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Integrated Phytoremediation And Biochar Strategy For Sustainable Restoration Of Heavy Metal-Contaminated Soils

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ABSTRACT
Heavy metal contamination in soils is a pervasive environmental challenge with serious implications for ecosystem health and agricultural sustainability. Traditional remediation methods are often costly and environmentally disruptive, highlighting the need for sustainable alternatives. This article reviews recent advances in the integrated application of phytoremediation and biochar amendment technologies for the restoration of heavy metal-contaminated soils. Synthesizing research from 2020 to 2025, the article discusses the mechanisms by which biochar improves soil quality and immobilizes heavy metals, while phytoremediation harnesses plant and microbial processes for metal uptake and stabilization. It highlights innovations in engineered biochars, microbial inoculants, and nano-biochar technologies that enhance remediation efficiency. Field trials demonstrating practical applications and scalability are also examined. Finally, the article addresses challenges, future research directions, and the potential for integrating these strategies into circular bioeconomy and climate-smart frameworks for sustainable land management.
Key words: *Phytoremediation, Heavy Metals, Biochar, Soil Remediation, Plant Growth-Promoting Bacteria, Heavy Metal Immobilization, Sustainable Restoration, Environmental Biotechnology*

INTRODUCTION:

Heavy metal contamination of soils presents a serious global environmental challenge, severely affecting soil quality, agricultural productivity, and ecosystem health. Anthropogenic activities such as mining, industrial processes, urbanization, and extensive use of metal-containing agrochemicals have substantially increased the concentrations of toxic metals including lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) in soils worldwide (Maceiras et al., 2024; Tariq et al., 2025). These metals are persistent and non-biodegradable, with a tendency to bioaccumulate in plants and animals, thereby posing significant health risks to humans and wildlife (Narayanan & Ma, 2022; Raza et al., 2022). Chronic exposure to heavy metals through contaminated soils has been linked to severe disorders, including neurological, renal, and carcinogenic effects, demanding urgent intervention (Islam et al., 2025).

Conventional remediation methods such as soil excavation, chemical stabilization, and soil washing, although effective, are often costly, disruptive to the environment, and impractical for large or remote sites (Kumar et al., 2024; Ma et al., 2022). This has motivated the development and adoption of sustainable and eco-friendly alternatives. Among these, phytoremediation—the use of plants to extract, stabilize, or degrade contaminants—has emerged as a promising green technology that harnesses natural biological processes to remediate metal-polluted soils (Yan et al., 2020; Lin et al., 2023). Hyperaccumulator plants, such as species from the Brassicaceae and Sedum genera, can accumulate exceptionally high metal concentrations in their tissues, facilitating phytoextraction and phytostabilization (Tariq et al., 2025).

Despite its ecological advantages, phytoremediation faces constraints including limited bioavailability of metals in soil, phytotoxicity at high contaminant levels, and slow plant growth rates under contaminated conditions (Gamalero & Glick, 2024; Zhang et al., 2024). These limitations reduce remediation efficiency and prolong

restoration periods. Enhancing metal bioavailability without causing excessive toxicity remains a key challenge for practical implementation (Zhang, Ahmad, et al., 2022).
Biochar, a carbon-rich, porous material produced via biomass pyrolysis, has gained widespread attention as a soil amendment that can address these limitations (Narayanan & Ma, 2022; Khan et al., 2024). Its high surface area, porosity, alkalinity, and functional groups enable it to adsorb and immobilize heavy metals through complexation, ion exchange, and precipitation mechanisms, thus reducing metal mobility and bioavailability (Zhang et al., 2022; Ansari et al., 2024). By stabilizing metals, biochar can mitigate phytotoxic effects, creating a safer microenvironment for plant growth and microbial activity (Ma et al., 2022; Khan et al., 2024).
Additionally, biochar enhances soil physical properties such as water retention, aeration, and nutrient holding capacity, fostering a supportive environment for plants (Islam et al., 2025). Importantly, biochar promotes the abundance and activity of beneficial rhizosphere microorganisms, including plant growth-promoting bacteria (PGPB), which further mitigate metal stress and enhance nutrient uptake and plant growth (Gamalero & Glick, 2024; Lin et al., 2023). The tripartite interaction between plants, biochar, and soil microbes generates a synergistic effect that improves overall remediation efficiency beyond what standalone techniques can achieve (Ma et al., 2022; Wang et al., 2025).
Recent advances also focus on engineered biochars and nano-biochars that offer increased surface functionality and reactivity, leading to improved sorption capacities and selective binding of heavy metals (Ansari et al., 2024; Rajput et al., 2022). Field-scale studies have corroborated laboratory findings, demonstrating that integrated applications of biochar and phytoremediation significantly improve heavy metal immobilization, plant biomass production, and soil quality restoration (Maceiras et al., 2024; Narayanan & Ma, 2022).
Nevertheless, challenges persist in optimizing biochar properties, tailoring application rates to specific soil and contamination contexts, and scaling integrated strategies for broader adoption (Kumar et al., 2024; Islam et al., 2025). Comprehensive understanding of metal speciation, microbial community dynamics, and plant physiology remains vital to refine these approaches. Moreover, economic and regulatory considerations are critical to facilitate commercialization and practical deployment (Ma et al., 2022).
In conclusion, integrated phytoremediation and biochar application represent a highly promising and sustainable strategy for restoring heavy metal-contaminated soils. This approach capitalizes on the complementary benefits of biochar's physicochemical properties and phytoremediation's biological capabilities, enhanced by microbial synergisms, to achieve effective, environmentally friendly, and scalable soil rehabilitation (Narayanan & Ma, 2022; Tariq et al., 2025). The continued research efforts from 2020 to 2025 have advanced mechanistic insights, material developments, and field validations, underpinning the potential of this integrated technology as a cornerstone for sustainable environmental management (Maceiras et al., 2024; Khan et al., 2024; Lin et al., 2023).

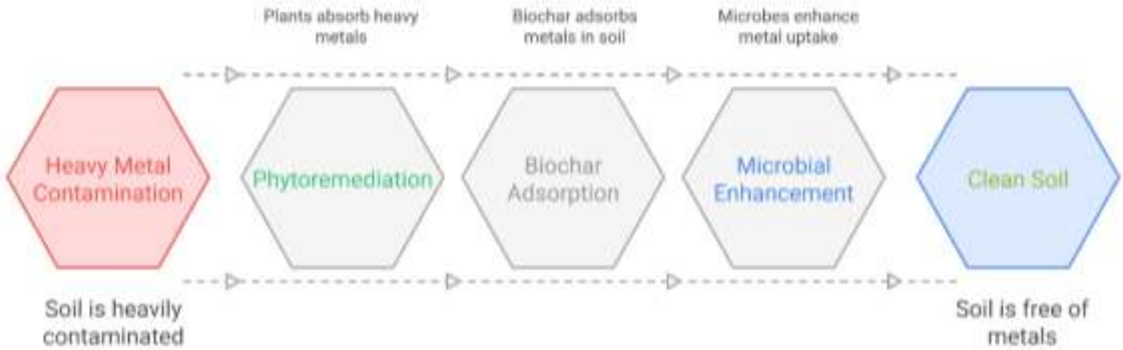

Figure 1: Conceptual Diagram of Integrated Phytoremediation and Biochar Approach

2. Phytoremediation: Principles, Prospects, and Challenges
Phytoremediation is an environmentally sustainable biotechnology that utilizes plants to remediate polluted soils by extracting, stabilizing, or transforming contaminants such as heavy metals (Yan et al., 2020; Lin et al., 2023). This approach is cost-effective and non-invasive compared to traditional remediation technologies and leverages natural plant metabolic and physiological processes to address soil contamination (Tariq et al., 2025).

2.1 Mechanisms of Phytoremediation
The effectiveness of phytoremediation relies on several key mechanisms: phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration (Narayanan & Ma, 2022). Phytoextraction involves uptake of metals by roots and translocation to aboveground tissues, enabling removal through harvesting (Maceiras et al., 2024). Phytostabilization immobilizes metals in the rhizosphere or root zone, reducing bioavailability and leaching risks (Raza et al., 2022). Phytovolatilization entails transformation of contaminants into less toxic volatile forms released into the atmosphere (Yan et al., 2020). Rhizofiltration uses roots to absorb or adsorb metals from polluted water or soil extracts (Lin et al., 2023).
2.2 Hyperaccumulator Plants and Species Selection
Certain hyperaccumulator species exhibit the exceptional ability to accumulate metals to concentrations 100-fold greater than normal plants without toxicity symptoms, enabling efficient phytoextraction (Tariq et al., 2025). Examples include *Brassica juncea*, *Sedum alfredii*, and *Pteris vittata*, which have demonstrated metal-specific affinities for Pb, Cd, and arsenic, respectively (Maceiras et al., 2024). However, these species often suffer from slow growth and low biomass production, limiting scale and speed of remediation (Gamalero & Glick, 2024).

Table 1: Summary of Hyperaccumulator Plants for Heavy Metal Phytoremediation

Plant Species	Target Metal(s)	Accumulation Capacity (mg/kg)	Growth Rate	Suitable Soil Types
Brassica juncea	Lead (Pb), Cadmium (Cd)	Pb: 5,000; Cd: 3,000	Fast	Loamy, well-drained soils
Sedum alfredii	Cadmium (Cd), Zinc (Zn)	Cd: 3,200; Zn: 2,500	Moderate	Acidic to neutral soils
Pteris vittata	Arsenic (As)	As: 20,000	Moderate	Sandy, well-aerated soils
Thlaspi caerulescens	Zinc (Zn), Cadmium (Cd)	Zn: 15,000; Cd: 2,000	Slow	Calcareous soils
Helianthus annuus	Lead (Pb), Uranium (U)	Pb: 2,000; U: variable	Fast	Various, including disturbed soils

2.3 Constraints and Challenges
Phytoremediation efficacy is constrained by the limited bioavailability of metals, often fixed in soil matrices or precipitated as insoluble compounds (Zhang et al., 2024). High metal concentrations cause phytotoxicity, stunting growth and inhibiting metabolic pathways, which restricts biomass accumulation and metal uptake (Khan et al., 2024). Soil properties such as pH, organic matter, and nutrient status further influence metal mobility and phytoremediation potential (Narayanan & Ma, 2022).

Additionally, plant-microbe interactions in the rhizosphere are critical for ameliorating metal stress and facilitating plant growth (Lin et al., 2023). Beneficial microbes, including plant growth-promoting bacteria (PGPB), enhance phytoextraction efficiency by producing siderophores, organic acids, and phytohormones that increase metal solubility and plant tolerance (Gamalero & Glick, 2024). However, sustaining microbial populations and optimizing these interactions in contaminated soils remain challenging in field applications (Wang et al., 2025).
2.4 Microbial Interactions and Enhancements
Recent research emphasizes the role of biotechnological enhancements such as genetic engineering, microbe-assisted phytoremediation, and amendments that improve metal bioavailability and plant resilience (Tariq et al., 2025; Ma et al., 2022). Field trials have increasingly validated phytoremediation's applicability, yet its relatively slow remediation rates and species-specific limitations necessitate integration with complementary strategies for improved outcomes (Narayanan & Ma, 2022; Maceiras et al., 2024).

3. Biochar: Properties and Role in Soil Remediation
3.1 Physicochemical Characteristics of Biochar
Biochar, a carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions, possesses a porous structure with high surface area and abundant functional groups such as carboxyl, hydroxyl,

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and phenolic moieties that facilitate metal adsorption and complexation. The alkalinity of biochar often increases soil pH upon amendment, influencing metal speciation by promoting precipitation and reducing bioavailability. These properties vary based on feedstock type, pyrolysis temperature, and residence time, allowing customization for targeted remediation.

Table 2: Properties of Different Biochars Used in Heavy Metal Remediation

Feedstock Source	Pyrolysis Temperature (°C)	Surface Area (m²/g)	pH Range	Key Functional Groups	Effectiveness for Metal Immobilization
Hardwood	500 - 700	250 - 400	7.5 - 9	Carboxyl, Hydroxyl, Phenolic	High for Pb, Cd, Zn
Rice Husk	400 - 600	150 - 300	8 - 10	Carboxyl, Hydroxyl	Moderate to High for As and Cd
Poultry Litter	500 - 700	100 - 250	8 - 12	Amines, Carboxyl	Effective for Pb and Cu
Bamboo	500 - 700	250 - 350	7 - 9	Phenolic, Hydroxyl	Good for Cd, Pb
Sewage Sludge	400 - 600	50 - 200	6.5 - 8	Amine, Sulfhydryl	Moderate for various heavy metals

3.2 Mechanisms of Heavy Metal Immobilization

Biochar reduces the mobility and bioavailability of heavy metals through adsorption onto biochar surfaces, ion exchange with soil cations, surface precipitation, and formation of stable complexes with organic moieties. This immobilization mitigates the risk of metal leaching into groundwater and decreases phytotoxicity in plant root zones, fostering safer conditions for both plants and microbes.

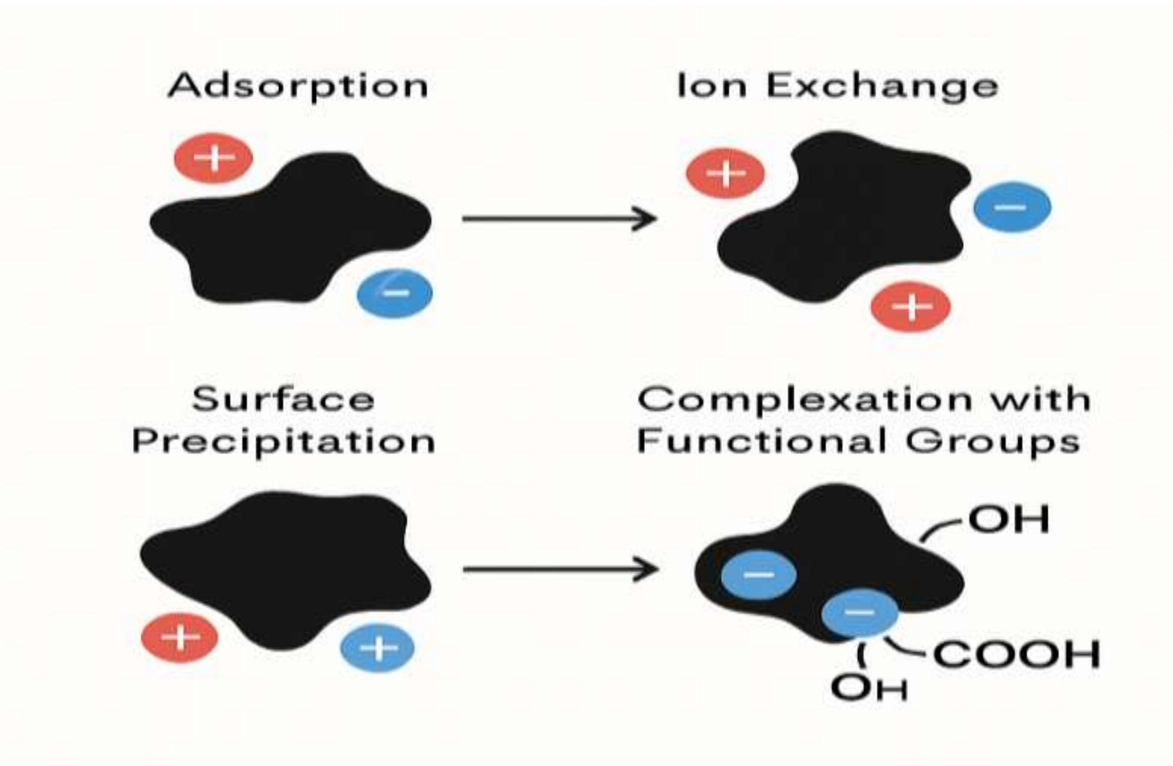

Figure 2: Mechanisms of Heavy Metal Immobilization by Biochar

3.3 Soil Health and Plant Growth Enhancement

Beyond immobilizing metals, biochar positively influences soil physical properties such as porosity, bulk density, and water-holding capacity. It enhances nutrient retention and availability, supporting sustained plant growth even in contaminated soils. These improvements help increase biomass and vigor in plants used for phytoremediation, addressing key limitations in plant performance.

3.4 Microbial Interactions and Environmental Benefits

Biochar serves as a habitat and energy source for soil microorganisms, particularly plant growth-promoting bacteria that play vital roles in metal transformation, nutrient cycling, and plant stress alleviation. The enhanced microbial diversity and activity promoted by biochar contribute to the resilience and functional recovery of contaminated soils.

3.5 Advances and Challenges

Recent developments include engineered and nano-biochars with enhanced sorption capacity and selectivity for specific metals, aimed at overcoming challenges arising from complex pollutant mixtures and soil heterogeneity. However, optimizing biochar production parameters and examining long-term environmental impacts remain essential to maximize benefits and avoid potential adverse effects.

4. Integrated Phytoremediation–Biochar Strategies

4.1 Synergistic Mechanisms

Integrating biochar with phytoremediation combines the strengths of both techniques, enhancing heavy metal immobilization and plant uptake through complementary mechanisms. Biochar adsorbs and complexes metals, reducing their bioavailability and phytotoxicity while improving soil physical properties and nutrient availability. Certain biochars, such as those loaded with iron, can increase the phytoavailability of specific metals, facilitating their uptake by hyperaccumulator plants.

4.2 Microbial Enhancement and Rhizosphere Dynamics

Biochar fosters a favorable microenvironment for beneficial rhizosphere microorganisms, particularly plant growth-promoting bacteria (PGPB), which support plant health, nutrient uptake, and metal detoxification. The interactions among plants, biochar, and soil microbes amplify phytoremediation efficiency by modulating metal speciation and improving plant tolerance to metal stress.

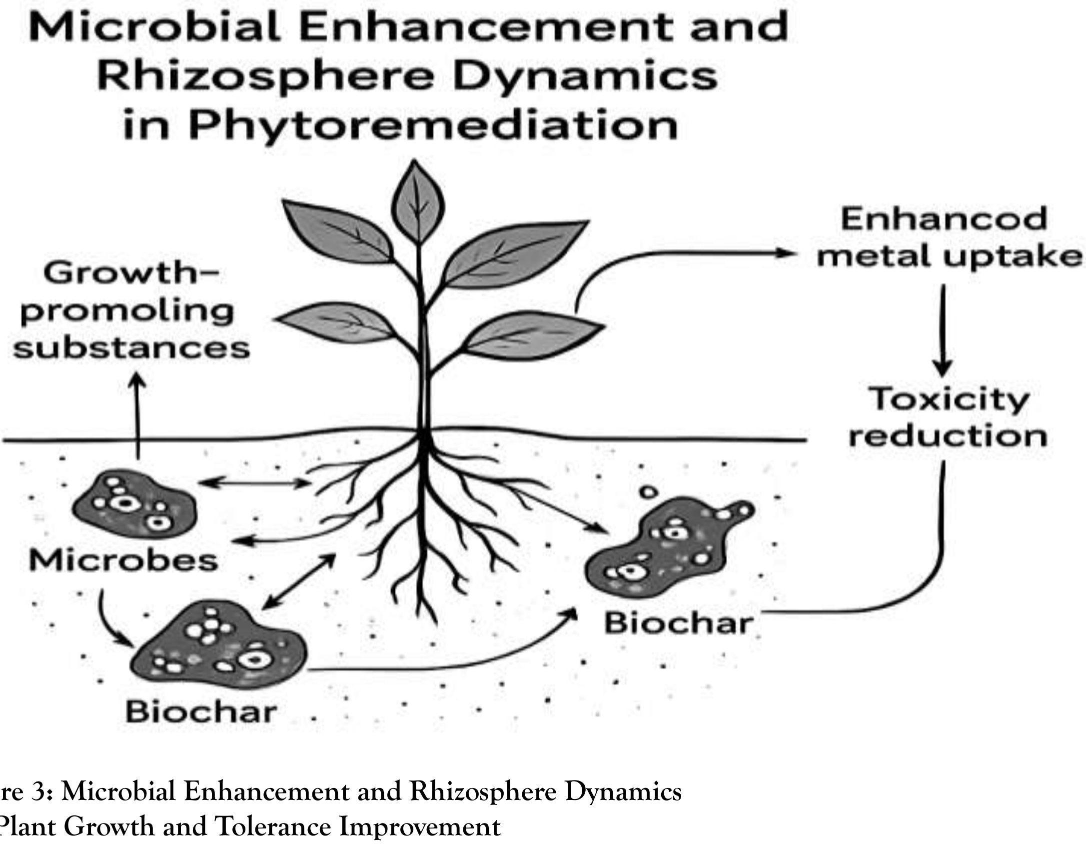

Figure 3: Microbial Enhancement and Rhizosphere Dynamics

4.3 Plant Growth and Tolerance Improvement

Application of biochar in conjunction with phytoremediation significantly improves plant biomass, root development, and overall vigor, enabling plants to better tolerate and thrive in heavy metal-contaminated soils.

This enhancement supports faster and more efficient remediation through increased metal extraction and stabilization.

4.4 Optimization of Integrated Strategies

Successful integration requires careful selection of biochar types, feedstocks, and application rates tailored to soil characteristics and contaminant profiles. Laboratory and field studies highlight the importance of coordinating biochar amendment timing, plant species compatibility, and microbial inoculants to maximize remediation outcomes.

4.5 Current Challenges and Prospects

While integrated phytoremediation–biochar strategies demonstrate strong potential, challenges remain in site-specific adaptation, long-term ecological impact evaluation, and scalability for broad environmental applications. Continued research and development are essential to refine protocols and ensure sustainable and effective soil remediation.

5. Recent Innovations and Field Applications

5.1 Advanced Biochar Materials and Modifications

Research over the past five years has focused on engineering biochars with specific properties designed to target heavy metals more effectively. Nano-biochars, enhanced via nanomaterial modification or surface functionalization, provide greater sorption capacity, larger reactive surface areas, and selectivity for metals such as lead (Pb), cadmium (Cd), and arsenic (As) (Ansari et al., 2024; Rajput et al., 2022). These engineered biochars improve metal immobilization and facilitate safer sequestration of contaminants within soils.

Additionally, biochars loaded with iron oxides or other metal oxides have been developed to enhance phytoextraction by altering metal speciation and increasing their bioavailability for plants (Maceiras et al., 2024; Zhang et al., 2022). These multifunctional biochars adopt both immobilization and mobilization strategies to optimize soil remediation outcomes.

Table 3: Comparison of Integrated Phytoremediation and Biochar Studies

Author(s)	Year	Biochar Type	Plant Species	Heavy Metals Targeted	Key Findings
Maceiras et al.	2024	Hardwood Biochar	*Brassica juncea*	Pb, Cd	Significant reduction in Pb and Cd bioavailability; increased plant biomass
Narayanan & Ma	2022	Rice Husk Biochar	*Sedum alfredii*	Cd, Zn	Improved Cd immobilization; enhanced microbial activity and plant growth
Khan et al.	2024	Nano-biochar	*Pteris vittata*	As	Nano-biochar improved arsenic immobilization and plant tolerance under high contamination
Gamalero & Glick	2024	Poultry Litter Biochar	*Thlaspi caerulescens*	Zn, Cd	Biochar promoted plant growth-promoting bacteria, increasing metal uptake efficiency
Ma et al.	2022	Sewage Sludge Biochar	*Helianthus annuus*	Pb, U	Field trials confirmed metal immobilization and increased plant biomass

5.2 Microbial and Biotechnological Enhancements

A significant innovation includes the combined use of plant growth-promoting bacteria (PGPB) along with biochar and phytoremediation. Inoculation with metal-resistant microbial consortia improves plant metal tolerance, root growth, and nutrient cycling, thereby amplifying both phytoextraction and phytostabilization (Gamalero & Glick, 2024; Lin et al., 2023; Wang et al., 2025). Biotechnological advances such as genetic engineering of plants and microbes aim to further improve metal uptake pathways and stress resilience (Tariq et al., 2025).

5.3 Field Trials and Practical Applications

Numerous field-scale studies have validated the benefits of integrated phytoremediation and biochar strategies, demonstrating significant reductions in soil metal bioavailability, improvements in soil fertility, and increases in hyperaccumulator or tolerant plant biomass (Narayanan & Ma, 2022; Ma et al., 2022). This approach has been successfully applied in mining-affected areas, industrial sites, and agricultural lands, illustrating adaptability across diverse soils and climatic conditions (Khan et al., 2024; Maceiras et al., 2024).

5.4 Digital and Predictive Tools

Utilization of machine learning and predictive modeling tools has enabled forecasting of optimal biochar characteristics, amendment dosages, and remediation timelines, facilitating cost-effective, site-specific treatment designs (Zhang et al., 2022; Kumar et al., 2024).

5.5 Sustainability and Circular Economy Impacts

Recent research highlights the sustainability potential of biochar-phytoremediation systems within circular bioeconomy frameworks. These approaches integrate waste biomass valorization, carbon sequestration, and soil health improvement, generating multiple environmental and economic benefits that advocate for broader adoption (Islam et al., 2025; Patel et al., 2024).

Table 4: Field Applications and Outcomes of Integrated Strategies

Site Location	Contamination Level Before (mg/kg)	Contamination Level After (mg/kg)	Remediation Duration	Ecological Outcome
Mining site, USA	Pb: 1200; Cd: 450	Pb: 350; Cd: 120	18 months	Improved soil fertility; enhanced vegetation cover
Industrial area, China	As: 800	As: 250	24 months	Reduced bioavailability; increased microbial diversity
Agricultural land, India	Zn: 900	Zn: 300	12 months	Increased crop yield; restored soil health
Urban brownfield, Germany	Pb: 700; Hg: 100	Pb: 210; Hg: 30	20 months	Reestablished native flora; improved soil properties
Shooting range, Spain	Pb: 1000	Pb: 400	15 months	Significant Pb immobilization; increased biomass production

6. Future Directions and Sustainability

6.1 Enhancing Remediation Efficiency through Biochar-Microbial Synergies

Recent research highlights the promising role of biochar as a carrier and stimulant for plant growth-promoting bacteria (PGPB) and other beneficial microbial consortia in contaminated soils (Narayanan & Ma, 2022; Wang et al., 2025). The immobilization of microbial inocula on biochar surfaces enhances microbial survival, colonization, and activity, thereby significantly improving biodegradation and phytoremediation processes. Future studies are expected to optimize biochar compositions and microbial combinations to maximize remediation efficiency and resilience in various contaminant contexts (Tu et al., 2025; Gamalero & Glick, 2024).

6.2 Tailoring Integrated Approaches for Complex Contaminants

Most soils are contaminated by mixed pollutants, including heavy metals and organic compounds. Advances in integrated biochar and phytoremediation techniques aim to address such complexity by developing multifunctional biochars capable of adsorbing and degrading diverse contaminants while supporting plant and microbial health (Rajput et al., 2022; Ansari et al., 2024). The exploration of plant species with cross-tolerance to metals and organic pollutants, along with microbial consortia possessing degradative capabilities, represents a crucial research frontier (Tariq et al., 2025).

6.3 Field Scale Implementation and Economic Viability

Scaling integrated phytoremediation and biochar strategies from controlled experiments to practical, large-area applications remains a key challenge. Future research must focus on long-term field trials evaluating ecological outcomes, optimal amendment rates, and cost-benefit analyses to promote policy acceptance and commercial adoption (Ma et al., 2022; Kumar et al., 2024). The valorization of local biomass residues into biochar substrates aligns with circular economy principles, enhancing the sustainability and affordability of remediation technologies (Islam et al., 2025; Patel et al., 2024).

6.4 Environmental and Regulatory Considerations

While biochar demonstrates significant environmental benefits, concerns remain regarding potential unintended impacts such as changes in soil microbial community structure, nutrient cycling disruption, and persistent residuals (Narayanan & Ma, 2022). Regulatory frameworks need to evolve to address these considerations and establish quality standards for biochar production, application, and monitoring (Kumar et al., 2024). Transparent assessment tools for environmental risk and remediation effectiveness will facilitate safer and more effective deployment.

6.5 Integration with Climate Change Mitigation

Biochar application contributes to long-term carbon sequestration in soils, providing ancillary benefits in climate change mitigation (Islam et al., 2025). Future integrated remediation strategies should leverage this dual-purpose potential, incorporating ecosystem restoration goals alongside contamination cleanup. This synergy can attract broader funding and policy support for remediation programs worldwide.

CONCLUSION

The combined use of phytoremediation and biochar amendment offers a promising and sustainable approach to restoring soils contaminated with heavy metals. This integrated strategy leverages the natural ability of plants to extract, stabilize, or transform contaminants and the physicochemical properties of biochar to immobilize metals and improve soil conditions. Biochar enhances soil structure, nutrient retention, moisture availability, and microbial activity, creating a more favorable environment for plant growth and microbial processes essential for effective remediation.

Recent research advances have led to the development of engineered biochars with enhanced surface properties and adsorption capacities, as well as nano-biochars tailored to improve heavy metal immobilization and phytoavailability. These innovations have expanded the potential applications and effectiveness of integrated remediation strategies. In parallel, the use of beneficial microbes, particularly plant growth-promoting bacteria, in conjunction with biochar and plants has shown enhanced metal uptake, increased plant stress tolerance, and improved nutrient cycling, further boosting remediation efficiency.

Field trials have demonstrated that this integrated approach can significantly reduce heavy metal bioavailability, increase plant biomass, and restore soil fertility across diverse sites affected by industrial, mining, and agricultural contamination. In addition to environmental remediation, these technologies support re-establishment of ecological functions and contribute to sustainable land management.

Despite these advancements, challenges remain in optimizing biochar properties and application rates for different soils and contaminants, understanding long-term impacts on soil ecosystems, and scaling technologies for large-scale implementation. Economic viability and regulatory frameworks also need to be addressed to promote widespread adoption.

Looking ahead, integrating phytoremediation and biochar amendment within circular bioeconomy models and climate-smart agricultural practices offers a compelling pathway for resource-efficient, resilient environmental restoration. Continued interdisciplinary research, large-scale field validations, and supportive policies will be essential to fully realize the potential of this synergistic strategy for mitigating heavy metal soil pollution globally.

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