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Biochar-Based Composite Materials for the Remediation of Contaminated Water and Polluted Soil: Mechanisms, Influencing Factors, Practical Constraints, and Future Prospects

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Abstract. Biochar-based composites have attracted growing attention because they combine biochar with minerals, metal oxides, and other functional components. Compared with pristine biochar, these composites generally provide more active surface sites, stronger ion-exchange capacity, improved electron-transfer behavior, and in some cases catalytic, photocatalytic, or magnetic properties. This review discusses four closely related aspects: feedstock and modification strategy, applications in wastewater treatment and soil remediation, the main variables governing remediation efficiency, and the constraints limiting large-scale use. Available evidence shows that lignocellulosic biomass is suitable for constructing stable porous matrices, while MgO-, ZnO-, and Fe-based modifications can introduce adsorption, co-precipitation, catalytic degradation, photocatalysis, and redox transformation functions. However, performance remains highly dependent on pyrolysis temperature, pH, contact time, pollutant concentration, coexisting species, and regeneration conditions. Wider practical use is still restricted by variability in material properties, limited knowledge of long-term stability, difficulties in spent material management, and economic barriers to scale-up. Future work should therefore emphasize standardized synthesis, mechanism-oriented characterization, life-cycle-aware design, and validation under realistic pilot- and field-scale conditions.

1 Introduction

The accumulation of hazardous contaminants in aquatic and terrestrial environments has become a persistent global concern. Heavy metals, dyes, pesticides, antibiotics, pharmaceuticals, and other emerging pollutants are widely detected in surface water, groundwater, soils, and sediments. Many of these substances are toxic, mobile, resistant to degradation, and capable of exerting long-term ecological and human health risks. Conventional remediation technologies, including chemical precipitation, membrane separation, advanced oxidation, excavation, and thermal treatment, can be effective in specific contexts, but they are often associated with high cost, limited selectivity, poor adaptability, or the generation of secondary wastes [1,8].

Among available treatment approaches, adsorption-based remediation remains attractive because of its simplicity, operational flexibility, and compatibility with integrated treatment systems. In this context, biochar has emerged as a carbon-rich material of considerable interest due to its low cost, broad feedstock availability, porous structure, and chemically tunable surface. Biochar is generally produced through the thermochemical conversion of biomass under oxygen-limited conditions, and its final properties are strongly influenced by both feedstock type and pyrolysis regime.

Despite these advantages, pristine biochar often lacks the selectivity, catalytic capability, and structural consistency needed for optimal performance in complex environmental matrices. To address these limitations, increasing attention has shifted toward biochar-based composite materials, in which biochar is integrated with minerals, metal oxides, iron phases, or other functional components. Such modifications can tailor pore architecture, enrich surface chemistry, improve electron mobility, strengthen pollutant immobilization, and in some cases enable catalytic degradation or magnetic recovery. As a result, the field has evolved from the study of simple biochar sorbents toward the design of multifunctional remediation platforms. A clearer understanding of how feedstock, modification route, material structure, and environmental conditions interact is therefore essential for advancing practical applications [3,8,9].

2 Feedstock Selection and Modification Strategy as Determinants of Composite Performance

In this review, “biochar-based composites” are materials in which biochar is intentionally combined with a distinct secondary phase (e.g., metal oxides, minerals, or iron phases), rather than merely modified biochar unless otherwise stated. The remediation behavior of biochar-

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based composites is determined primarily by two interrelated factors: the intrinsic characteristics of the biomass precursor and the strategy used to functionalize the material.

Lignocellulosic feedstocks such as wood, straw, and sawdust generally yield biochars with higher carbon content, more developed aromatic frameworks, and relatively stable pore structures. These characteristics make them especially suitable as robust porous scaffolds for further functionalization. By contrast, manure-derived and sludge-derived biochars usually contain higher ash fractions and a broader range of mineral phases. Although such materials may show less structural uniformity, their mineral content can promote ion exchange, co-precipitation, and stabilization processes, particularly in the treatment of metal-contaminated soils [2-4,9].

The second major determinant is the modification route. Common strategies include acid or alkali treatment, surface oxidation, ball milling, hydrothermal processing, co-precipitation, metal salt impregnation, and in situ mineral growth. The incorporation of MgO or ZnO can alter surface charge, increase the density of reactive sites, and introduce catalytic or photocatalytic behavior. Iron modification is especially important because iron-containing phases may provide redox activity, magnetic recoverability, and stronger affinity for selected metals and redox-sensitive organic pollutants. Additional chemical functionalization, including the introduction of oxygen-containing or nitrogen-containing groups, can further enhance coordination, hydrogen bonding, electrostatic attraction, and other specific interactions.

These distinctions are important because pollutant removal by biochar-based composites rarely occurs through a single mechanism. Depending on material design and environmental conditions, relevant pathways may include pore filling, hydrophobic partitioning, π - π interaction, electrostatic attraction, hydrogen bonding, surface complexation, ion exchange, mineral precipitation, catalytic degradation, and electron transfer. Accordingly, feedstock selection should not be regarded merely as a starting material choice, but as an integral component of remediation design. The best-performing composite is not necessarily the material with the highest surface area; rather, it is the one whose structural and chemical features are best aligned with the target pollutant and the intended application environment [5,6,8]. Representative design routes and remediation roles are summarized in Table 1.

Table 1. Representative biochar-composite design routes and remediation roles.

Category	Typical feedstocks or modifiers	Distinctive properties	Representative remediation roles
Lignocellulosic biochar	Wood chips, straw, sawdust	High carbon content, stable porous framework, relatively good structural stability	Suitable for adsorption of dyes and many dissolved metals; useful as a base matrix for further modification
Manure- or sludge-derived biochar	Animal manure, sewage sludge, mixed organic waste	Higher ash and mineral content, stronger ion-exchange and precipitation potential	Often effective for cationic metal immobilization in soils, but impurity management is important
Metal oxide-modified biochar	MgO-, ZnO-, and related mineral coatings	More active sites, altered surface charge, possible catalytic or photocatalytic activity	Enhanced Pb(II) removal and improved treatment of dye-containing wastewaters
Iron/biochar composites	Impregnation with Fe salts, co-precipitation, thermal conversion, ball milling	Redox-active surfaces, magnetic response in some systems, multifunctional stabilization behavior	Promising for chlorinated organics, redox-sensitive pollutants, and heavy-metal-contaminated soils

3 Applications of Biochar-Based Composites in Water and Soil Remediation

3.1 Wastewater treatment

Wastewater treatment is among the most extensively investigated applications of biochar-based composites. In dye-contaminated effluents, these materials often outperform pristine biochar because they can integrate adsorption with catalytic or photocatalytic degradation. For example, when ZnO is loaded onto a porous carbon framework, pollutants may first be concentrated near reactive sites through adsorption and subsequently degraded through photocatalytic pathways. This dual-function behavior can improve removal efficiency and reduce the limitations associated with saturation of adsorption sites [4].

Heavy metal removal is another major area of application. MgO-modified composites frequently show strong affinity for Pb(II) and related cationic metals because they provide alkaline reactive surfaces and facilitate precipitation or surface complexation. Iron-containing composites may further improve treatment performance by coupling adsorption with redox transformation, particularly for contaminants whose mobility or toxicity depends on oxidation state.

At the same time, wastewater treatment performance is strongly affected by solution chemistry. Pollutant charge, hydrophobicity, pH, dissolved organic matter, and the presence of competing cations or anions can all influence both pollutant speciation and the effective surface properties of the composite. Materials that perform well in simplified laboratory systems may therefore behave differently in realistic effluents. For practical implementation, composite selection should be based on a pollutant-specific and matrix-specific design strategy rather than on the assumption that a single sorbent can be universally effective.

3.2 Soil remediation

In soil systems, biochar-based composites often serve functions that extend beyond direct adsorption. Rather than physically extracting contaminants from the matrix, they are commonly used to reduce contaminant mobility, lower bioavailability, and mitigate ecological risk. Their effects may involve simultaneous changes in soil pH, cation exchange capacity, water-holding ability, nutrient availability, and microbial activity, along with the stabilization of heavy metals and agricultural contaminants.

Among reported materials, manure-derived biochar composites and iron-containing systems are especially relevant for soil remediation. Mineral-rich materials may promote ion exchange and precipitation, while iron phases can enhance stabilization and, under favorable conditions, mediate redox transformations that alter contaminant behavior. These combined functions make iron/biochar composites particularly attractive for soils contaminated by multiple classes of pollutants [6,8].

However, soil is inherently heterogeneous and dynamic. Texture, mineralogy, organic matter content, rainfall, redox fluctuations, microbial activity, plant-root interactions, and aging processes may all influence composite stability and remediation performance. As a result, materials that appear highly effective in controlled laboratory experiments may not provide the same benefits under long-term field conditions. More realistic validation is therefore essential before broad practical use can be recommended [8,9].

4 Key Factors Governing Remediation Efficiency

Even when a biochar-based composite is deliberately engineered, its remediation performance depends strongly on operational and environmental conditions. These factors do not act independently, but interact in ways that shape the dominant pollutant-removal mechanisms.

Pyrolysis temperature is a fundamental determinant of composite structure and reactivity. It affects aromaticity, pore development, mineral retention, and the abundance of surface functional groups. Lower temperatures may preserve more oxygen-containing groups that support surface complexation and hydrogen bonding, whereas higher temperatures often improve structural stability and porosity. The optimal temperature therefore depends on whether adsorption, complexation, precipitation, redox transformation, or catalysis is expected to dominate [5-7].

Environmental pH is equally important because it governs both pollutant speciation and the surface charge of the composite. Alkaline conditions may favor the immobilization or precipitation of some cationic metals, but the same conditions are not necessarily beneficial for every contaminant class. Contact time controls the transition from rapid initial uptake at external sites to slower intra-particle diffusion and eventual equilibrium. Regeneration strategy determines reuse potential, economic feasibility, and whether pollutant-loaded composites pose a secondary environmental hazard after treatment [5,6].

Additional variables such as initial pollutant concentration, coexisting ions, dissolved organic matter, redox status, and temperature may also significantly affect performance. Because these parameters interact, process optimization should be conducted in an integrated way rather than through isolated single-factor testing under idealized conditions. Major operating parameters are summarized in Table 2.

Table 2. Major operating parameters influencing remediation performance.

Parameter	General response	Implication for practical design
Feedstock composition	Controls ash content, aromaticity, mineral phases, and pore development	Choose biomass sources according to the dominant contaminants and whether adsorption or immobilization is the main objective
Pyrolysis temperature	Alters structural order and functional-group density; may improve some capacities while weakening others	Optimize temperature jointly with the intended modifier instead of maximizing temperature alone
pH of water or soil	Changes surface charge, pollutant speciation, and precipitation behavior	Match the composite to the expected environmental pH range and the charge characteristics of the target pollutants

5 Limitations to Large-Scale Application

Despite substantial progress, several barriers still restrict the broader use of biochar-based composites. First, synthesis methods remain insufficiently standardized. Even when similar feedstocks are used, variations in pretreatment, modifier dosage, impregnation ratio, heating rate, pyrolysis atmosphere, and post-treatment can produce materials with markedly different physicochemical properties. This variability reduces reproducibility, complicates comparison among studies, and hinders the transition from laboratory optimization to engineering deployment [8,9].

Second, the management of spent materials remains a critical concern. Once pollutants are captured, the composite itself may become a source of secondary contamination if regeneration, reuse, or disposal is not properly handled. This issue is especially important for wastewater treatment applications involving toxic metals, pharmaceuticals, or persistent organic pollutants. Exhausted sorbents may accumulate hazardous substances and require careful post-treatment management to prevent pollutant re-release.

Third, economic feasibility continues to be a practical limitation. Although biomass feedstocks are often inexpensive and widely available, some modification routes depend on costly chemicals, multi-step synthesis, or energy-intensive processing. Transport, drying, impregnation, pyrolysis, and regeneration all contribute to the total cost of production and use. As a result, the viability of these materials should be evaluated from a broader life-cycle and scale-up perspective rather than on the basis of laboratory performance alone.

Finally, long-term environmental stability and ecotoxicological behavior remain insufficiently understood. A newly prepared composite may behave quite differently after aging, repeated wetting-drying cycles, microbial attack, long-term exposure to mixed pollutants, or changes in environmental redox conditions. These uncertainties must be addressed before biochar-based composites can be regarded as dependable engineering materials rather than promising laboratory sorbents. Relative to conventional activated carbon or ion-exchange resins, biochar-based composites may be cost-competitive when low-cost biomass feedstocks and simple preparation routes are used, but this advantage can diminish when expensive modifiers, multi-step synthesis, or frequent regeneration are required.

6 Future Perspectives

Future research should advance along four closely related directions. The first priority is the development of standardized and economically realistic production routes. Greater consistency in feedstock selection, pretreatment, modifier dosage, thermal conditions, and characterization protocols would improve reproducibility and enable more meaningful cross-study comparison. Greener and less chemically intensive modification strategies should also be emphasized to improve sustainability.

The second priority is deeper mechanistic clarification. Advanced spectroscopy, microscopy, and quantitative modeling should be used to distinguish the relative roles of adsorption, surface complexation, ion exchange, precipitation, catalytic degradation, and redox transformation. Such mechanism-oriented understanding would support more rational material design and help avoid oversimplified interpretation of removal behavior. The third priority is more realistic validation. Pilot-scale and field-scale studies are urgently needed and should include mixed contaminants, fluctuating pH, natural organic matter, coexisting ions, microbial interactions, and long-term aging. Only under such conditions can the true robustness and environmental value of these materials be assessed.The fourth priority is life-cycle-oriented design and end-of-life management. Composites that are magnetically recoverable, readily regenerable, structurally stable, or suitable for secondary utilization may offer better practical value and lower environmental risk. Post-use management should not be treated as an afterthought; it should be incorporated into material design from the beginning.

By integrating material synthesis, remediation performance, regeneration, and long-term environmental behavior, future work can strengthen the role of biochar-based composites in wastewater treatment, soil restoration, and broader pollution-control strategies, especially in resource-constrained settings.

7 Conclusions

Biochar-based composite materials are promising multifunctional remediation agents for contaminated water and polluted soils because they provide improved pore structure, enhanced surface reactivity, and additional adsorption, catalytic, precipitation, and redox functions relative to pristine biochar. Their performance, however, depends strongly on feedstock type, modification route, pyrolysis temperature, environmental chemistry, and post-use management. Practical application therefore requires not only high removal efficiency but also better standardization, long-term stability, regeneration, economic feasibility, and field validation. With further progress, these materials will play a larger role in pollution control and ecological restoration.

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