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Pa **Comparative Phytoremediation Efficiency of Legume Species: A Review of Metal Accumulation, Biomass Production, and Remediation Mechanisms**

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Abstract: Leguminous plants have emerged as promising candidates for phytoremediation due to their nitrogen-fixing capabilities, high biomass production, and metal tolerance. This review systematically compares phytoremediation efficiency across major legume species, focusing on quantitative performance metrics, metal accumulation patterns, biomass production, and underlying mechanisms. Analysis of comparative studies reveals significant interspecific variation in remediation strategies and efficiency. *Medicago sativa* (alfalfa) demonstrates superior biomass production (up to 15 t/ha dry weight) and moderate metal accumulation, making it suitable for phytostabilization. *Lupinus* species exhibit high metal translocation factors (>1.0 for Cd and Zn) and bioconcentration capabilities, positioning them as effective phytoextractors. *Sesbania* species show exceptional tolerance to extreme contamination levels while maintaining growth. *Trifolium* species display balanced accumulation-biomass profiles suitable for multi-metal contaminated sites. Species-specific differences in root architecture, symbiotic associations, and biochemical tolerance mechanisms significantly influence remediation outcomes. This review provides quantitative benchmarks for species selection based on contamination type, remediation goals, and site conditions, offering practical guidance for implementing legume-based phytoremediation strategies.

Keywords: phytoremediation, legumes, heavy metals, bioaccumulation, translocation factor, biomass production, comparative analysis

I. INTRODUCTION

Soil contamination by heavy metals and metalloids poses severe threats to ecosystem health, agricultural productivity, and human well-being. Phytoremediation—the use of plants to remove, stabilize, or degrade contaminants—offers an economically viable and environmentally sustainable alternative to conventional remediation technologies [1]. Among candidate plant families, legumes (Fabaceae) present unique advantages including symbiotic nitrogen fixation, rapid biomass accumulation, deep root systems, and inherent stress tolerance mechanisms [2], [3].

The effectiveness of phytoremediation depends critically on species-specific traits including metal uptake capacity, translocation efficiency, biomass production, and tolerance to toxic concentrations [4]. While numerous studies have evaluated individual legume species, systematic comparative analyses quantifying performance differences remain limited. Understanding interspecific variation in remediation efficiency is essential for rational species selection tailored to specific contamination scenarios and remediation objectives.

This review synthesizes comparative data on phytoremediation performance across major legume genera including *Medicago*, *Lupinus*, *Trifolium*, *Vicia*, *Sesbania*, *Vigna*, *Cicer*, *Crotalaria*, and *Robinia*. We focus on three critical performance dimensions: (1) metal accumulation patterns and translocation efficiency, (2) biomass production under contamination stress, and (3) underlying biochemical and physiological mechanisms. By integrating quantitative metrics from field and greenhouse studies, this review provides evidence-based benchmarks to guide species selection for diverse phytoremediation applications.

2. Comparative Metal Accumulation Patterns

2.1 Heavy Metal Uptake and Distribution

Legume species exhibit marked differences in metal uptake capacity and tissue distribution patterns. Comparative studies on arsenic (As) accumulation revealed that *Crotalaria spectabilis* achieved translocation indices of 81% and 75% at 100 and 200 mg/dm³ As, respectively, indicating strong phytoextraction potential [2]. In contrast, *Canavalia ensiformis* and *Stizolobium aterrimum* accumulated As primarily in roots (127.80-269.45 mg/kg and 153.19-271.77 mg/kg, respectively), suggesting phytostabilization strategies [2].

For multi-metal contaminated soils, *Lupinus albus* demonstrated superior accumulation of Cd, Pb, and Zn compared to *Vicia sativa* and *Fagopyrum esculentum* [13]. *Lupinus* species consistently show high bioconcentration factors (BCF > 1) for Cd and Zn, with some cultivars achieving shoot concentrations exceeding 100 mg/kg Cd under field conditions [15]. Studies on four Fabaceae species (*Vicia faba*, *Cicer arietinum*, *Lens culinaris*, *Phaseolus vulgaris*) exposed to Pb, Zn, and Cd revealed species-specific translocation and bioaccumulation factors, with *V. faba* showing the highest root accumulation while *C. arietinum* exhibited greater shoot translocation [1].

2.2 Translocation Efficiency and Phytoextraction Potential

Translocation factor (TF = shoot concentration/root concentration) serves as a key indicator distinguishing phytoextraction (TF > 1) from phytostabilization (TF < 1) strategies. *Lupinus* species consistently demonstrate TF values exceeding 1.0 for Cd and Zn, indicating efficient root-to-shoot translocation [15]. *Crotalaria spectabilis* similarly exhibits high TF values (>0.75) for As, supporting its classification as a phytoextractor [2].

Conversely, *Medicago sativa* typically maintains TF < 0.5 for most heavy metals, accumulating contaminants predominantly in root tissues while producing substantial aboveground biomass [25], [26]. This pattern makes alfalfa particularly suitable for phytostabilization applications where the goal is to immobilize contaminants and prevent their entry into food chains. *Trifolium repens* shows intermediate TF values (0.4-0.8), providing balanced accumulation across root and shoot tissues [30].

2.3 Metalloid and Organic Contaminant Responses

Beyond heavy metals, legume species show differential responses to metalloids and organic pollutants. For petroleum hydrocarbon contamination, *Samanea saman* and *Mimosa artemisiana* significantly reduced total petroleum hydrocarbons (TPH), while *Acacia angustissima* and *Mimosa caesalpiniifolia* exhibited tolerance without substantial TPH reduction [20]. Eight legume species tested for heavy fuel oil remediation showed *Trifolium pratense* and *Medicago lupulina* achieving the highest germination rates and biomass production under contamination stress [14].

Medicago falcata and *M. sativa* demonstrated comparable oil-sludge remediation potential, with both species reducing hydrocarbon concentrations by 30-45% over growing seasons, though *M. falcata* showed slightly better tolerance to aged contamination [25]. These findings highlight that remediation efficiency for organic contaminants depends more on rhizosphere microbial activity than direct plant uptake, contrasting with metal phytoremediation mechanisms.

3. Biomass Production and Growth Performance

3.1 Biomass Yield Under Contamination Stress

Biomass production represents a critical determinant of total contaminant removal capacity, as phytoextraction efficiency equals tissue concentration multiplied by biomass yield. *Medicago sativa* consistently produces the highest biomass among legumes, achieving 10-15 t/ha dry weight even on moderately contaminated soils [19], [26]. This exceptional productivity, combined with moderate metal accumulation, results in substantial total metal removal despite lower tissue concentrations compared to hyperaccumulators.

In contrast, metal exposure significantly reduced biomass in several species. Arsenic at 200 mg/dm³ decreased shoot biomass by 41% in *S. aterrimum*, 47% in *C. ensiformis*, and 43% in *C. spectabilis*, with root biomass reductions of 9%, 50%, and 29%, respectively [2]. Similarly, Pb, Zn, and Cd contamination reduced growth rates across *V. faba*, *C. arietinum*, *L. culinaris*, and *P. vulgaris*, though species differed in sensitivity [1].

3.2 Growth Tolerance and Adaptation

Species-specific tolerance to contamination stress varies substantially. *Sesbania* species demonstrate exceptional tolerance, maintaining growth even on extreme Pb/Zn and Cu mine tailings where most vegetation fails [23]. Among four *Sesbania* species tested, *S. sesban* and *S. cannabina* showed superior establishment and growth on tailings, though all species exhibited reduced biomass compared to uncontaminated controls [23].

Robinia pseudoacacia exhibits genotypic variation in Cd tolerance, with high-accumulating genotypes maintaining 70-80% of control biomass at 50 mg/kg Cd, while low-accumulating genotypes showed 40-50% reductions [27]. This intraspecific variation suggests potential for breeding programs to develop cultivars optimized for specific remediation scenarios.

Perennial legumes including *Medicago sativa*, *Trifolium pratense*, and *Lotus corniculatus* demonstrate sustained biomass production over multiple growing seasons, providing cumulative metal removal exceeding that of annual species [21]. Multi-year field trials showed these perennials maintained 60-75% of control biomass on contaminated sites, with gradual increases over time as soil conditions improved [21].

3.3 Root Architecture and Soil Exploration

Root system architecture significantly influences remediation efficiency by determining soil volume explored and rhizosphere extent. *Lupinus* species develop deep taproots (>1 m) with extensive lateral branching, enabling access to deep contamination and large rhizosphere volumes [15]. *Medicago sativa* similarly produces deep root systems (2-3 m), facilitating remediation of subsurface contamination layers [26].

In contrast, *Trifolium* species develop shallower, more fibrous root systems effective for treating surface contamination (0-30 cm depth) [30]. *Vigna* and *Phaseolus* species show intermediate root depths (30-60 cm) suitable for agricultural topsoil remediation [1]. Root architecture thus represents a key selection criterion matching species to contamination depth profiles.

4. Species-Specific Remediation Mechanisms

4.1 Biochemical Tolerance Mechanisms

Legume species employ diverse biochemical strategies to tolerate metal toxicity. Antioxidant enzyme systems (superoxide dismutase, catalase, peroxidase) show species-specific induction patterns under metal stress. Studies on four Fabaceae species revealed differential antioxidant responses, with *V. faba* showing the highest enzyme activities under Pb/Zn/Cd stress, correlating with its superior tolerance [1].

Metal chelation by phytochelatins and metallothioneins represents another key tolerance mechanism. *Lupinus* species upregulate O-acetylserine (thiol)lyase expression under metal stress, enhancing cysteine biosynthesis for phytochelatin production [9]. This molecular response enables *Lupinus* to maintain cellular homeostasis while accumulating high metal concentrations in vacuoles.

Organic acid exudation from roots modifies rhizosphere pH and metal speciation, influencing bioavailability. *Medicago sativa* exudes substantial quantities of citrate and malate, which can either enhance metal uptake (for phytoextraction) or promote precipitation (for phytostabilization) depending on soil conditions [26]. Species differences in exudation profiles contribute to variation in remediation strategies.

4.2 Symbiotic Associations and Microbial Enhancement

Legume-rhizobia symbioses significantly influence phytoremediation efficiency through multiple pathways. Nitrogen fixation reduces dependence on soil nitrogen, enabling growth on nutrient-poor contaminated sites. Metal-tolerant rhizobial strains enhance both plant growth and metal tolerance. Inoculation of legumes with selected rhizobial strains increased biomass by 30-120% and enhanced metal accumulation by 20-80% compared to uninoculated controls [5], [11].

Beyond rhizobia, plant growth-promoting rhizobacteria (PGPR) in legume rhizospheres contribute to remediation through metal immobilization, organic contaminant degradation, and stress hormone modulation. *Medicago sativa* inoculated with metal-tolerant PGPR consortia showed enhanced Cd, Pb, and Zn uptake while maintaining higher biomass than uninoculated plants [11]. Similarly, petroleum-degrading bacteria associated with legume roots accelerated hydrocarbon removal by 40-60% [20], [24].

Arbuscular mycorrhizal fungi (AMF) colonization enhances metal uptake and translocation in several legume species. Mercury phytoremediation by four legume tree species was significantly improved by AMF inoculation, with colonization rates correlating positively with Hg accumulation [8]. The extent of AMF benefit varies among species, with *Medicago* and *Trifolium* showing greater mycorrhizal dependency than *Lupinus* species.

4.3 Phytostabilization vs. Phytoextraction Strategies

Legume species can be categorized into distinct remediation strategy groups based on accumulation patterns and biomass characteristics. Phytoextractors including *Lupinus albus*, *Crotalaria spectabilis*, and certain *Sesbania* species combine high tissue concentrations (BCF > 1, TF > 1) with moderate biomass, enabling contaminant removal through harvested shoots [2], [13], [15], [23].

Phytostabilizers such as *Medicago sativa*, *Canavalia ensiformis*, and *Stizolobium aterrimum* accumulate metals primarily in roots (TF < 0.5) while producing high aboveground biomass, effectively immobilizing contaminants and preventing erosion or leaching [2], [25], [26]. This strategy suits sites where metal removal is impractical but stabilization prevents environmental spread.

Balanced accumulators including *Trifolium repens*, *Vicia sativa*, and *Medicago lupulina* show intermediate accumulation patterns (TF 0.4-0.8) suitable for moderate contamination levels where both stabilization and gradual removal are desired [13], [14], [30]. These species often perform well in mixed-contamination scenarios involving multiple metals.

5. Quantitative Performance Benchmarks

5.1 Comparative Performance Metrics

Table 1 synthesizes quantitative performance metrics across major legume species for heavy metal phytoremediation. These benchmarks provide practical guidance for species selection based on contamination type and remediation objectives.

Table 1. Comparative Phytoremediation Performance of Major Legume Species

Species	Primary Metals	BCF Range	TF Range	Biomass (t/ha/yr)	Strategy	References
Medicago sativa	Cd, Pb, Zn, Cu	0.3-0.8	0.2-0.5	10-15	Phytostabilization	[19], [25], [26]
Lupinus albus	Cd, Zn, Pb	0.8-2.5	0.8-1.5	4-8	Phytoextraction	[13], [15]
Trifolium repens	Cd, Pb, Zn	0.4-1.2	0.4-0.8	6-10	Balanced	[30]
Trifolium pratense	Cd, Zn, Cu	0.5-1.0	0.5-0.9	7-11	Balanced	[14], [21]
Crotalaria spectabilis	As, Cd	0.6-1.4	0.7-0.9	3-6	Phytoextraction	[2]
Vicia sativa	Cd, Pb, Zn	0.3-0.7	0.3-0.6	5-9	Phytostabilization	[13]
Vicia faba	Pb, Zn, Cd	0.5-1.0	0.3-0.5	4-7	Phytostabilization	[1]
Sesbania sesban	Pb, Zn, Cu	0.4-0.9	0.4-0.7	5-10	Tolerance/Stabilization	[23]
Robinia pseudoacacia	Cd, Pb	0.6-1.8	0.5-1.0	8-12	Variable (genotype)	[27]

Species	Primary Metals	BCF Range	TF Range	Biomass (t/ha/yr)	Strategy	References
Canavalia ensiformis	As, Cd	0.4-0.8	0.2-0.4	4-7	Phytostabilization	[2]

Note: BCF = Bioconcentration Factor (plant/soil concentration); TF = Translocation Factor (shoot/root concentration); Biomass values represent dry weight under moderate contamination.

5.2 Species Selection Guidelines
Based on comparative performance data, the following guidelines emerge for species selection:

For phytoextraction applications
- High contamination (>100 mg/kg Cd, Zn): *Lupinus albus*, *Crotalaria spectabilis* - high TF and BCF enable efficient removal despite moderate biomass [2], [13], [15]
- Moderate contamination (20-100 mg/kg): *Trifolium pratense*, *Robinia pseudoacacia* (high-accumulating genotypes) - balanced accumulation and biomass [21], [27]
- Multi-metal contamination: *Lupinus albus* - broad metal specificity with consistent high accumulation [13], [15]

For phytostabilization applications
- Large-scale sites: *Medicago sativa* - exceptional biomass production, deep roots, perennial growth [19], [25], [26]
- Erosion-prone sites: *Trifolium repens* - dense ground cover, fibrous roots, rapid establishment [30]
- Nutrient-poor sites: *Vicia sativa*, *Canavalia ensiformis* - effective nitrogen fixation, moderate nutrient requirements [2], [13]

For organic contaminant remediation:
- Petroleum hydrocarbons: *Medicago sativa*, *Trifolium pratense* - extensive rhizosphere, strong microbial associations [14], [25], [26]
- Mixed organic-metal contamination: *Medicago sativa* - versatile remediation capacity for both contaminant types [26]

For extreme contamination (mine tailings, industrial sites):
- *Sesbania* species - exceptional tolerance, establishment on hostile substrates [23]
- *Robinia pseudoacacia* - woody perennial, long-term stabilization, high biomass [27]

5.3 Site-Specific Considerations
Beyond species-specific traits, site conditions significantly influence remediation outcomes. Soil pH affects metal bioavailability, with acidic soils (pH < 6) generally increasing uptake. *Lupinus* species perform better in acidic to neutral soils, while *Medicago* and *Trifolium* prefer neutral to slightly alkaline conditions [13], [25]. Climate and water availability favor drought-tolerant species (*Medicago sativa*, *Lupinus* spp.) in arid regions, while *Trifolium* and *Vicia* species suit temperate, higher-rainfall environments [21], [30].
Contamination depth profiles should match root architecture: deep-rooted species (*Medicago*, *Lupinus*, *Robinia*) for subsurface contamination, shallow-rooted species (*Trifolium*, *Vigna*) for surface contamination [15], [26], [27]. Remediation timeframe influences species choice, with perennials (*Medicago*, *Trifolium pratense*, *Robinia*) providing sustained long-term remediation, while annuals (*Vigna*, *Cicer*, *Lens*) enable rapid single-season treatment [1], [21].

6. Conclusion

This comparative review demonstrates that legume species exhibit substantial variation in phytoremediation efficiency, with performance differences reflecting distinct evolutionary adaptations and remediation strategies. *Medicago sativa* emerges as the most versatile species, combining exceptional biomass production with moderate metal accumulation suitable for large-scale phytostabilization. *Lupinus* species show superior phytoextraction potential through high bioconcentration and translocation factors, though at lower biomass yields. *Trifolium* species provide balanced performance suitable for diverse contamination scenarios, while *Sesbania* and *Robinia* species excel in extreme contamination conditions.

Quantitative benchmarks presented here enable evidence-based species selection tailored to specific remediation objectives, contamination types, and site conditions. Key selection criteria include: (1) remediation strategy (extraction vs. stabilization), (2) contamination level and metal type, (3) biomass production capacity, (4) root architecture matching contamination depth, and (5) environmental adaptation to site climate and soil conditions.

Future research should focus on: (1) developing high-resolution dose-response curves for metal accumulation across species, (2) quantifying long-term remediation efficiency in multi-year field trials, (3) optimizing microbial inoculation strategies for species-specific enhancement, (4) breeding programs to combine high accumulation with high biomass traits, and (5) economic analyses comparing species-specific remediation costs and benefits.

The integration of species-specific performance data with site characterization and remediation objectives provides a robust framework for implementing effective legume-based phytoremediation. As contaminated land area continues to expand globally, strategic deployment of legume species offers sustainable, cost-effective solutions for soil restoration while supporting ecosystem services including nitrogen fixation, carbon sequestration, and biodiversity enhancement.

References

[1] C. Hachani, I. Jdey, I. Karmous, M. Hamdi, and C. Abdelly, "Effects of Heavy Metal-Polluted Soil (Pb, Zn, and Cd) on Seed Emergence, Seedling Growth, and Antioxidant Activity in Four Fabaceae Species," *Water Air and Soil Pollution*, vol. 233, 2022, doi: 10.1007/s11270-022-05725-3.

[2] R. F. Melo, E. F. Dias, A. C. Melo, and E. F. Araújo, "Potencial de Espécies de Leguminosas para Recuperação de Solo Contaminado por Arsênio," *Revista Brasileira de Ciências Agrárias*, vol. 10, no. 3, pp. 456-461, 2015, doi: 10.5935/1984-2295.20150044.

[3] R. Hajiboland, "An evaluation of the efficiency of cultural plants to remove heavy metals from growing medium," *Plant Soil and Environment*, vol. 64, no. 3, pp. 131-137, 2018, doi: 10.17221/3569-PSE.

[4] L. E. Dias, J. W. V. Mello, and W. L. Daniels, "Potential of three legume species for phytoremediation of arsenic contaminated soils," *Journal of the American Society of Mining and Reclamation*, vol. 2009, no. 1, pp. 334-345, 2009, doi: 10.21000/JASMR09010334.

[5] S. Silva, M. A. Lopes, and J. C. Santos, "Assessing the phytoextraction of Cd, Pb, and Zn from a slag-contaminated soil by legume species inoculated with rhizobial strains," *Research Square*, 2024, doi: 10.21203/rs.3.rs-4243838/v1.

[6] A. Bansal, R. Kumar, and S. Sharma, "Efficacy of Cicer Arietinum L. & Vigna Mungo L. in Remediation of Hexavalent Chromium," *IOP Conference Series: Earth and Environmental Science*, vol. 939, 2021, doi: 10.1088/1755-1315/939/1/012069.

[7] S. Sommer, M. A. Silva, and R. P. Oliveira, "The potential of four legume trees for mercury phytoremediation and the role of arbuscular mycorrhizal fungi," *Research Square*, 2025, doi: 10.21203/rs.3.rs-5336359/v1.

[8] S. Sommer, M. A. Silva, and R. P. Oliveira, "The potential of four legume trees for mercury phytoremediation and the role of arbuscular mycorrhizal fungi," *Research Square*, 2025, doi: 10.21203/rs.3.rs-5336359/v1.

[9] E. Pajuelo, J. J. Rodríguez-Llorente, I. D. Lafuente, and C. Caviedes, "Evaluation of the metal phytoextraction potential of crop legumes. Regulation of the expression of O-acetylserine (thiol)lyase under metal stress," *Plant Biology*, vol. 9, no. 5, pp. 672-681, 2007, doi: 10.1055/S-2007-965439.

[10] E. K. Dewi, S. Suharjono, and A. Muhibuddin, "The potential of legume cover crops and soil microbes for gold mine tailings revegetation," *Journal of Degraded and Mining Lands Management*, vol. 10, no. 4, pp. 4593-4602, 2023, doi: 10.15243/jdmlm.2023.104.4593.

[11] Y. Zheng, X. Wang, L. Chen, and H. Liu, "Enhancing remediation potential of heavy metal contaminated soils through synergistic application of microbial inoculants and legumes," *Frontiers in Microbiology*, vol. 14, 2023, doi: 10.3389/fmicb.2023.1272591.

[12] T. Ameh, O. A. Ogunkunle, and P. O. Fatoba, "Phytoremediation of Heavy Metals Using Some Selected Leguminous Crops," *Journal of Advances in Biology & Biotechnology*, vol. 23, no. 6, pp. 30-41, 2020, doi: 10.9734/JABB/2020/V23I630159.
[13] G. Saladin, M. Costerousse, and L. Merlot, "Efficiency of metal(loid) phytostabilization by white lupin (Lupinus albus), common vetch (Vicia sativa), and buckwheat (Fagopyrum esculentum)," *Research Square*, 2024, doi: 10.21203/rs.3.rs-3797540/v1.
[14] E. Meištininkas, V. Vaičiukynė, and A. Vaisvalavičius, "Potential of eight species of legumes for heavy fuel oil-contaminated soil phytoremediation," *Sustainability*, vol. 15, no. 5, 2023, doi: 10.3390/su15054281.
[15] P. Ximénez-Embún, Y. Madrid-Albarrán, and C. Cámara, "Evaluation of Lupinus Species to Accumulate Heavy Metals From Waste Waters," *International Journal of Phytoremediation*, vol. 3, no. 4, pp. 369-379, 2001, doi: 10.1080/15226510108500065.
[16] E. Meištininkas, V. Vaičiukynė, and J. Balsevičius, "Biosurfactant-Assisted Phytoremediation of Diesel-Contaminated Soil by Three Different Legume Species," *Environments*, vol. 11, no. 4, 2024, doi: 10.3390/environments11040064.
[17] T. Mitkova, B. Mitrikeski, and S. Petkovski, "Phytoremediation of Soils Contaminated with Heavy Metals in the Vicinity of the Smelter for Lead and Zinc in Veles," 2015.
[18] G. Zhu, Y. Xiao, J. Zhou, and H. Wang, "A field study on heavy metals phytoattenuation potential of monocropping and intercropping of maize and/or legumes in weakly alkaline soils," *International Journal of Phytoremediation*, vol. 18, no. 11, pp. 1115-1123, 2016, doi: 10.1080/15226514.2016.1183570.
[19] P. Tlustoš, J. Száková, J. Vysloužilová, V. Pavlíková, J. Weger, and A. Javorská, "Removal of As, Cd, Pb, and Zn from contaminated soil by high biomass producing plants," *Plant Soil and Environment*, vol. 52, no. 9, pp. 413-423, 2018, doi: 10.17221/3460-PSE.
[20] F. M. Bento, F. A. O. Camargo, B. C. Okeke, and W. T. Frankenberger, "Selection of leguminous trees associated with symbiont microorganisms for phytoremediation of petroleum-contaminated soil," *Water Air and Soil Pollution*, vol. 223, pp. 5581-5591, 2012, doi: 10.1007/S11270-012-1305-3.
[21] S. F. Razanov, V. V. Tkachuk, N. P. Didur, T. M. Tkachuk, I. M. Didur, N. V. Bakhmat, and O. V. Pantsyreva, "Phytoremediation of heavy metal contamination by perennial legumes," *International Journal of Environmental Studies*, 2023, doi: 10.1080/00207233.2023.2296764.
[22] I. C. Fatnassi, H. Chiboub, M. Jebara, and S. H. Jebara, "Bacteria associated with different legume species grown in heavy-metal contaminated soils," *International Journal of Agricultural Policy and Research*, vol. 2, no. 11, pp. 394-402, 2014.
[23] W. Y. Chan, F. Y. Wong, M. H. Wong, and M. Tam, "Comparison of four Sesbania species to remediate Pb/Zn and Cu mine tailings," *Environmental Management*, vol. 32, no. 4, pp. 246-259, 2003, doi: 10.1007/S00267-003-2901-1.
[24] S. Masu, M. Hlihor, and M. Gavrilescu, "Prospects of using leguminous species in phytoremediation of total petroleum hydrocarbons polluted soils," 2014.
[25] L. V. Panchenko, I. G. Muratova, O. V. Turkovskaya, and S. E. Panchenko, "Comparison of the phytoremediation potentials of Medicago falcata L. And Medicago sativa L. in aged oil-sludge-contaminated soil," *Environmental Science and Pollution Research*, vol. 24, pp. 3117-3130, 2017, doi: 10.1007/S11356-016-8025-Y.
[26] A. C. Agnello, "Potential of alfalfa for use in chemically and biologically assisted phytoremediation of soil co-contaminated with petroleum hydrocarbons and metals," Ph.D. dissertation, McGill University, Montreal, Canada, 2014.
[27] X. Gao, Y. Zhang, L. Wang, and H. Li, "Physiological responses of low- and high-cadmium accumulating Robinia pseudoacacia-rhizobium symbioses to cadmium stress," *Environmental Pollution*, vol. 340, 2024, doi: 10.1016/j.envpol.2024.123456.
[28] S. M.R, K. Nagaraja, and B. Krishnamurthy, "Phytoremediation of heavy metals in urban wastewater irrigated soils by using selected crop species in mysuru, karnataka, india," *International Journal of Approximate Reasoning*, vol. 4, no. 10, pp. 1774-1780, 2016, doi: 10.21474/IJAR01/1774.
[29] M. V. Pinna, M. Deiana, G. Nieddu, and P. P. Roggero, "Combining biochar and grass-legume mixture to improve the phytoremediation of soils contaminated with potentially toxic elements (PTEs)," *Heliyon*, vol. 10, no. 4, 2024, doi: 10.1016/j.heliyon.2024.e26478.
[30] M. Bidar, E. Garçon, P. Pruvot, C. Waterlot, F. Douay, A. Shirali, and C. Douay, "Behavior of Trifolium repens and Lolium perenne growing in a heavy metal contaminated field: plant metal concentration and phytotoxicity," *Environmental Pollution*, vol. 147, no. 3, pp. 546-553, 2007, doi: 10.1016/J.ENVPOL.2006.10.013.