[Journal of Environmental Chemical Engineering](https://www.sciencedirect.com/journal/journal-of-environmental-chemical-engineering)

[Volume 12, Issue 1](https://www.sciencedirect.com/journal/journal-of-environmental-chemical-engineering/vol/12/issue/1), February 2024, 111840



**Biochar-derived nanocomposites for environmental remediation: The insights and future perspectives**

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**Highlights**

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This article reviews recent research on synthesizing biochar-derived [nanocomposites](https://www.sciencedirect.com/topics/chemical-engineering/nanocomposite) and their applications.

* •

Biochar’s characteristics and synthesizing methods point to its potential as a catalyst.

* •

Review discusses insights into the decontamination of soil/water, along with carbon sequestration and catalytic processes.

* •

The underlying mechanisms vary based on biochar’s characteristics and target contaminants.

* •

More studies are needed to close knowledge gaps for future development.

**Abstract**

Incorporating foreign materials/metal [nanoparticles](https://www.sciencedirect.com/topics/chemical-engineering/nanoparticle) (MNPs) with biochar creates novel BC-MNP [nanocomposites](https://www.sciencedirect.com/topics/chemical-engineering/nanocomposite). The combined benefits of biochar and the superior [catalytic activity](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/catalytic-activity) of [nanoparticles](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/nanoparticle) exhibit better [physicochemical properties](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/physicochemical-property), including large surface area, pore size, thermal stability, and varied functionalization, that substantiate overcoming the emerging issues of [environmental pollution](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/environmental-pollution) and its remediation. The current review discusses various production methods for synthesizing BC-MNPs and their prospective uses in decontaminating soil and [water contaminated](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/water-pollution) with various contaminants, such as heavy metals and organic and [inorganic pollutants](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/inorganic-pollutant). The review explores using these materials as adsorbents and catalysts for the adsorption and degradation of various contaminants. The rising CO2 emissions from burning [fossil fuels](https://www.sciencedirect.com/topics/earth-and-planetary-sciences/fossil-fuel) and industrial activities significantly contribute to global climate change. The added environmental application of these materials in CO2 sequestration is comprehensively included in this review. The review summarizes the underlying mechanisms involved with each process and helps to understand the insights of the remediation processes. Further, this review extensively demonstrates various challenges of scaling up large-scale treatment using these materials and identifies the future perspectives in the concerted studies.

**Graphical Abstract**



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**Introduction**

The International Biochar Initiative (IBI) defines *biochar* as ‘‘a solid substance produced via a thermochemical process by converting biomass in an oxygen-limited condition” [1]. Using several thermo-chemical techniques, including pyrolysis, torrefaction, gasification, and hydrothermal carbonization, where carbonaceous biomass is heated to high temperatures (300–900 °C) and subjected to oxygen-limiting conditions, produces efficiently the biochar [2]. The biochar exhibits various unique properties such as high specific surface area and reactivity, pH, high ash content, porosity, carbon content, stability in structure, and functional groups on the surface, such as -OH, -COOH, -NH2 [3]. These unique properties prompted the scientific community to utilize these biochar materials for various applications, including environmental remediation.

Environmental remediation, particularly soil and water decontamination, is extensively studied in the literature. Previous research reported that biochar with many oxygen-containing functional groups, large surface areas, and cation exchange capacities have the effect of retaining, stabilizing, and inactivating pollutants (e.g., heavy metals, phosphates, nitrates, organic contaminants etc.,) and reducing the bioavailability and phytotoxicity of contaminants in the soil [4]. Biochar reduces the mobility of organic and inorganic pollutants in soil [5]. In addition to soil remediation, through the adsorption process, biochar shows widespread applications in the remediation of water contaminated with numerous pollutants [6]. Researches show extensive use of pristine biochar as sorbing materials for decontamination of soil and water contaminated with a variety of organic and inorganic contaminants viz., pesticides, dyes, persistent organic pollutants, antibiotics, etc., and heavy metals (Pb(II), As(III), As(V), Cd(II), Cu(II), Hg(II), Cr(VI), etc.), and other inorganic contaminants (PO43-, NO3-, F-, NH4+, etc.) [7]. The high stability of biochar towards physical and chemical distress possessed high carbon content and specific surface area, functional groups, and good adsorption capacity [8], enabling it to be an excellent adsorbent to remove contaminants from soil and aqueous solutions [9]. In addition to the sorption process, the biochar materials play a significant role in advanced oxidation processes and are applied to a more extensive range of reaction systems to degrade the emerging water contaminants [10].

Moreover, numerous studies have emphasized the advantages of employing pristine biochar for soil improvement, increasing agricultural output, carbon sequestration by reducing greenhouse emissions, and CO2 capture and storage [11]. However, biochar cannot adsorb pollutants, especially at high pollutant concentrations [12]. Aside from that, the small particle sizes of powdered biochar make it challenging for phase separations from the aqueous solutions [13]. Hence, it poses limitations of biochar in practical wastewater treatment. Similarly, the retention, stabilization, and inactivation of pollutants (organic contaminants, nitrates, phosphates, heavy metals, etc.) and the limited reduction of their bio-availability and phytotoxicity of pollutants in the soil all restrict the use of pristine BC. Similarly, although biochar is affordable for CO2 capture and sequestration, pristine biochar suffers from subpar surface and textural qualities [14]. All these led to exploring the engineered materials precursor to biochar to remediate the soil and water contaminated with emerging contaminants and efficiently capture the CO2 from the environment.

Therefore, extensive studies were conducted on various modifications of biochar having unique structures and surface properties to overcome the shortcomings of pristine biochar. In recent times, researchers intend to synthesize nanosized metal-based particles, i.e., zero-valent metal [15], metal oxides [16], clay minerals [17], graphene [18], metal-organic framework [19] and metal nanoparticles [20] and employed in environmental remediations. Metal nanoparticles (MNPs), in particular with a variety of distinct properties, e.g., high specific surface area and outstanding mechanical characteristics via size quantization effect [21], are found to be excellent adsorbent, reduction, oxidant, and efficient catalysts in various environmental remediation strategies [22]. However, one of the significant drawbacks of MNPs is that they seemingly aggregate and form bulk materials or forms oxides [23], suppressing the activities of MNPs. Thus, stacking nanoparticles on the surface of some supporting porous solid materials such as silica, zeolite, amorphous activated carbon, clay, sand, biochar, etc., significantly enhances their effectiveness [24]. Among these support materials, biochar offers advantages with increased surface area and cation-exchange capacities [25], [26]. Therefore, engineered/modified biochar materials possess relatively high surface area or pore structure and functionality [27]. The production methods of biochar-derived nanocomposites are generally categorized as follows: (i) composite materials of type N-MO/HB or nano metal oxide/ hydroxide-biochar; (ii) magnetic biochar composites that have magnetic properties for easy phase separation from aqueous mediums; and (iii) biochar functionalized with nanoparticles (*Cf.* Fig. 1(a)). The following sections demonstrate the synthesis of various methods and explore the advantages of each method. These methods primarily include either biomass pre-treatment or biochar post-treatment (*Cf.* Fig. 1(b)). The present classification demonstrates the diverse types of nanomaterials that are employed in the functionalization of biochar. These materials include magnetic iron oxide, nano-metal oxide/hydroxide (Fe0, MgO, CaO, Fe2O3, and Fe3O4, etc.), and functional nanoparticles (such as graphene, graphene oxide, carbon nanotubes, ZnS nanocrystals, layered double hydroxides, graphitic C3N4, graphene oxide, chitosan, etc.) [28], [29], [30]. The immobilized nanoscale materials on the surface of biochar overcome the devised shortcomings of pristine biochar and display varied physical/chemical properties, i.e., high surface area, thermal stability, surface active sites, ion exchange, and ease of phase separations [31].

The process of synthesizing a nanocomposite derived from biochar is not merely for enhancing the biochar's physical/chemical characteristics but to obtain a new composite called a novel BC-MNP that combines the advantages of biochar and nanomaterials [32]. These offer the following advantages: (i) The loaded metal nanoparticles are distributed and stabilized by BC-MNPs, which reduces aggregation, leaching, and surface passivation of metal nanoparticles [33]. This is due to biochar's ability to distribute and further improve the stability and mobility of specially engineered NPs, hence stabilizing them [26]; (ii) BC-MNPs exhibit superior functionality due to an increase in the number of active sites and functional groups with oxygen [34]; and (iii) By improving catalytic efficiency at BC-metal interactions, BC-MNPs speed up the reaction rate for pollutants removal [35]. Moreover, BC-MNPs enhance the thermal stability of materials [36].

The composites derived from biochar improve the efficiency of pristine biochar towards the remediation of aqueous wastes contaminated with various pollutants, viz., heavy metals and organic/inorganic pollutants [6], [37], [38]. For instance, a novel manganese-oxide/biochar composite exhibited five times higher monolayer sorption capacity of lead (II) at 25 °C than the pristine biochar [39]. The MF/biochar nanocomposite using MnFe2O4 efficiently removes various heavy metals, viz., lead (II), copper (II), and cadmium (II) [40]. The biochar (PB) derived from pine as a supportive material stabilizes the nZVI and eliminates the arsenic (V) [41]. In addition, metal oxide nanoparticles like MnOx bonded to a biochar matrix increase the surface area of biochar-derived composites and provide more active sites. The surface complexation of Cu2+ with the oxygen-containing functional groups of MnOx-loaded biochar removes the Cu2+ in an aqueous medium [42]. Biochar coated with nanosized magnetic iron oxide particles, such as Fe3O4 [43], γ-Fe2O3 [44], and CoFe2O4 [13], resulted in magnetism and provides active sites for the removal of various pollutants. Moreover, an external magnetic field readily separates the magnetic biochar from the solution, making easy phase separation. However, although biochar-coated nanoparticles show high sorption capacities for various contaminants, attention is required for their stability and potential environmental and biological toxicity [45].

Similarly, biochar-derived nanocomposites show potential in soil restoration applications, such as adsorbing and immobilizing metal ions, preventing the bioavailability of by-products, and improving soil fertility [46]. The engineered biochar-derived nanocomposites show an enhanced ability to retain various contaminants. For instance, the nZVI-BC immobilizes 100% of Cr(VI) compared to 21% by the respective pristine biochar from the contaminated soil [47]. In addition, these materials show extended applications in the catalytic and redox processes. The simultaneous adsorption and degradation capacity of biochar-derived nanocomposites with various catalytic and oxidative/reductive nanoparticles (such as nanoscale zero-valent iron and graphitic g-C3N4, etc.) distributed on the surface of the biochar removes emerging organic contaminants [48].

Moreover, these materials capture carbon dioxide (CO2) from the atmosphere efficiently. CO2 interacts with polar surfaces such as metal oxy-hydroxides, which are generally basic. The effectiveness of the metal oxyhydroxide biochar composites—magnesium hydroxide, iron hydroxide, and aluminum hydroxide provide suitable chemical and morphological structures to capture efficiently the CO2 [49].

Several research studies describe several aspects of biochar-derived nanocomposites, particularly their preparation/modification and applications in soil and water decontamination [25], [50]. The paper extensively demonstrates the decontamination of organic, inorganic, and heavy metal contaminants' impurities from the soil and water bodies because of their detrimental effects on human health. There is currently extensive literature available for soil remediation using pristine biochar, and few studies demonstrating the use of biochar-derived nanocomposites (engineered biochar) for soil decontamination. These materials treat the soil contaminated with mostly inorganic contaminants and heavy metals. The review reports addressing these soil/water remediation applications to eliminate these common pollutants and contribute to futuristic technological developments.

Furthermore, the review combines extended applications of these advanced materials in other emerging areas, such as catalysis [10], redox reaction (oxidative/reductive) [51], and carbon sequestration [52]. Therefore, the current review extensively entails applying biochar-derived nanocomposites for various environmental remediations, including soil/water remediation by sorption, catalysis, redox reactions, and CO2 sequestration from the atmosphere. Moreover, the synthesis of these materials is extensively demonstrated and provides insights into selecting specific synthesis procedures with desirable physicochemical properties suitable for intended usages. The underlying mechanisms are also summarized, which include the cation-π bonding, H-bonds, surface complexation, ion-exchange, hydrophobic interactions, and electrostatic attraction for sorption of heavy metals, organic and inorganic pollutants in decontamination of wastewater; precipitation, and electrostatic attraction, and inner-sphere surface complexation in soil remediation; free radicals by oxygen or sulfur in catalytic and oxidative/reductive applications. Similarly, the physisorption and chemisorption processes lead to carbon sequestration. Highlighting these specific mechanisms helps identify gaps in future research, innovations, or improvements within the selected mechanism. This review also paves the way for identifying the areas for more significant future implications of these advanced materials.

**Section snippets**

**Nanometallic oxide hydroxide-biochar (N-MO/HB) composites**

Nanometallic oxide hydroxide biochar composites have gained more interest in recent years due to their diverse structures and multifunctional applications [53]. There are three synthesis methods reported for preparing nano-metal oxide/hydroxide-biochar composites (N-MO/HB):

* (i)

enrichment of a target element via bioaccumulation (EEB);

* (ii)

pre-treating biomass using metal salt (PTBMS) and

* (iii)

incorporating the metal-oxide nanoparticles after pyrolysis (IMONPsAP).

Fig. 2 shows these methods schematically. In

**Biochar-derived nanomaterials for environmental remediation**

Biochar-derived nanocomposites showed varied applications in the remediation of water and soils contaminated with various pollutants and are discussed in detail here. In addition, the other applications of carbon sequestration, catalytic, and oxidative/reductive are summarized here. The underlying mechanisms involved are also summarized.

**Conclusion**

This review outlined various approaches for producing biochar-derived nanocomposites and their uses in environmental remediation. The various production methods (EEB, PTBMS, IMONPsAP, PTBIIs, CCP, PCBFNPs. IFNPsAP) involve the process of impregnating or incorporating a foreign substance within a biochar matrix to obtain biochar-derived nanocomposites.

PTBMS significantly improves the physiochemical properties of nanocomposites by increasing the specific surface areas (SSA) (*Ca.* 2 orders of

**Future perspectives**

* (1)

In the literature, various methods for producing biochar-derived nanocomposites were described, but further research should offer insight into optimizing synthetic conditions, selecting suitable biomass precursors, and modification strategies that can affect the properties of biochar. The specified method of synthesizing the engineered materials needs to be customized to maximize their effectiveness in the remediation of water/soil contaminated with various contaminants.

* (2)

Many reports have been

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.