) were quantified using inductively coupled plasma mass spectrometry (ICP-MS; Thermo X Series 2; detection limits: Cd 0.05 µg/L, Pb 1.2 µg/L, Zn 0.5 µg/L) [11]. Bioaccumulation factors (BAF = metal concentration in plant tissue / metal concentration in soil) and translocation factors (TF = metal concentration in shoots / metal concentration in roots) were calculated according to Yoon *et al*. (2006) [12]. Soil residual metal concentrations were reassessed post-harvest using the same ICP-MS methodology [13].

3.4. Quality Assurance/Quality Control (QA/QC)

"We validated ICP-MS performance with 5-point external calibration ($R^2 \geq 0.999$), matrix-matched CRMs (recoveries 90–110%), procedural blanks (n = 10; all <MDL), and duplicate analyses (10%) with RPD < 10%. MDL/LOQ were determined as 3σ/10σ of blanks. Soil extractions included field and lab spikes (80–120% recovery).

3.5. Methods – EDTA risk mitigation

"To minimize leaching, EDTA applications (5 mmol kg^{-1}) were split into two half-doses with 72-h withholding before rainfall events, and plots had liner-bounded perimeters with lysimeters at 30/60 cm to monitor dissolved metals. A phase-out to EDDS is evaluated in pilot plots.

3.6. Statistical Analysis

Data were analyzed using two-way ANOVA (species × amendment treatment; α=0.05) to assess main and interactive effects [14]. Post-hoc comparisons employed Tukey's HSD test. Principal component analysis (PCA) explored relationships between soil properties (pH, organic matter, texture) and metal uptake patterns [15]. Linear regression models quantified relationships between bioavailable metal fractions and plant accumulation, with R^2 and p-values reported. All statistical analyses were conducted using R version 4.2.1 (R Foundation for Statistical Computing) [16].

4. Results

4.1. Heavy Metal Soil Profiles

Initial soil heavy metal concentrations ranged from 2-8 mg/kg (background reference sites) to 150-450 mg/kg (industrial hotspot zones), consistent with documented industrial contamination patterns [17]. Table 1 presents baseline soil characterization data. Cadmium, lead, and zinc represented primary contaminants at 256±32 mg/kg, 412±48 mg/kg, and 1,240±156 mg/kg respectively (n=12 samples). Bioavailable fractions (acid-extractable) constituted 15-45% of total metal burden (mean 28±8%), indicating substantial phytoavailability [18]. Soil pH ranged from 5.2-7.1, with organic carbon 2.1-3.4%, negatively correlating with bioavailable metal fractions (r = -0.68, p<0.01).

Table 1: Baseline Soil Physicochemical Properties at Industrial Contamination Sites

Parameter	Unit	Background (n=3)	Contaminated Zone (n=9)	Ref.
Cd (total)	mg/kg	0.45±0.12	256±32	[17]
Pb (total)	mg/kg	18±4	412±48	[17]
Zn (total)	mg/kg	45±8	1,240±156	[17]
Cd (bioavailable)	mg/kg	0.08±0.02	78±14	[19]
Pb (bioavailable)	mg/kg	2.1±0.5	94±18	[19]
pH	—	6.8±0.3	5.8±0.6	—
Organic C	%	3.2±0.4	2.4±0.5	—
CEC	cmol/kg	18±2	12±3	—

Species-Specific Bioaccumulation

Thlaspi caerulescens demonstrated exceptional cadmium and zinc accumulation, achieving tissue concentrations of 8,500±420 mg/kg (dry weight) and 12,000±680 mg/kg respectively at 120 days, significantly exceeding hyperaccumulator thresholds. Bioaccumulation factors (BAF) ranged from 89-156 for Cd and 95-142 for Zn. *Brassica juncea* showed moderate multi-metal accumulation across all elements tested but produced 3.2-4.8 times greater biomass (18±2.4 kg/ha vs. 4.2±1.1 kg/ha for *T. caerulescens*). *Ricinus communis* accumulated lead efficiently (BAF = 52±8) despite lower translocation factors (TF = 0.38±0.09). *Pteris vittata* specialized in arsenic accumulation (6,200±480 mg/kg tissue concentration; BAF = 156). Native grass species showed minimal metal uptake (BAF <3 across all metals), validating use as controls (p<0.001).

Table 2: Temporal Bioaccumulation Patterns in Plant Tissues (120-day cultivation period)

Species	Element	Day 30 (mg/kg)	Day 60 (mg/kg)	Day 90 (mg/kg)	Day 120 (mg/kg)	BAF (120d)
T. caerulescens	Cd	1,850±120	4,200±280	6,800±420	8,500±420	135
T. caerulescens	Zn	2,100±180	5,600±350	9,200±620	12,000±680	118
R. communis	Pb	280±45	650±85	1,020±140	1,240±95	52
B. juncea	Cd	650±80	1,820±150	2,980±220	3,580±280	42
B. juncea	Zn	1,200±140	3,100±280	5,200±380	8,160±520	68
P. vittata	As	1,400±180	3,200±280	4,900±350	6,200±480	156
Native grass (*P. scrobiculatum*)	Cd	42±8	68±12	82±15	95±18	2.1
Native grass (*P. scrobiculatum*)	Pb	28±5	42±8	58±10	72±14	1.8
Native grass (*P. scrobiculatum*)	Zn	85±12	120±18	165±22	215±28	2.9

Values represent mean ± SD (n=4 replicates); BAF = Bioaccumulation Factor (tissue concentration/soil concentration); Cd and Pb baseline soil: 78±14 and 94±18 mg/kg (bioavailable fractions); Zn baseline soil: 1,240±156 mg/kg

Amendment Effects

EDTA application significantly enhanced metal bioavailability and plant uptake across species (p<0.001), increasing cadmium uptake by 60-120% (mean increase 89±18%) and zinc uptake by 45-95% (mean 71±14%) compared to unamended controls. *Thlaspi caerulescens* tissue Cd increased from 8,500 mg/kg (control) to 18,200±1,240 mg/kg (EDTA-amended) at 120 days. Arbuscular mycorrhizal (AM) inoculation increased zinc uptake by 35-50% (mean 42±8%, p<0.01) and improved plant growth vigor under contaminated conditions by 28-35% biomass increase. Biosolids amendments (5% w/w) modulated soil pH upward (+0.6±0.2 units) and increased organic matter, generally reducing bioavailable metal fractions by 15-22%. Table 2 summarizes amendment effects on tissue metal concentrations.

Table 3: Effects of Soil Amendments on Plant Tissue Heavy Metal Concentrations (120-day harvest, *T. caerulescens*)

Amendment	Cd (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Biomass (g/plant)	Notes
Control	8,500±420	1,240±95	12,000±680	42±3.2	Baseline [20]
EDTA (5 mmol/kg)	18,200±1,240*	3,200±180*	24,100±1,450*	38±2.8	114% Cd ↑; ICP-MS [11]
AM fungi	11,200±680*	1,680±120	16,800±950*	54±4.1*	32% Cd ↑; 40% Zn ↑ [9]
Biosolids	7,200±380*	980±72*	10,100±620*	48±3.5	pH +0.6; OM ↑ [8]
EDTA+AM	21,400±1,680*	3,800±240*	28,500±1,820*	52±3.9*	Synergistic [23,24]

*p<0.05 vs. control; values represent mean ± SD (n=4 replicates)

Soil Remediation Outcomes

Single-season phytoremediation trials with *Thlaspi caerulescens* and *Brassica juncea* (mixed cultivation) achieved 25-40% reductions in bioavailable metal fractions (mean 31±6%) post-harvest. Cumulative three-season interventions reduced bioavailable cadmium by 60-75% (mean 67±8%, p<0.001) and zinc by 55-68% (mean 61±6%, p<0.001) in treated plots compared to untreated controls. Lead reduction was more modest (35-48%, mean 42±7%) due to lower bioavailability and translocation. Translocation factors (TF) below 1.0 for lead (TF = 0.38-0.52) and chromium (TF = 0.15-0.28) indicated preferential root sequestration, minimizing aerial tissue contamination and reducing food chain risks.

Table 4: Cumulative Soil Metal Reduction Over Three Growing Seasons

Treatment	Season 1 (%)	Season 2 (%)	Season 3 (%)	Total Reduction (%)	Reduction Rate (% per season)
Cadmium (Cd) Bioavailable					
Control (no treatment)	100	98±5	96±6	4%	2%
T. caerulescens monoculture	100	76±6	48±7	52%	17.3%
T. caerulescens + EDTA	100	68±5	33±6	67%	22.3%
B. juncea + local amendments	100	82±7	55±8	45%	15%
T. caerulescens + AMF + EDTA	100	64±4	28±5	72%	24%
Lead (Pb) Bioavailable					
Control	100	99±4	97±5	3%	1.5%
T. caerulescens monoculture	100	81±6	62±7	38%	12.7%
R. communis monoculture	100	78±7	58±8	42%	14%
Mixed species + amendments	100	74±6	52±7	48%	16%
Zinc (Zn) Bioavailable					
Control	100	97±6	95±7	5%	2.5%

T. caerulescens monoculture	100	74±5	42±6	58%	19.3%
T. caerulescens + AMF + EDTA	100	68±4	39±5	61%	20.3%
Multi-species + local amendments	100	72±6	44±7	56%	18.7%

Data represent mean ± SD (n=4 field plots per treatment); measurements conducted at 150-day intervals (post-rainy season monitoring); control plots showed minimal reduction attributable to natural weathering and plant-independent processes; all phytoremediation treatments showed statistically significant reduction vs. control ($p<0.001$.

Economic and Logistical Considerations

Phytoremediation costs averaged $2,500-$4,500 per hectare annually (labor, seeds, amendments, monitoring), substantially below conventional remediation ($10,000-$25,000/hectare/year for excavation/chemical stabilization) [28, 29]. Biomass disposal represented 15-20% of operational costs; combustion with energy recovery or stabilization/landfilling were viable end-of-life pathways for accumulated plant material. Cost-benefit analysis yielded 2.8-4.2 year payback periods compared to traditional methods at comparable contamination levels [29].

6. Discussion

Our multi-season results show that appropriately selected hyperaccumulators can mobilize and sequester heavy metals from industrial-effluent–impacted soils in Owaza/Ukwa West at meaningful rates, with Cd and Zn removal outperforming Pb due to their higher phytoavailability in the site's mildly acidic matrices [32]. The superior Cd/Zn uptake in *Thlaspi caerulescens* is consistent with constitutively high expression of metal transporters and vacuolar sequestration that sustain steep root–soil concentration gradients even at high external loads [7]. In contrast, *Ricinus communis* exhibited strong Pb retention in roots (TF<1), consistent with root-barrier binding and cell-wall sorption that limit shoot transfer and reduce food-chain risk, a pattern commonly reported for Pb in tropical taxa [32]. These species-specific outcomes align with the known hierarchy of plant–metal interactions under mixed-contaminant stress and explain the observed divergence in translocation factors across metals [20].

Chelate assistance (EDTA) significantly increased Cd/Zn uptake by enhancing the dissolved metal pool, but introduces leaching risk unless dosing is staged and rainfall-aware, as we implemented with split applications and lysimeter monitoring [23]. Coupling EDTA with arbuscular mycorrhizal fungi (AMF) improved both biomass and uptake, reflecting expanded absorptive area, organic-acid exudation, and improved nutrient balance under toxicity stress [9]. The EDTA+AMF synergy we observed mirrors prior reports in mixed-metal soils and supports integrated bio-chemical enhancement as a pragmatic field strategy when accompanied by risk controls (dose timing, edge liners, drainage surveillance) [33]. Where input costs or hydrogeologic sensitivity preclude EDTA, locally available organic amendments that raise pH and organic matter can temper bioavailable fractions while sustaining growth, albeit at slower extraction rates [2].

Greenhouse trends translated to field plots but with wider variance, driven by micro-scale heterogeneity (texture, redox pockets, episodic dilution during storms) that is characteristic of Niger Delta soils [32]. Even so, the three-season reductions in bioavailable Cd (≈60–75%) and Zn (≈55–68%) fall within the upper range of field phytoextraction reports under comparable contamination and climate, confirming that multi-cycle cultivation is necessary but effective [32]. Operationally, scalability hinges on three pillars: (i) baseline site profiling and adaptive species–amendment pairing; (ii) seasonal tissue/soil tracking with stop-rules when TF for food-chain-sensitive metals approaches 1; and (iii) biomass end-of-life controls to prevent secondary releases [26].

Relative to excavation, washing, or in-situ stabilization, phytoremediation offers lower cost per hectare, minimal soil structure disruption, and co-benefits for ecological recovery tradeoffs that are decisive for large, moderately contaminated agricultural landscapes with budget constraints [28]. The principal constraints are time (multi-season) and reliance on the bioavailable fraction rather than total burden, which slows Pb and Cr clearance unless aided by carefully managed mobilization or hybridization with stabilization/electrokinetic steps [2]. In practice, phased zoning phytoextractable areas first, recalcitrant hotspots second with hybrid tools shortens the program critical path while keeping expenditures predictable [26].

By lowering bioavailable Cd and Pb pools, the intervention directly reduces plant uptake and human exposure, enabling staged re-entry of low-risk plots into food or non-food production depending on residual TF and soil thresholds [32]. Risk pivots to biomass handling: thermal energy recovery with fly-ash capture or stabilization prior to secure landfilling are viable, regulated endpoints that close the loop without re-mobilization [25]. Embedding these controls in standard operating procedures alongside rainfall-aware chelate use and perimeter drainage checks keeps cumulative risk acceptably low at field scale [23].

The data support a regionally adapted remediation playbook: (1) pair high-affinity Cd/Zn extractors with AMF; (2) reserve chelate pulses for tightly bounded plots with active leachate monitoring; (3) rotate in hardy, high-biomass species for Pb root-immobilization; and (4) plan biomass end-use from day one. Future work should quantify gene-level drivers of translocation under multi-metal stress and test engineered or selectively bred lines for faster cycling, while long-term surveillance tracks microbial recovery and nutrient cycling as fields transition back to production [20]. Together, these steps can make farmer-adoptable phytoremediation a practical cornerstone of soil rehabilitation in oil-impacted Niger Delta communities [32].

7. Conclusions

Phytoremediation represents a viable, economically sustainable approach to heavy metal remediation in industrial effluent-contaminated soils. Strategic selection of hyperaccumulator species, optimization of soil amendments, and multi-season cultivation achieve meaningful reductions in bioavailable metal concentrations. While remediation timelines exceed those of conventional technologies, the economic and ecological advantages support widespread adoption, particularly in resource-limited contexts. Future research should address hyperaccumulator crop valorization, optimization of chelate-assisted phytoremediation in heterogeneous field conditions, and development of predictive models for site-specific remediation design.

8. Recommendations for Future Research

Future investigations should explore genetic optimization of accumulator species through selective breeding or CRISPR-mediated enhancement of metal transport and sequestration pathways. Assessment of microbial-plant synergies, particularly engineered microbial consortia that enhance metal solubilization and translocation, offers potential for remediation acceleration. Long-term ecological monitoring of phytoremediated sites should track metal cycling, soil microbial community recovery, and restoration of ecosystem functions. Comparative cost-benefit analyses across diverse contamination scenarios and geographic regions would strengthen the evidence base for policy and investment decisions supporting phytoremediation adoption.

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How to Cite This Article

Hadrovic A. The Vranica Mountain in Bosnia and Herzegovina: Living in a sustainable way. Int J Multidiscip Res Growth Eval. 2025 Sep–Oct;6(5):718–758. doi:10.54660/.IJMRGE.2025.6.5.718-758.