WEP
Warwick
Evans
Publishing

International Journal of Materials Science and Technology Studies

ISSN: 3006-7693 (Print), ISSN: 3006-3744 (Online) | Volume 3, Number 3, Year 2025
DOI: https://doi.org/10.62051/ijmsts.v3n3.01
Journal homepage: https://wepub.org/index.php/IJMSTS/index

Advances in Biochar-Based Materials for Environmental Remediation: Mechanisms, Applications, and Future Perspectives

Yaning Liu [*], Jingxin Li, Shengyan Lei, Min Chen, Xiuzhen Nong

West Yunnan University of Applied Sciences, Pu 'er 665000, China

ABSTRACT

Biochar-based materials have emerged as a promising solution for addressing multiple environmental challenges through sustainable biomass utilization. Derived from agricultural and forestry waste via pyrolysis and hydrothermal carbonization, these carbon-rich substances exhibit exceptional adsorption capabilities due to their porous architecture and abundant surface functional groups. Recent advancements in modification techniques, particularly chemical activation and nanomaterial integration, have substantially enhanced their pollutant removal efficiency and structural stability. Practical applications demonstrate remarkable effectiveness in immobilizing heavy metal contaminants, degrading persistent organic pollutants, and restoring degraded soils through improved nutrient retention and microbial activity enhancement. The materials' dual functionality in carbon sequestration and waste valorization presents a cost-effective strategy for mitigating climate change impacts. However, scalability challenges persist in optimizing production parameters for diverse feedstock types while maintaining consistent quality. Long-term ecological impacts require thorough investigation regarding potential secondary contamination risks and soil ecosystem interactions. Future research directions should prioritize developing standardized characterization protocols, intelligent responsive materials for targeted remediation, and synergistic systems combining biochar with phytoremediation technologies. This comprehensive analysis underscores the need for interdisciplinary collaboration to bridge laboratory innovations with practical environmental engineering applications, ultimately contributing to sustainable circular economy models in ecological restoration.

KEYWORDS

Biochar-Based Materials; Environmental Remediation; Heavy Metal Immobilization; Soil Amendment; Carbon Sequestration; Sustainable Remediation

1. RESEARCH BACKGROUND AND OBJECTIVES

The global environmental crisis demands urgent solutions for soil degradation, water contamination, and climate change. Traditional remediation methods often face limitations in cost-effectiveness and ecological sustainability, particularly when dealing with complex pollution scenarios involving heavy metals and persistent organic compounds. This context has driven scientific exploration of circular economy approaches that transform waste into remediation resources, creating a critical foundation for biochar-based material research.

Biochar, a carbon-rich substance produced through thermal processing of organic waste, has emerged as an environmentally responsive material. Originating from ancient agricultural practices of charcoal amendment, modern biochar technology represents a significant evolution. Unlike historical uses focused solely on soil fertility, contemporary research leverages biochar's unique structure -

characterized by honeycomb-like pores and reactive surface chemistry - to address multiple environmental challenges simultaneously. The material's development reflects growing recognition of biomass waste's potential, with agricultural residues and forestry byproducts being transformed from disposal burdens into valuable remediation agents.

Three fundamental properties position biochar-based materials as superior environmental solutions. First, their porous architecture acts like a molecular sponge, effectively capturing heavy metals and organic pollutants through physical entrapment and chemical bonding. Second, the stable carbon matrix enables long-term carbon sequestration, directly contributing to climate change mitigation. Third, the material's compatibility with various modification techniques allows performance enhancement for specific remediation needs. These attributes align with circular economy principles by converting waste biomass into functional materials while addressing pollution control and carbon neutrality goals.

Current research faces critical knowledge gaps requiring systematic investigation. While numerous studies demonstrate biochar's effectiveness in controlled laboratory conditions, practical applications require better understanding of field performance variations across different soil types and climate conditions. The relationship between biochar production parameters and final material properties needs clearer elucidation to guide standardized manufacturing. Moreover, the long-term ecological impacts of large-scale biochar application remain insufficiently documented, particularly regarding soil microecosystem interactions and potential secondary contamination risks.

This study aims to establish a comprehensive framework for developing biochar-based environmental solutions through three primary objectives: (1) Systematically analyzing preparation methods and their influence on material characteristics, providing guidance for optimizing production processes. (2) Clarifying the mechanisms through which biochar-based materials interact with various pollutants, including physical adsorption, chemical transformation, and biological degradation pathways. (3) Identifying practical challenges in scaling up laboratory successes to real-world applications, proposing strategies for performance enhancement and ecological risk mitigation. By addressing these aspects, the research seeks to bridge the gap between academic innovation and practical environmental engineering applications.

2. PREPARATION AND CHARACTERIZATION OF BIOCHAR-BASED MATERIALS

2.1. Synthesis Methods and Technological Advancements in Biochar Modification

The development of biochar-based materials begins with controlled thermal processing of biomass, where production parameters critically determine final material properties. Two primary methods dominate biochar synthesis: pyrolysis and hydrothermal carbonization. Pyrolysis involves heating organic feedstocks like crop residues or wood chips in oxygen-limited environments, with temperature ranges (300-900°C) and heating rates creating distinct material characteristics. Slow pyrolysis at lower temperatures (400-500°C) over several hours produces biochar with well-developed micropores, while fast pyrolysis at higher temperatures (700°C+) generates more bio-oil alongside mesoporous biochar. Hydrothermal carbonization offers an alternative approach using pressurized water (180-250°C) to convert wet biomass like sewage sludge into hydrochar, preserving oxygen-containing functional groups beneficial for pollutant interaction.

Recent advancements focus on enhancing biochar's natural properties through targeted modifications. Chemical activation proves effective in expanding surface area and creating reactive sites. Potassium hydroxide or phosphoric acid treatments etch new pores into the carbon matrix while generating oxygen-rich surface groups. Metal oxide impregnation introduces magnetic nanoparticles or catalytic iron species, enabling both pollutant adsorption and advanced oxidation processes. A notable innovation combines biochar with graphene oxide nanosheets, creating hybrid materials that leverage graphene's conductivity for electrochemical contaminant degradation while maintaining biochar's adsorption capacity.

The integration of nanotechnology has opened new frontiers in biochar engineering. Embedding zero-valent iron particles within biochar matrices creates magnetic composites that simultaneously adsorb heavy metals and break down organic pollutants through Fenton-like reactions. Clay-biochar composites demonstrate improved cation exchange capacity for enhanced nutrient retention in soil remediation. Emerging techniques employ plasma treatment to graft nitrogen-containing functional groups onto biochar surfaces, significantly boosting its affinity for heavy metal ions. These modifications address original biochar's limitations in selectivity and treatment efficiency while introducing multifunctional capabilities.

Process optimization technologies are revolutionizing biochar production sustainability. Microwave-assisted pyrolysis reduces energy consumption by 40% compared to conventional methods while achieving more uniform heating. Machine learning algorithms now predict optimal combinations of feedstock type, pyrolysis temperature, and activation methods for specific remediation targets. Life cycle assessments guide the selection of agricultural waste streams that minimize carbon footprints during production. Recent breakthroughs in solvent-free mechanochemical synthesis eliminate chemical waste generation, aligning with green chemistry principles.

Current research prioritizes balancing performance enhancement with environmental safety. Modified biochars undergo rigorous leaching tests to ensure heavy metal immobilization stability under varying pH conditions. Surface passivation techniques prevent nanoparticle release from composite materials while maintaining catalytic activity. The field is moving toward closed-loop systems where spent biochar from water treatment applications gets repurposed as soil amendment, creating cascading environmental benefits. These technological strides position biochar-based materials as adaptable solutions for diverse remediation scenarios while addressing scalability and safety concerns.

2.2. Physicochemical Properties and Functional Mechanisms of Biochar Composites

Biochar composites exhibit unique structural and chemical characteristics that determine their environmental remediation capabilities. The three-dimensional porous network formed during pyrolysis creates a sponge-like architecture with high surface area, providing numerous binding sites for pollutants. Micropores (<2 nm) trap small molecules through physical adsorption, while mesopores (2-50 nm) facilitate ion transport and microbial colonization. This hierarchical porosity enables simultaneous removal of diverse contaminants - heavy metals accumulate in smaller pores while organic compounds adsorb in larger channels.

Surface chemistry plays a pivotal role in pollutant interactions. Oxygen-containing functional groups (-COOH, -OH) formed during thermal decomposition act as chemical anchors for heavy metal ions through complexation and ion exchange. The aromatic carbon matrix provides electron-rich regions for π-π interactions with organic pollutants like polycyclic aromatic hydrocarbons. In modified composites, introduced iron particles create redox-active sites that transform toxic chromium (VI) into less mobile chromium(III), demonstrating combined adsorption and chemical reduction capabilities.

The electrical properties of biochar composites enhance their environmental functionality. The graphitic domains in high-temperature biochar exhibit semiconductor behavior, enabling photocatalytic degradation of organic pollutants under sunlight. When combined with iron oxides, these composites initiate Fenton-like reactions that break down persistent pesticides through hydroxyl radical generation. The material's surface charge, typically negative due to deprotonated functional groups, facilitates electrostatic attraction of cationic heavy metals while requiring surface modification for anion capture.

Biochar's role as a microbial habitat significantly contributes to soil remediation. The porous structure shelters microorganisms from environmental stressors while the carbon matrix provides sustained nutrient release. Iron-biochar composites demonstrate dual functionality - magnetic properties allow easy recovery from treated water, while iron oxidation creates favorable conditions for aerobic microbial communities. In hydrocarbon-contaminated soils, biochar-amended soils show enhanced microbial diversity, accelerating petroleum degradation through improved oxygen diffusion and enzyme activity stimulation.

Synergistic effects emerge when combining biochar with other materials. Clay mineral composites leverage biochar's adsorption capacity and clay's cation exchange properties for comprehensive soil improvement. Biochar-supported nano zero-valent iron particles prevent nanoparticle aggregation while maintaining reactivity, achieving higher heavy metal removal efficiency than either component alone. The carbon matrix also buffers pH fluctuations in treated environments, maintaining optimal conditions for both chemical reactions and microbial metabolism.

Environmental stability determines long-term remediation performance. The aromatic structure of properly carbonized biochar resists microbial decomposition, ensuring decade-scale carbon sequestration. Surface passivation through mineral coatings or polymer encapsulation prevents premature release of immobilized contaminants. However, excessive surface oxidation during modification can create unstable complexes that leach bound metals under acidic conditions, highlighting the need for balanced functionalization strategies.

Functional mechanisms vary across application scenarios. In water treatment, physical filtration dominates for particulate matter removal, while chemical adsorption addresses dissolved pollutants. Soil applications involve complex interactions - biochar improves soil structure through aggregate formation, enhances nutrient retention via cation exchange capacity, and mediates microbial redox processes for contaminant degradation. Recent studies reveal biochar's role in catalyzing natural attenuation processes, where it accelerates the transformation of mobile pollutant forms into stable mineral phases.

Understanding these structure-function relationships guides material optimization. High-surface-area biochars with abundant oxygen groups excel in heavy metal immobilization, while composites with redox-active components prove effective for organic pollutant degradation. The integration of multiple functional groups through chemical modification enables simultaneous removal of mixed contaminants, addressing real-world pollution scenarios. Current research focuses on tailoring biochar composites for specific environmental matrices, balancing adsorption capacity, catalytic activity, and ecological safety requirements.

3. APPLICATIONS IN ENVIRONMENTAL REMEDIATION

3.1. Biochar-based Materials for Water Pollution Control and Heavy Metal Immobilization

Biochar-based materials demonstrate remarkable potential in addressing water contamination and immobilizing toxic heavy metals through multiple interaction mechanisms. The carbon-rich structure derived from agricultural and forestry waste functions like a molecular sponge, effectively capturing pollutants through physical and chemical processes. Its honeycomb-like pores provide extensive surface area for contaminant adsorption, while oxygen-containing surface groups chemically bind with metal ions through ion exchange and complexation reactions.

In water treatment applications, biochar's layered pore system enables simultaneous removal of diverse contaminants. Micropores trap smaller heavy metal ions like cadmium and lead through size exclusion, while larger mesopores facilitate the adsorption of organic pollutants such as pesticides. Modified biochar composites enhance this natural capacity – iron-impregnated variants introduce magnetic properties for easy recovery from treated water while enabling redox reactions that transform toxic chromium (VI) into less harmful chromium (III). The integration of clay minerals improves cation exchange capacity, particularly effective in removing copper and zinc ions from industrial wastewater.

Heavy metal immobilization in contaminated soils benefits from biochar's dual action of adsorption and pH modulation. The material's alkaline nature neutralizes acidic soils, reducing metal solubility and bioavailability. Field studies demonstrate that biochar amendments convert mobile heavy metal fractions into stable forms through chemical precipitation and surface complexation. Iron-modified composites further enhance this process by forming insoluble metal-hydroxide complexes, significantly decreasing plant uptake of contaminants.

Recent innovations combine biochar with microbial communities for synergistic remediation. The porous structure shelters pollutant-degrading bacteria while providing essential nutrients through gradual carbon release. This biochar-microbe system achieves continuous contaminant breakdown – microbes metabolize organic pollutants adsorbed on biochar, while the carbon matrix prevents toxic metal ions from inhibiting microbial activity. In mining-impacted areas, such systems have successfully restored aquatic ecosystems by simultaneously reducing heavy metal concentrations and degrading residual hydrocarbons.

Practical applications highlight biochar's adaptability across pollution scenarios. For diffuse agricultural runoff containing pesticides and phosphates, biochar filters in drainage systems show sustained contaminant retention capabilities. In industrial wastewater treatment, engineered biochar pellets effectively remove multiple heavy metal species through sequential adsorption mechanisms. The material's reusability after simple acid washing maintains cost-effectiveness, though regeneration efficiency gradually decreases with repeated cycles.

Environmental safety considerations guide modern biochar applications. Advanced stabilization techniques prevent re-release of captured metals under varying pH conditions, addressing concerns about secondary contamination. Composite materials with mineral coatings demonstrate enhanced long-term stability in both aquatic and soil environments. Current research focuses on optimizing biochar formulations for specific pollution profiles – high-temperature biochars excel in organic pollutant adsorption, while phosphorus-enriched variants preferentially bind lead and cadmium ions.

Despite demonstrated effectiveness, challenges persist in scaling up laboratory successes. Variability in raw material composition affects batch consistency, necessitating quality control protocols during production. Field trials reveal reduced efficiency in waters with extreme salinity or complex pollutant mixtures, highlighting the need for site-specific material engineering. Ongoing developments in nanotechnology integration and intelligent responsive designs promise next-generation biochar materials capable of self-regulating their adsorption properties based on environmental conditions.

The combination of natural adsorption capacity with engineered enhancements positions biochar-based solutions as versatile tools for water purification and metal immobilization. By converting agricultural waste into functional remediation materials, this approach aligns with circular economy principles while addressing pressing environmental health concerns. Future advancements will focus on optimizing material longevity and developing integrated treatment systems that combine biochar with traditional remediation technologies.

3.2. Soil Quality Improvement and Carbon Sequestration through Biochar Amendments

Biochar amendments demonstrate multifaceted benefits in revitalizing degraded soils while contributing to long-term carbon storage. The porous structure of biochar acts as a physical scaffold in soil systems, improving aeration and water retention capabilities particularly in compacted or sandy terrains. This structural enhancement facilitates root penetration and microbial colonization, creating favorable conditions for vegetation restoration in contaminated sites. In acidic soils, biochar's alkaline nature effectively neutralizes pH imbalances, reducing aluminum toxicity while increasing nutrient availability for plant uptake.

The carbon sequestration potential stems from biochar's stable aromatic structure, which resists microbial decomposition for centuries compared to untreated organic matter. Field applications show that incorporating biochar into agricultural soils significantly reduces greenhouse gas emissions by suppressing methane production and nitrous oxide release through improved soil oxygenation. The material's high cation exchange capacity enhances nutrient retention, decreasing fertilizer leaching and maintaining soil fertility over multiple growing seasons.

Microbial communities experience notable improvements in biochar-amended soils, with increased diversity and metabolic activity observed across various contamination scenarios. The porous network provides protected habitats for beneficial microorganisms while the gradual release of pyrogenic carbon serves as a sustainable energy source. This synergy between biochar and soil microbiota accelerates organic pollutant degradation through enhanced enzymatic activity and promotes the formation of stable organo-mineral complexes that immobilize heavy metals.

Practical soil restoration projects illustrate biochar's adaptability to different pollution types. In metal-contaminated sites, modified biochar composites effectively reduce metal mobility through combined mechanisms of surface complexation and precipitation. The alkaline environment created by biochar amendments promotes the formation of insoluble metal hydroxides, while iron-enhanced variants demonstrate superior performance in stabilizing multiple heavy metal species simultaneously. For organic pollutant degradation, biochar's role as an electron mediator facilitates microbial redox reactions that break down persistent hydrocarbons and pesticides.

Long-term field monitoring reveals improved soil aggregation and organic carbon content in biochar-treated areas, with enhanced water-stable aggregate formation protecting against erosion. The material's water retention properties prove particularly valuable in arid regions, where biochar amendments reduce irrigation requirements while maintaining crop yields. In urban soil rehabilitation projects, biochar helps remediate compacted soils by restoring natural porosity and supporting vegetation establishment in brownfield sites.

Carbon sequestration efficiency varies with biochar production parameters and application methods. High-temperature biochars exhibit greater stability against oxidation, while finer particle sizes ensure homogeneous distribution in soil matrices. Combined applications with organic fertilizers create synergistic effects, where biochar protects labile carbon compounds from rapid decomposition while improving nutrient cycling. Life cycle assessments confirm that biochar production from agricultural residues achieves net negative carbon emissions when considering both soil carbon storage and avoided methane release from biomass decomposition.

Challenges remain in optimizing application rates for different soil types and contamination levels. Excessive biochar application can temporarily immobilize essential nutrients, requiring precise dosage calculations based on soil characteristics. Recent advancements in biochar-mineral composites address this limitation by incorporating nutrient-rich clay components that balance soil chemistry. The development of site-specific biochar formulations through machine learning optimization represents a promising approach for maximizing remediation effectiveness while minimizing material inputs.

The integration of biochar amendments into circular economy models demonstrates environmental and agricultural co-benefits. Converting crop residues into soil-stable carbon not only sequesters atmospheric CO_2 but also improves farmland productivity, creating economic incentives for widespread adoption. Municipal-scale applications utilizing urban green waste-derived biochar showcase potential for closing organic material loops while rehabilitating degraded urban soils.

Ongoing research focuses on enhancing biochar's multifunctionality through engineered surface modifications and intelligent response mechanisms. pH-responsive biochar variants that adjust their surface charge according to soil conditions show improved heavy metal retention in dynamic environments. The emerging concept of "designer biochars" tailors material properties to specific soil remediation needs, combining contamination treatment with carbon management objectives. These developments position biochar amendments as a cornerstone technology for sustainable soil management in the context of climate change mitigation and ecological restoration.

4. CHALLENGES AND FUTURE PERSPECTIVES

While biochar-based materials show great promise in environmental remediation, several challenges must be addressed to realize their full potential. A primary limitation lies in maintaining consistent material quality across different production batches, as natural variations in biomass feedstocks – including moisture content and chemical composition – can significantly alter biochar properties. This variability complicates large-scale applications where predictable performance is essential.

Long-term ecological impacts remain insufficiently understood, particularly regarding how biochar interacts with complex soil ecosystems over decades. Concerns persist about potential secondary contamination from heavy metals or organic compounds released during biochar degradation, especially under extreme environmental conditions like acid rain or flooding. The material's effects on soil microbial communities require deeper investigation, as prolonged exposure might unintentionally alter nutrient cycling processes.

Current technical barriers hinder practical implementation. Most studies focus on single-pollutant systems, while real-world environments typically contain mixed contaminants that interact unpredictably with biochar. The material's effectiveness decreases significantly in highly saline or alkaline conditions common in industrial sites, necessitating site-specific modifications. Energy-intensive production methods and transportation costs further limit economic viability for large-area remediation projects.

Future research should prioritize developing standardized protocols for biochar characterization and application. Establishing universal quality indicators – such as stability ratings and contaminant adsorption thresholds – would enable better comparison between studies and safer field deployments. Advances in artificial intelligence could optimize production parameters by analyzing relationships between feedstock properties, pyrolysis conditions, and final material performance.

Innovative material designs show promise for overcoming current limitations. "Smart" biochar composites responsive to environmental stimuli could automatically adjust their porosity or surface chemistry when detecting specific pollutants. Integrating self-cleaning mechanisms through embedded catalytic nanoparticles might extend material lifespan by breaking down accumulated contaminants. Biochar hybrids combining adsorption capabilities with renewable energy functions – such as solar-activated pollutant degradation – represent another exciting frontier.

Combining biochar technology with other remediation strategies could enhance overall effectiveness. Coupling biochar amendments with phytoremediation creates synergistic systems where plants extract contaminants while biochar improves soil conditions and prevents pollutant spread. Developing integrated treatment trains that sequentially use biochar filtration, microbial degradation, and constructed wetlands may address complex pollution scenarios more comprehensively than single-method approaches.

Economic and social factors require equal attention to technical advancements. Creating sustainable supply chains using local biomass waste can reduce production costs while supporting circular economy models. Public education programs must address misconceptions about biochar safety and demonstrate its benefits compared to conventional remediation methods. Policy frameworks encouraging biochar use in environmental projects through subsidies or carbon credits could accelerate adoption.

The path forward demands collaborative efforts across scientific disciplines and stakeholder groups. Materials scientists need to work with ecologists to assess long-term environmental impacts, while engineers should collaborate with economists to optimize production scalability. Bridging laboratory innovations with practical field applications will require standardized testing protocols that simulate real-world conditions more accurately. By addressing these challenges through coordinated research and development, biochar-based solutions can evolve into reliable, multifunctional tools for global environmental restoration.

REFERENCES

[1] Matos, J.Eco-Friendly Heterogeneous Photocatalysis on Biochar-Based Materials Under Solar Irradiation [J]. Topics in Catalysis, 2016, 59(2-4):394-402. DOI:10.1007/s11244-015-0434-5.

[2] Bayuo J, Alayande A B, Mtei K M, et al. Biochar-based technology in water and wastewater treatment [J]. Low Cost Water and Wastewater Treatment Systems: Conventional and Recent Advances, 2025:153-194.

[3] Xiong X, Liu J, Xiao T, et al. Remediation of uranium-contaminated water and soil by biochar-based materials: a review [J]. Biochar, 2025, 7(1). DOI:10.1007/s42773-025-00438-2.

[4] Priya A K, Muruganandam M, Suresh S. Bio-derived carbon-based materials for sustainable environmental remediation and wastewater treatment [J]. Chemosphere, 2024, 362. DOI:10.1016/j.chemosphere.2024.142731.

[5] Wei Z, Wei Y, Liu Y, et al. Biochar-based materials as remediation strategy in petroleum hydrocarbon-contaminated soil and water: Performances, mechanisms, and environmental impact [J]. Journal of Environmental Sciences, 2024, 138:350-372. DOI:10.1016/j.jes.2023.04.008.

[6] Lu W, Cai H, Zhang K H X. Aramid nanofibers/biochar nanosheets co-assembled composites for wastewater remediation under harsh environments [J]. Industrial Crops and Products, 2024, 207(Pt.1). DOI:10.1016/j.indcrop.2023.117759.

[7] Manikandan S K, Pallavi P, Shetty K, et al.Effective Usage of Biochar and Microorganisms for the Removal of Heavy Metal Ions and Pesticides [J]. Molecules (Basel, Switzerland), 2023, 28(2). DOI:10.3390/molecules28020719.

[8] Karre A V, Cai T. Review of innovative uses of biochar in environmental applications for nitrobenzene removal in aqueous and soil phases [J]. 2023. DOI:10.3389/fceng.2023.1186878.

[9] Lu L, Yu W, Wang Y, et al. Application of biochar-based materials in environmental remediation:from multi-level structures to specific devices [J]. Biochar, 2020, 2(1):31. DOI:10.1007/s42773-020-00041-7.

[10] Tam Do MinhSong, JianzhiDeb, AnjanCha, LigenSrivastava, VarshaSillanpaa, Mika.Biochar based catalysts for the abatement of emerging pollutants: A review [J]. Chemical Engineering Journal, 2020, 394(000):25. DOI:10.1016/j.cej.2020.124856.

[11] Lawrinenko M. Biochar for sustainable advances in agriculture and environmental remediation [J]. 2016. DOI:10.31274/ETD-180810-5578.

[12] Guo Q, Wang X, Chen W. Synthesis and Characterization of beta-Cyclodextrin Modified Biochar Environmental Remediation Materials [J]. Journal of Materials Science and Chemical Engineering, 2024, 12(4):42-52. DOI:10.4236/msce.2024.124004.

[13] Irewale A T, Dimkpa C O, Elemike E E, et al. Water hyacinth: Prospects for biochar-based, nano-enabled biofertilizer development [J]. Heliyon, 10(17):e36966[2025-03-17]. DOI:10.1016/j.heliyon.2024.e36966.

[14] Mazarji M, Bayero M T, Minkina T, et al. Realizing United Nations Sustainable Development Goals for Greener Remediation of Heavy Metals-Contaminated Soils by Biochar: Emerging Trends and Future Directions [J]. Sustainability, 2021, 13. DOI:10.3390/su132413825.