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Review article

Use of Nanocomposite Biochar for Environmental Remediation, Soil Health, and Sustainable Agriculture

Ping Huang*[1]*, Shoucheng Huang*[2]**

[1] College of Chemistry and Materials Engineering, Anhui Science and Technology University, Bengbu 233000, China; huangp@ahstu.edu.cn
[2] Biomedical and Health Sciences, Anhui Science and Technology University, Fengyang,233100, Anhui, China; huangsc@ahstu.edu.cn

* Correspondence: huangsc@ahstu.edu.cn

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Abstract

Nanocomposite biochar has emerged as a multifunctional carbon-based material with exceptional potential to address interconnected challenges in environmental remediation, soil degradation, and sustainable agriculture. By integrating biochar with nanoscale constituents such as metal oxides, carbon nanostructures, and mineral nanoparticles, the resulting composites exhibit markedly enhanced surface reactivity, porosity, redox activity, and functional group diversity compared with conventional biochar. These advanced properties enable efficient immobilization and removal of heavy metals, organic contaminants, and emerging pollutants from soil and water systems, while simultaneously improving nutrient retention, soil structure, and microbial activity. Recent evidence also highlights the role of nanocomposite biochar in promoting crop productivity, mitigating abiotic stresses, enhancing fertilizer use efficiency, and contributing to long-term carbon sequestration and climate change mitigation. Although several reviews have discussed conventional biochar applications, limited attention has been given to the multifunctional role of nanocomposite biochar, which integrates adsorption, catalysis, nutrient management, and climate-resilient agricultural applications within a single framework. Moreover, critical discussions regarding synthesis strategies, environmental safety, scalability, and future agricultural implementation remain fragmented in the existing literature. This review critically synthesizes recent progress in synthesis strategies, physicochemical characterization, and application pathways of nanocomposite biochar across environmental and agricultural domains. Key challenges related to environmental safety, long-term stability, scalability, and regulatory considerations are examined, and future research priorities are outlined to support responsible development and field-level adoption. Overall, nanocomposite biochar represents a promising, integrative platform for advancing resilient agroecosystems and sustainable environmental management.

Keywords: Nanocomposite biochar; environmental remediation; soil quality; sustainable agriculture; nanomaterials

1. Introduction

Biochar is a carbon-rich material produced by thermochemical conversion of organic biomass under oxygen-limited conditions, commonly known as pyrolysis (Ghosh *et al.*, 2023). The structural characteristics of biochar—high porosity, large specific surface area, and abundance of functional groups (e.g., hydroxyl, carboxyl, and carbonyl groups)—make it an attractive material for environmental and agricultural applications (Niedziński *et al.*, 2023, Jiang *et al.*, 2024, Varkolu *et al.*, 2025). The carbonaceous matrix of biochar originates primarily from the aromatic condensation of lignocellulosic components of biomass, leading to a highly stable, recalcitrant structure that can persist in soil for decades, thereby contributing to long-term carbon sequestration (Li & Tasnady, 2023, Nepal *et al.*, 2023, Pandian *et al.*, 2024). Biochar's origins can be traced back to traditional practices, such as the Amazonian "terra preta," which demonstrated enhanced soil fertility and pollutant stabilization, revealing biochar's potential for contemporary environmental management (Oelbermann, 2020).

Despite its inherent advantages, conventional biochar exhibits several limitations that restrict its broader applicability. Its adsorption efficiency is often limited by relatively low surface reactivity and poor selectivity towards specific contaminants (Chen *et al.*, 2022, Arabzadeh *et al.*, 2024). The porous network of biochar can be underutilized due to the heterogeneous distribution of its active sites, resulting in suboptimal pollutant removal. Moreover, conventional biochar shows limited multifunctionality; while it can immobilize heavy metals or enhance soil fertility individually, its performance in simultaneous remediation of multiple pollutants or in combined enhancement of soil and water quality is inadequate (Chen *et al.*, 2022, Hu *et al.*, 2025). Mechanistically, this is attributed to the predominantly passive adsorption processes—such as physisorption and cation exchange—without sufficient catalytic or redox-active sites to drive complex degradation reactions of persistent organic pollutants (Masud et al., 2025, Tibebu et al., 2025).

To overcome these limitations, nanocomposite biochar (NCB) has emerged as a promising class of engineered materials. NCB integrates biochar with nanoparticles or nanostructured materials—such as metal/metal oxide nanoparticles (Fe_3O_4, TiO_2, ZnO), carbon-based nanomaterials (graphene oxide, carbon nanotubes), or polymeric nanocomposites—to enhance both the physicochemical and catalytic properties of the parent biochar (Amdeha, 2024, Hayder & Naim, 2025). The incorporation of nanomaterials introduces reactive surface sites, electron-transfer capabilities, and photocatalytic properties, enabling advanced remediation mechanisms (Arabzadeh *et al.*, 2024). For instance, Fe_3O_4-loaded biochar can facilitate Fenton-like reactions for oxidative degradation of organic pollutants, while TiO_2-functionalized biochar can promote photocatalytic generation of reactive oxygen species under UV-visible irradiation, achieving simultaneous adsorption and degradation (Ambaye *et al.*, 2021). Nanocomposite biochar thus converts the passive adsorption of conventional biochar into an active, multifunctional system capable of interacting with pollutants via electrostatic attraction, complexation, redox reactions, and catalytic transformation pathways (Chadar, 2025).

The significance of NCB spans several critical domains. In soil systems, NCB improves nutrient retention, enhances microbial activity, and immobilizes heavy metals, reducing bioavailability and potential uptake by crops. In aqueous systems, NCB acts as a superior adsorbent and catalyst for the removal of heavy metals, pesticides, dyes, and emerging contaminants through a combination of adsorption, reduction, and photocatalysis (Tewari *et al.*, 2023). Moreover, due to its stable carbon framework and engineered multifunctionality, NCB contributes to carbon sequestration and mitigates greenhouse gas emissions, aligning with sustainable environmental management strategies. Additionally, NCB demonstrates potential for air purification, energy storage, and catalysis in industrial applications, showcasing its multifunctional versatility (Canadell & Schulze, 2014, Kholmirzaeva *et al.*, 2023, Sudharsana *et al.*, 2024).

Globally, research on NCB has expanded rapidly over the last decade, with studies highlighting its superior adsorption capacities, enhanced reaction kinetics, and broader environmental applications compared to conventional biochar. Bibliometric analyses indicate that China, the USA, and European countries are leading in NCB development, targeting applications ranging from wastewater treatment and soil remediation to energy storage and sensor technology (Ramanayaka *et al.*, 2020, Kumar *et al.*, 2023). Industrial interest is increasing due to the potential for scalable, cost-effective synthesis and for integrating waste biomass and environmentally benign nanomaterials. These trends underscore the emerging role of NCB not merely as a derivative of biochar but as a next-generation material for multifunctional environmental remediation and sustainable agriculture (Ramanayaka *et al.*, 2020, Bhandari *et al.*, 2023).

Therefore, the objective of this review is to comprehensively evaluate recent advances in nanocomposite biochar synthesis, characterization, pollutant removal mechanisms, and agricultural applications. The review further aims to critically examine the multifunctional role of nanocomposite biochar in environmental remediation, soil health improvement, carbon sequestration, and sustainable agricultural production while highlighting current challenges, environmental risks, and future research opportunities for field-scale implementation.

1.1 Synthesis and Fabrication of Nanocomposite Biochar

Nanocomposite biochar (NCB) synthesis involves the strategic integration of biochar with functional nanomaterials to enhance its physicochemical properties and environmental performance (Bhandari *et al.*, 2023, Zheng *et al.*, 2025). The effectiveness of NCB is strongly influenced by the choice of feedstock, type of nanomaterials incorporated, synthesis route, and subsequent characterization. This section comprehensively discusses these aspects to elucidate structure–property–function relationships in NCB systems (Thakur *et al.*, 2021, Sudharsana *et al.*, 2024) (Figure 1).

2. Biochar Feedstocks

Biochar feedstocks play a crucial role in determining the physicochemical characteristics and functional performance of the resulting nanocomposite biochar. Common feedstocks include agricultural residues (rice husk, wheat straw, corn stover, cotton stalks), forestry wastes (sawdust, wood chips, bark), animal manures, sewage sludge, and agro-industrial by-products (Fawzy *et al.*, 2021). These biomass sources differ significantly in lignocellulosic composition, ash content, mineral nutrients, and volatile matter, which directly influence biochar yield, porosity, surface functional groups, and stability (Ferraro *et al.*, 2024).

Agricultural residues typically yield biochar with high carbon content and well-developed pore structures, which favor adsorption-based applications. Manure- and sludge-derived biochar's, in contrast, often contain higher ash and mineral contents, providing intrinsic metal-binding sites but sometimes lower surface area (Zhang, 2021, Bartoli *et al.*, 2023). The feedstock-derived variability affects not only the parent biochar but also the dispersion, anchoring efficiency, and stability of incorporated nanoparticles. For instance, biochar's with abundant oxygen-containing functional groups facilitate stronger interactions with metal oxide nanoparticles, enhancing NCB reactivity and durability. Therefore, careful selection of feedstock is essential for tailoring NCB performance to specific remediation or agricultural objectives (Liu *et al.*, 2020).

3. Nanomaterials Used

A wide range of nanomaterials has been incorporated into biochar matrices to develop multifunctional nanocomposite biochar's.

3.1 Metal and metal oxide nanoparticles

Metal and metal oxide nanoparticles such as TiO_2, ZnO, Fe_3O_4, and MgO, are among the most widely used due to their catalytic, photocatalytic, and magnetic properties (Munzeiwa *et al.*, 2025). TiO_2 and ZnO enhance photocatalytic degradation of organic pollutants, while Fe_3O_4 imparts magnetic separability and enables Fenton-like redox reactions. MgO-based NCBs are particularly effective for heavy metal immobilization due to strong surface alkalinity and ion-exchange capacity (Zheng *et al.*, 2024).

3.2 Carbon-based nanomaterials

Carbon-based nanomaterials, including graphene, graphene oxide, and carbon nanotubes (CNTs), significantly increase surface area, electrical conductivity, and π–π interaction potential. Their incorporation enhances the adsorption of aromatic organic pollutants and improves electron transfer during catalytic processes (Fahlman, 2023).

3.3 Polymer-based nanoparticles

Polymer-based nanoparticles, such as chitosan, polyaniline, and polypyrrole, are increasingly used to impart selectivity, flexibility, and functional responsiveness. These polymers introduce amine, hydroxyl, or redox-active groups, enabling enhanced binding of metals and organic contaminants while improving mechanical stability (Maponya *et al.*, 2021) (Table 1).

4. Methods of Synthesis

Various synthesis strategies have been developed to fabricate NCB, each influencing nanoparticle distribution, bonding strength, and functional performance.

4.1 Impregnation and co-precipitation

Impregnation and co-precipitation methods involve soaking biochar in precursor solutions followed by chemical reduction or precipitation of nanoparticles. These approaches are simple and cost-effective but may result in uneven nanoparticle distribution (Bhandari *et al.*, 2023, Zheng *et al.*, 2023).

4.2 Hydrothermal and solvothermal

Hydrothermal and solvothermal methods allow simultaneous carbonization and nanoparticle formation under controlled temperature and pressure. These techniques promote strong interfacial bonding, uniform nanoparticle dispersion, and enhanced crystallinity, although they are relatively energy-intensive (Ndlwana *et al.*, 2021).

4.3 Pyrolysis-assisted nanoparticle incorporation

Pyrolysis-assisted nanoparticle incorporation involves the direct pyrolysis of biomass preloaded with nanoparticle precursors, enabling in situ formation and encapsulation of nanoparticles within the biochar matrix. This approach improves nanoparticle stability and minimizes leaching risks (Karunaratne *et al.*, 2022).

From a mechanistic perspective, in-situ synthesis generally produces stronger integration and better long-term stability than ex-situ approaches, where nanoparticles are added after biochar formation. However, ex-situ methods provide greater flexibility in material design and post-modification (Xiu *et al.*, 2017).

4.4 Characterization Techniques

Comprehensive characterization is essential for understanding NCB structure and function.

4.3.1 Physicochemical characterization

Physicochemical characterization commonly employs scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to examine morphology and nanoparticle dispersion. X-ray diffraction (XRD) identifies crystalline phases, while Fourier transform infrared spectroscopy (FTIR) reveals surface functional groups and bonding interactions. Brunauer–Emmett–Teller (BET) analysis provides information on surface area, pore volume, and pore-size distribution.

4.3.2 Functional property characterization

Functional property characterization includes zeta potential analysis to assess surface charge behavior, thermal stability evaluation using thermogravimetric analysis (TGA), and surface chemistry assessment through X-ray photoelectron spectroscopy (XPS). These parameters are critical for predicting adsorption behavior, catalytic activity, and environmental stability (Salame & Bandosz, 2001, Laisney *et al.*, 2021) (Figure 2).

Table 1. Feedstocks, incorporated nanomaterials, synthesis methods, and physicochemical properties of nanocomposite biochar systems

Biochar Feedstock	Nanomaterial Incorporated	Synthesis Method	Key Findings / Properties	Study (Year)
Rice husk / wheat straw	Fe_3O_4	Impregnation + pyrolysis	Enhanced magnetism, high surface area, improved adsorption	(Siddiqui, 2024)
Sewage sludge	ZnO	Hydrothermal	High metal immobilization due to high ash and mineral content	(Li et al., 2022)
Animal manure	MgO	Co-precipitation	Strong alkalinity, excellent heavy metal adsorption	(Wang et al., 2024)
Wood biochar	Graphene oxide	Ex-situ coating	Enhanced conductivity & π–π interactions for organics	(Aravind & Kamaraj, 2024)
Corn stover	Chitosan	Chemical grafting	Improved selective adsorption, stability & functional groups	(de Andrade Neto et al., 2020)

Table 2. Pollutant removal mechanisms and remediation efficiencies of nanocomposite biochar for environmental applications

Pollutant Type	NCB Composition	Removal Mechanism	Removal Efficiency / Capacity	Study (Year)
Organic dyes	TiO_2-biochar	Photocatalysis + adsorption	92% degradation in 60 min	(Let *et al.*, 2025)
Organic pollutants	Fe_3O_4-biochar	Fenton-like oxidation	87% removal	(Feng *et al.*, 2022)
Pb^{2+}, Cd^{2+}	GO-biochar	Complexation + ion exchange	120 mg/g (Pb)	(Chinedu *et al.*, 2026)
Pesticides	CNT-biochar	π–π interaction	85% adsorption	(Inyang *et al.*, 2015)
Cr(VI)	Fe_3O_4 + GO biochar	Reduction + adsorption	98% reduction	(Wang *et al.*, 2015)

Table 3. Comparative Advantages of Nanocomposite Biochar in Comparison to Conventional Biochar

Parameter	Conventional Biochar	Nanocomposite Biochar (NCB)	Improvement
Adsorption capacity	Moderate	High	Enhanced by nanomaterials (Li et al., 2012)
Selectivity	Low	High	Functional groups & catalytic sites (Anan et al., 2008)
Multi-pollutant removal	Limited	High	Adsorption + degradation (Li et al., 2024)
Regeneration	Low	High	Magnetic separation & stability (Sadiq et al., 2016)
Catalytic activity	None	High	ROS generation & redox reactions (Liu et al., 2014)
Cost	Low	Moderate	Higher but scalable (Callery et al., 2016)
Environmental risk	Low	Moderate	Nanoparticle leaching risk (Wang et al., 2016)

5. Mechanisms of Pollutant Removal

The superior performance of NCB over conventional biochar arises from synergistic adsorption and catalytic mechanisms that enable both immobilization and degradation of pollutants (Hu *et al.*, 2025).

5.1 Adsorption Mechanisms

Adsorption by NCB occurs through multiple physicochemical interactions, including electrostatic attraction, surface complexation, π–π interactions, hydrogen bonding, and ion exchange. Negatively charged biochar surfaces effectively attract cationic heavy metals such as Pb^{2+}, Cd^{2+}, and Cr^{3+}, while oxygen- and nitrogen-containing functional groups form stable inner-sphere complexes (Meurer *et al.*, 2020).

Carbon-based nanomaterials enhance π–π interactions with aromatic pesticides, whereas polymer-functionalized NCBs improve hydrogen bonding and selective adsorption. Case studies consistently demonstrate higher adsorption capacities of NCB than those of pristine biochar, particularly under variable pH and ionic strength conditions (Kah et al., 2017).

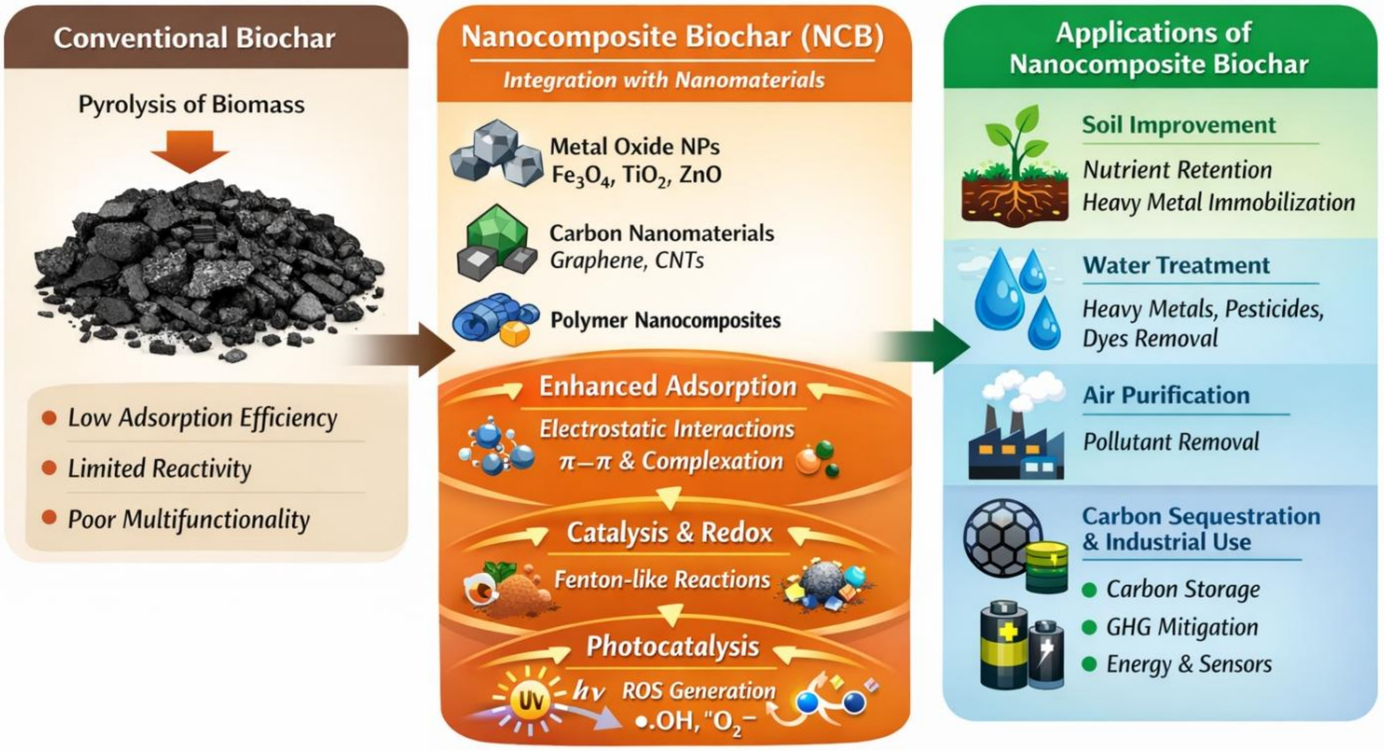

Figure 1. Design and functional evolution of nanocomposite biochar (NCB) from biomass to advanced environmental material.

5.2 Catalytic/Photocatalytic Mechanisms

Incorporated nanoparticles enable catalytic and photocatalytic degradation of organic contaminants. Under light or chemical activation, metal oxide nanoparticles generate reactive oxygen species (ROS) such as hydroxyl radicals and superoxide ions, which oxidize persistent organic pollutants into less toxic compounds (Prakruthi & Deepakumari, 2024).

Fe_3O_4-based NCBs facilitate Fenton-like reactions, while TiO_2- and ZnO-based systems enable photocatalysis under UV or visible light. The biochar matrix enhances electron transport, suppresses nanoparticle aggregation, and prolongs catalytic activity, thereby increasing degradation efficiency and reaction stability (Cui et al., 2020).

5.3 Soil and Water Remediation Synergy

NCB uniquely combines adsorption and catalytic transformation, enabling simultaneous immobilization and degradation of contaminants. In soil systems, NCB reduces the bioavailability of heavy metals through adsorption and precipitation while promoting microbial activity (Sudharsana et al., 2024). In aqueous systems, adsorption concentrates pollutants near reactive sites, enhancing catalytic degradation kinetics. This synergistic behavior significantly improves remediation efficiency compared to single-function materials (Yu *et al.*, 2026) (Table 2).

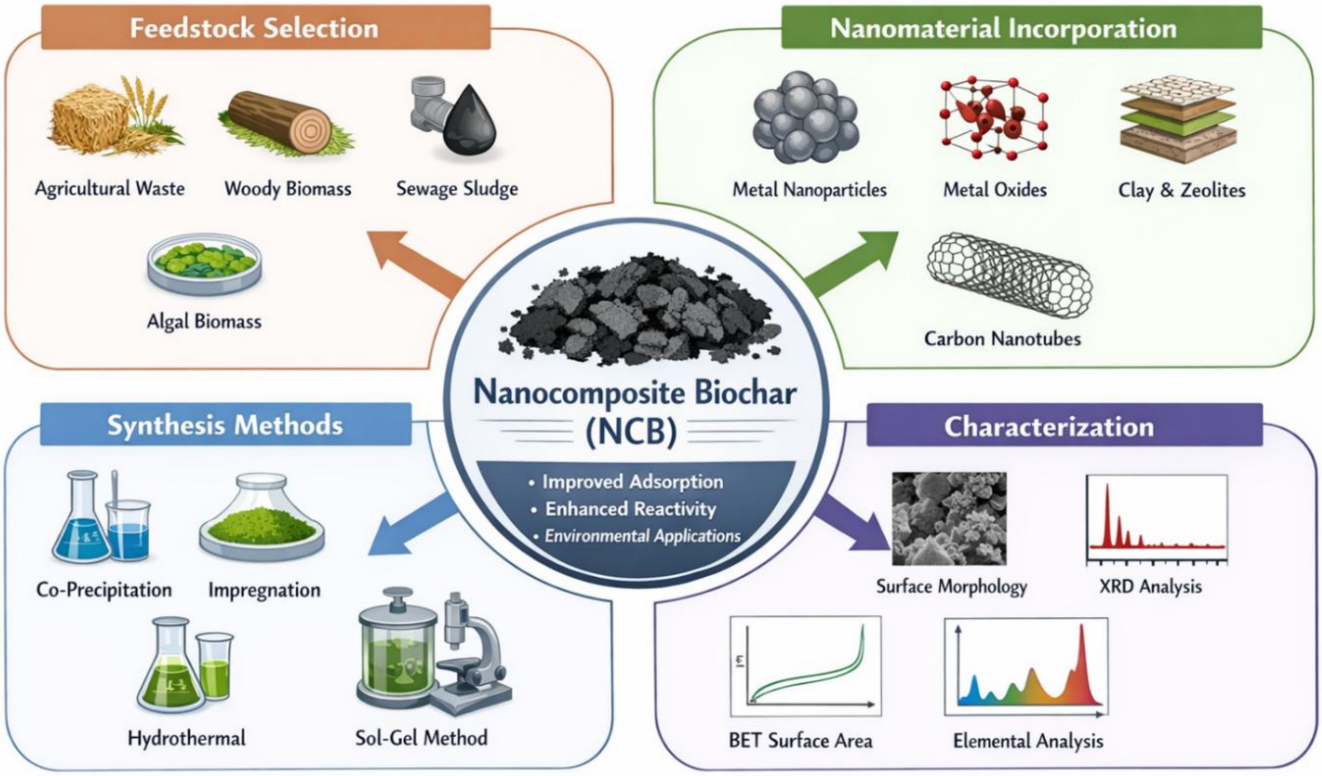

Figure 2. Synthesis strategies and structural engineering approaches for nanocomposite biochar fabrication.

6. Applications of Nanocomposite Biochar

6.1 Environmental Remediation

NCB has been widely applied for the removal of heavy metals, dyes, pesticides, pharmaceuticals, and emerging contaminants from soil and water. Comparative studies consistently report superior adsorption capacities, faster reaction kinetics, and improved reusability of NCB relative to conventional biochar (Jiang *et al.*, 2023).

6.2 Agricultural and Soil Health Applications

In agricultural systems, NCB enhances nutrient retention, reduces fertilizer leaching, and functions as a slow-release nutrient carrier. It improves soil microbial activity, root development, and crop productivity while immobilizing toxic elements. Additionally, its stable carbon structure supports long-term carbon sequestration and mitigates greenhouse gas emissions (Mosharrof *et al.*, 2021).

6.3 Energy and Industrial Applications

Beyond remediation, NCB is increasingly explored in supercapacitors, bio electrochemical systems, pollutant sensors, and industrial catalysis. Synergistic integration with conductive nanomaterials enables multifunctional applications that bridge environmental and energy technologies (Sudharsana *et al.*, 2024).

7. Factors Influencing Performance

NCB performance depends on biochar porosity, surface area, nanoparticle type, size, and loading rate. Environmental conditions such as pH, temperature, ionic strength, and competing ions significantly affect adsorption and catalytic efficiency. Aging, regeneration, and reuse potential are critical for long-term sustainability and cost-effectiveness (Olawade et al., 2024) (Table 3)**.**

8. Challenges and Limitations

Despite its promise, NCB faces challenges including potential nanoparticle toxicity, synthesis costs, scalability constraints, and regulatory uncertainties. Nanoparticle leaching and long-term ecological impacts remain key concerns requiring comprehensive risk assessment**.**

9. Future Perspectives

Future research should prioritize long-term field-scale investigations to evaluate the environmental fate, persistence, and ecological safety of nanocomposite biochar under diverse agroecosystems. Standardized synthesis protocols and lifecycle assessment frameworks are also required to improve reproducibility and scalability. Moreover, integrating artificial intelligence, precision agriculture tools, and biochar–microbe interactions may open new opportunities to develop climate-smart, resource-efficient agricultural technologies**.**

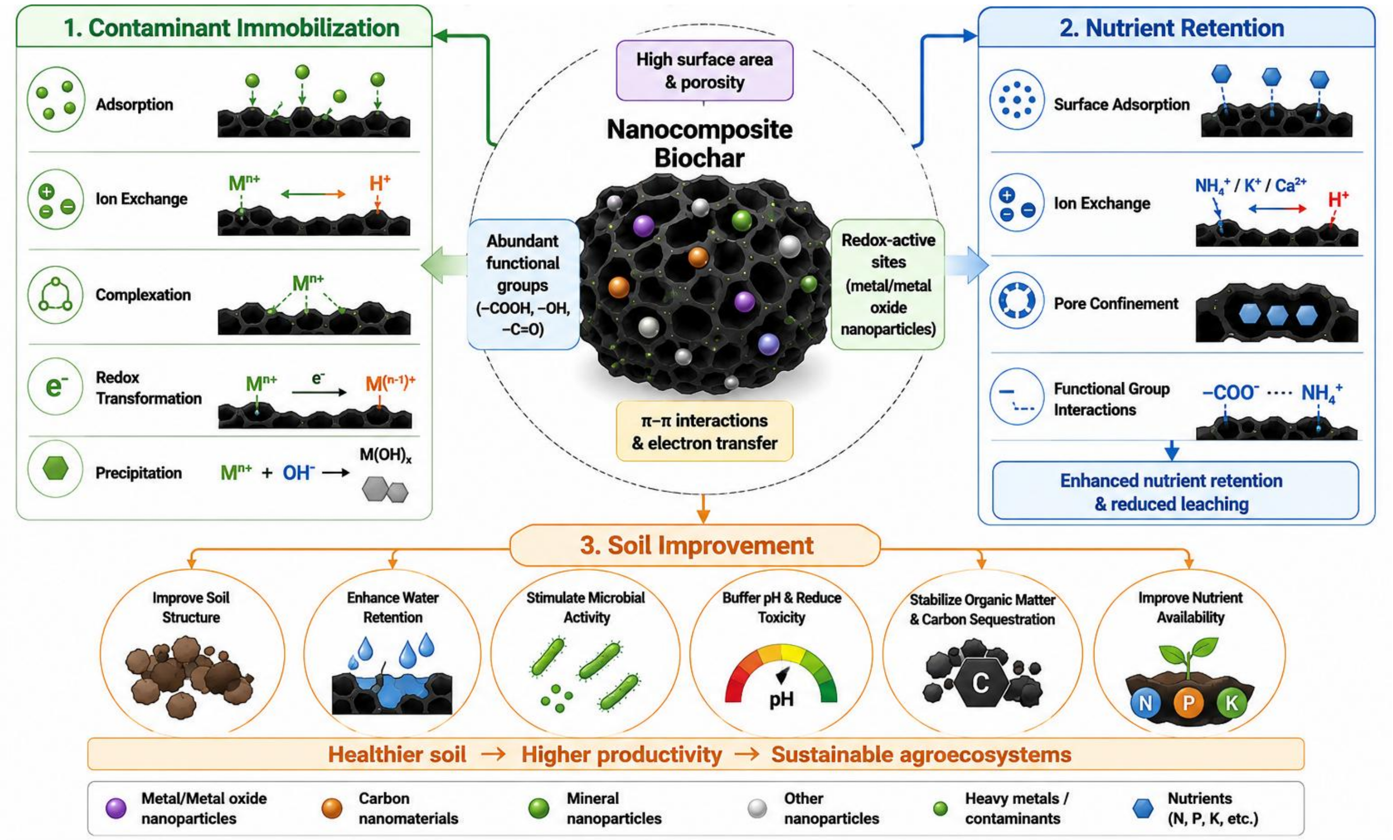

Figure 3. Mechanisms of contaminant immobilization, nutrient retention, and soil improvement by nanocomposite biochar

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